HYPERLOOP – OPPORTUNITY FOR UK SUPPLY CHAIN

FINAL REPORT

September 2018

FORWARD

Hyperloop offers a potential revolution in transport. It could transform how we perceive distance by enabling aircraft speeds at ground level in an on-demand point-to-point transport system. Bristol could become a suburb of Edinburgh! Frankfurt, Schiphol, Heathrow and Charlies de Gaulle could become a new super-hub airport and it would open up opportunities we can't even conceive of yet.

So how likely is it that Hyperloop will become a reality? Virgin Hyperloop One's DevLoop in the Nevada desert is already an impressive feat of engineering. The approach Hyperloop Transportation Technologies have demonstrated to developing this new mode of transport is highly innovative. Things are moving fast, and although still a concept, there appears every possibility that a Hyperloop will be built somewhere in the world within the next five years. This presents the UK with a significant opportunity to get involved, to demonstrate the fantastic capability of British engineering, and to deliver valuable economic growth

The UK is renowned for its world-beating innovation. Just look at the proportion of the Formula 1 paddock that is British. The UK is world renowned for its aerospace industries, for ingenuity in design, and for delivering major infrastructure projects. This agility and capability in high precision engineering are the skills required for delivering an entirely new mode of transport such as Hyperloop in what are clearly ambitious timescales.

The UK has the industry, the gravitas and the experience to be a central player in the development of this potentially revolutionary new transport mode. This document should be used as a guide for those at the forefront of innovation in this exciting domain.

In the 18th Century the canals revolutionised transport. A second revolution was seen in the 19th century through the introduction of the railways. The 20th century delivered two step changes in mobility through the private car and aviation. The UK has been prominent in all of these and this report is intended to help ensure that the UK is front and centre of the next potential major development, the Hyperloop.

Venn Chesterton

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EXECUTIVE SUMMARY

This report has been prepared by the Transport Systems Catapult (TSC), with assistance from the High Value Manufacturing Catapult (HVMC), on behalf of Innovate UK to explore the potential opportunities for jobs and growth within the UK supply chain associated with hyperloop.

Hyperloop refers to the concept described by Elon Musk in his paper, Hyperloop Alpha, published in 2013. It involves either passenger or freight carrying vehicles operating inside tubes with air evacuated. The reduced air resistance resulting from the low-pressure environment could enable the vehicles to reach very high speeds; 2-3 times faster than high speed rail. Proponents also claim that the system can enable direct, on-demand travel rather than a scheduled service as provided by other forms of public transport, could be more environmentally friendly than other modes and could be cheaper than high-speed rail.

The UK Government's Science Advisory Council (SAC) published a position statement on hyperloop in November 2017 which stated:

> **The SAC recognises that a UK Hyperloop network has the potential to stimulate economic development across the country by substantially reducing journey times. Indeed, stated maximum speeds of around 700 mph correspond to travel times of less an hour between most UK destinations. This could have a transformational impact, for example allowing commuters to live anywhere within the country and easily commute great distances. It would also provide a means of connecting separate towns and cities to deliver agglomeration benefits.**

The project team consulted with hyperloop developers, industry and academia to investigate the technical requirements and challenges of hyperloop. These challenges were mapped onto the capability of the UK supply chain, and prioritisation of those key areas where investment of public funding will stimulate UK Industry to provide future support to hyperloop and associated technology applications to the benefit of the UK economy.

Prioritisation of potential investment areas was undertaken by first considering the key challenge areas facing hyperloop developers. A simple scale of 1-5 was used for the main challenges, with 5 being of most value to hyperloop development and 1 being least value.

A score was then applied based on the extent to which the UK has capability to assist, relative to other countries. If the UK is a world leader in a particular field, this scores highly. Again, a scale of 1-5 was used.

Each challenge area was colour coded according to whether it is a short term, medium term or longer-term requirement. Short term can indicatively be considered as 0-2 years, medium term is 2-5 years and longer term is 5+ years (although this will vary depending on the ambitions of the hyperloop developer).

The following diagram summarises the results:

On this basis it may be useful to consider in more detail how the UK can assist in areas such as Enterprise Business Models, Solution Architecture, Propulsion / Energy Storage / Thermal Management and Communications technology. In the slightly longer term (or maybe in the short term with a view of creating the business case) minimising the cost of infrastructure will be of huge importance.

This project has not attempted to assess the technical feasibility of hyperloop. Hyperloop is relatively early in the R&D lifecycle, although the information presented to the project team suggests that there is no technical reason why a hyperloop cannot be built, and the more significant challenge is associated with minimising infrastructure cost. Some key system design decisions still appear to be yet to be finalised, and discussions suggest that there are technical areas where further development is needed. This includes energy storage, thermal management, propulsion and connectivity. Other areas that would assist hyperloop developers include creating enterprise business models.

Enabling the supply chain to engage with hyperloop development overseas is challenging. UK capabilities would need to be clearly preferable to those of the local supply chain to win contracts. However, it is understood that UK arms of multi-national companies are actively involved in pursuing large contracts for hyperloop construction. It has been suggested that top level Government support could assist in helping to support the potentially large contracts that could be available. In addition, the UK has specific expertise that could assist with hyperloop development, such as world leading manufacturers of linear induction motors and suppliers to the motorsport industry. Such expertise could undoubtedly help to optimise aspects of the hyperloop system.

If a hyperloop testing facility were to be constructed in the UK it could create a hub of activity and ensure expertise is developed in the UK, and the UK supply chain is favoured. There would also be secondary benefits in that technology developed for hyperloop would also be valuable in other sectors. An example could be improving the efficiency and reducing the cost of tunnelling, which would be of benefit to many subterranean infrastructure projects.

Applications of hyperloop could assist with other major infrastructure challenges. For example, linking airports with hyperloop connections could provide an alternative to airport expansion. Linking cities could avoid the need for new road and rail links. Hyperloop could play a part in helping to rebalance the UK economy by enabling commuters to live further from their work, thus reducing the pressure on housing in the South East. It should also be noted that indications suggest hyperloop construction costs may compare favourably to high speed rail costs.

Freight pipelines and personal rapid transit systems are applications that use similar types of technology to that needed for a hyperloop and could be more deliverable in the short term. These types of systems could take advantage of the hyperloop publicity and excitement and could act as stepping stones towards hyperloop deployment.

The following Government initiatives are recommended based on the findings of this study:

1. Launch a UK event to bring hyperloop developers and interested parties from the UK supply chain together. This could develop into an annual conference which accelerates collaboration in this area.
2. Coordinate with UK industry to offer a joined-up offering of UK capabilities to hyperloop developers, with focus on those areas identified in this report. This could provide greater impact than small companies attempting to sell their services individually. Top level Government support should be available for supporting the UK supply chain in this activity.
3. Undertake an independent deep dive into the technical and economic feasibility of hyperloop. This would better inform the decision as to whether to construct large scale testing facilities in the UK, and potential timescales for likely hyperloop deployment which is crucial in considering hyperloop alongside other transport solutions.
4. Undertake a review into the potential opportunities and economic benefits presented by hyperloop. This should consider how linking certain airports with hyperloop could help with airport capacity issues, how hyperloop could impact on the housing market and how it could save the need for investment in other types of infrastructure.
5. Undertake an investigation into the feasibility and business case surrounding freight pipelines, with a view of using public finance to help develop testing facilities and enable commercial deployment and export.
6. Undertake an investigation into the feasibility and business case surrounding personal rapid transit schemes and innovative new modes that is based on similar technology.

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DISCLAIMER

This report has been produced by the Transport Systems Catapult on behalf of Innovate UK. Any views expressed in this report are not necessarily those of Innovate UK.

ACRONYM LIST

ACRONYM	TERM
BEIS	Department of Business, Energy and Industrial Strategy
CCAV	Centre for Connected and Autonomous Vehicles
DfT	Department for Transport
FE	Force Engineering Ltd
HS1	High Speed Rail 1
HS2	High Speed Rail 2
HTT	Hyperloop Transportation Technologies
HVMC	High Value Manufacturing Catapult
IUK	Innovate UK
MagLev	Magnetic Levitation
SAC	Science Advisory Council
TSC	Transport Systems Catapult
VH1	Virgin Hyperloop One

1 INTRODUCTION

1.1 INTRODUCTION

This report has been prepared by the Transport Systems Catapult (TSC), with assistance from the High Value Manufacturing Catapult (HVMC), on behalf of Innovate UK to explore the potential opportunities for jobs and growth within the UK supply chain associated with hyperloop.

Hyperloop refers to the concept described by Elon Musk in his paper, Hyperloop Alpha[1], published in 2013 and involves either passenger or freight carrying vehicles that operate inside tubes with air evacuated to create a low-pressure environment. The reduced air resistance resulting from the low-pressure environment could enable the vehicles to reach very high speeds; 2-3 times faster than high speed rail. Proponents also claim that the system can enable direct, on-demand travel rather than a scheduled service as provided by other forms of public transport, could be more environmentally friendly than other modes and could be cheaper than high-speed rail.

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> “The SAC recognises that a UK Hyperloop network has the potential to stimulate economic development across the country by substantially reducing journey times. Indeed, stated maximum speeds of around 700 mph correspond to travel times of less an hour between most UK destinations. This could have a transformational impact, for example allowing commuters to live anywhere within the country and easily commute great distances. It would also provide a means of connecting separate towns and cities to deliver agglomeration benefits.

In terms of supporting its development, the SAC stated:

> “The SAC believes that the United Kingdom has a significant level of relevant expertise and experience from its strong academic and industry base to support the worldwide development and delivery of Hyperloop systems.

The paper went on to state:

> “The SAC believes that British engineering expertise supported by our strong professional services and infrastructure delivery sectors could play an important role in developing and commercialising the technology.

Transport Systems Catapult – Hyperloop – Opportunity for UK Supply Chain

1.2 SCOPE

This report investigates:

- the technical requirements and challenges of hyperloop,
- a mapping onto the capability of the UK supply chain,
- and prioritisation of those key areas where investment of public funding will stimulate UK Industry to provide future support to hyperloop and associated technology applications to the benefit of the UK economy.

The report does not review the technical nor economic feasibility of hyperloop or attempt to predict timescales for the first implementations of hyperloop. The assumption is that hyperloop may happen and asks what opportunities are presented for the UK supply chain.

1.3 APPROACH

The project team visited the facilities of two hyperloop developers in Nevada and California as part of this study.

Interviews were conducted with key experts, which included:

- Organisations developing hyperloop systems
- Partners of organisations developing hyperloop systems
- Experts on capabilities that might be relevant in addressing hyperloop challenges.

The above engagement was supplemented with desk-based research and analysis.

1.4 REPORT STRUCTURE

This report is structured as follows:

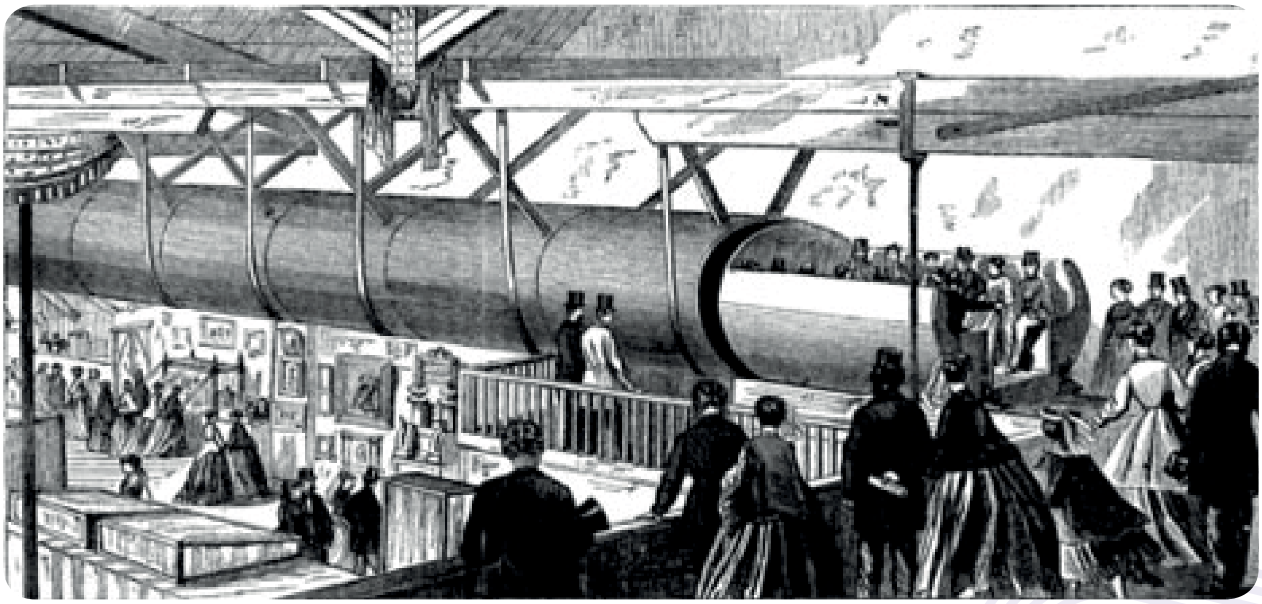
- **Section 2** confirms the organisations that the project team spoke to in order to gather information for this report and highlights the types of organisation with which further dialogue could be beneficial.
- **Section 3** discusses the existing and planned test facilities associated with some of the main hyperloop developers and outlines the future vision of these main companies.
- **Section 4** discusses the requirements and challenges facing hyperloop systems.
- **Section 5** considers the strengths of UK Industry in relation to hyperloop, both existing and those with the potential for growth resulting from future benefits.
- **Section 6** outlines some of the issues and opportunities relating to constructing UK based hyperloop systems, either for testing purposes or full-scale deployment.
- **Section 7** considers the comparisons with Freight Pipelines, and other forms of innovate 'guided transport' technology.
- **Section 8** maps the hyperloop requirements onto the capabilities of the UK supply chain.
- **Section 9** presents the conclusions and recommendations.

Appendix A reproduces the AECOM Hyperloop One Global Challenge submission dated October 2016,
Appendix B includes a summary of the related opportunity of 'Freight Pipelines'.
Appendix C discusses the opportunities around Personal Rapid Transit and associated systems.

2 HYPERLOOP BACKGROUND

2.1 CONTEXT

The idea of a mass transport system that involves propelling vehicles along low pressure tubes was discussed as long ago as the late 17th century following the invention of the world's first artificial vacuum. Many subsequent configurations have been attempted for transporting both small parcels and messages, and even passengers, such as the following experimental system erected at the American Institute in New York in 1867:



Alfred Ely Beach's experimental pneumatic elevated subway on display in 1867[3]

Pneumatic tubes have been in common usage for the delivery of messages and small parcels, for example the system that linked the London Stock Exchange to the city's main telegraph station, built in 1853. Such tubes have been widely used to transport cash in banks and supermarkets. The picture to the right illustrates a system that transports messages in Washington in the 1940s[4].

'Vactrains' or 'pneumatic subway systems' capable of transporting large numbers of human passengers have been developed to various degrees, but the idea was recently energised and popularised by the publication of a paper by Elon Musk in 2013, where he termed the concept 'Hyperloop'.

[1] By Alfred Ely Beach [Public domain], via Wikimedia Commons
[2] [Public domain], via Wikimedia Commons

2.2 WHAT IS HYPERLOOP?

Hyperloop refers to the concept described by Elon Musk in his paper, Hyperloop Alpha[5], published in 2013 and involves either passenger or freight carrying vehicles that operate inside tubes with air evacuated to create a low-pressure environment. The reduced air resistance resulting from the low-pressure environment could enable the vehicles to reach very high speeds; 2-3 times faster than high speed rail. Proponents also claim that the system can enable direct, on-demand travel rather than a scheduled service as provided by other forms of public transport, could be more environmentally friendly than other modes and could be cheaper than high-speed rail.

The main hyperloop developers are primarily focussed on creating a passenger moving hyperloop, which is the focus of this report, although exclusively freight moving solutions have also been considered later in the report.

The consensus regarding levitation and propulsion appears to be that vehicles will be levitated using passive magnetic levitation (rather than air bearings as originally proposed by Musk) and propelled using electric motors as illustrated in videos produced by Hyperloop Transportation Technologies[6], Virgin Hyperloop One[7] and in a paper published by Transpod[8].

The tube could be built in either steel or concrete or a wide number of composite materials. The optimal material is currently being developed. The tube could be below ground, on the ground or above ground on pylons. To reach the highest speeds envisioned (around 700mph) the vertical and horizontal alignment must be straight to avoid uncomfortable G-forces on passengers, although this could be mitigated by slowing the vehicle through curving sections combined with banking the track within the tube.

Air could be evacuated using standard industrial pumps positioned along the tube. The whole system would be under low pressure, but could be returned to atmospheric pressure in case of emergencies. Some hyperloop companies have discussed a system at stations were a walkway extends to the vehicle door and forms a seal so that passengers can board and alight, avoiding the need for vehicles to pass through air locks.

Vehicles could be fully-automated and smaller than those used in traditional rail systems, but could operate at much higher service frequency which creates a more demand-responsive service. Vehicles could be able to switch between tubes to enable 'main line' and 'sidings' so that passengers would not need to stop at every station on route, although the detail of how switching works has not been provided to the project team.

[5] http://www.spacex.com/sites/spacex/files/hyperloop_alpha-20130812.pdf
[6] https://www.youtube.com/watch?time_continue=66&v=RPAtHvyvV[illegible]k
[7] https://hyperloop-one.com/hyperloop-explained
[8] http://transpodresearch.org/files/docs/TransPod_ProcediaEngineering2017Janzen.pdf

2.3 WHO IS DEVELOPING HYPERLOOP?

The following organisations are developing some form of hyperloop. This list may not be exhaustive.

ORGANISATION	LINK TO WEBSITE	BASE OF OPERATIONS	SUMMARY NOTES
Virgin Hyperloop One (VH1)	https://hyperloop-one.com/	Los Angeles, USA	Constructed 'DevLoop' test facility in Nevada. Pod vehicles tested up to 240mph. Significant investment from Virgin Group. Development interests include India (Mumbai – Pune) and Dubai – Abu Dhabi. Approx. 250 employees.
Hyperloop Transportation Technologies (HTT)	http://www.hyperloop.global/	Los Angeles, USA	Developing test facilities in Toulouse, France, due to begin testing later this year and plans to develop Hyperloop Innovation Center in Toulouse. Innovative business model which leverages input from a wide pool of contributors in exchange for stock options. Full-scale capsule interior developed. Agreement to undertake feasibility study to connect Abu Dhabi and Al Ain.
TransPod	https://transpod.com/en/	Toronto, Canada	Plans for construction to commence on half-scale test facility near Limoges in France later this year. Partnership with Liebherr-Aerospace. Initial cost study released which found TransPod system would cost 50% less than high-speed rail in Southwestern Ontario. Peer reviewed paper released on physics of TransPod system.
DGW Hyperloop	https://www.dgwhyperloop.cf/	Indore, India	Subsidary of Diniclix Groundworks, an engineering company based in India. Focus on corridor between Delhi and Mumbai.
Hardt Global Mobility	https://hardt.global/	Delft, Netherlands	Emerged from TU Delft team that won SpaceX Pod competition in 2017. Establishing full-scale test centre in Delft, Netherlands. Plans for 5km test facility in province of Flevoland, Netherlands. Anticipated cost is 120 million euros. Dutch House of Representatives voted in favour of investigating financing.
rLoop	https://www.rloop.org/	Global online community	Global community of engineers collaborating to develop hyperloop concept. Won SpaceX innovation award.
Hyper Poland	http://transpodresearch.org/files/docs/TransPod_ProcediaEngineering2017_Janzen.pdf	Warsaw, Poland	Took part in SpaceX Pod Competition II. Over 20 engineers.
Hyper Chariot	https://www.hyperchariot.com/	Santa Monica, USA	Plans to build a smaller version of hyperloop that can reach speeds of 4,000mph.
Zeleros	http://zeleros.com/	Valencia, Spain	Emerged from Hyperloop UPV team from Universitat Politècnica de València, which was awarded "Top Design Concept" and "Propulsion/Compression Subsystem Technical Excellence" by SpaceX at Hyperloop Design Weekend. Constructed prototype and 12m test track in Spain. Awarded Everis Foundation price in 2017.

2.4 VISIONS OF HYPERLOOP

This section outlines visions of hyperloop as provided by hyperloop developers.

VIRGIN HYPERLOOP ONE

VH1 has presented a vision of how hyperloop could work. *The following images show how stations could look in Dubai:*

Virgin Hyperloop One vision for station in Dubai

HYPERLOOP TRANSPORTATION TECHNOLOGIES

HTT present the following images on their website showing the infrastructure and the vehicle.

Hyperloop Transportation Technologies tube and vehicle concepts

[9] Hyperloop Explained, Virgin Hyperloop One, published 2nd August 2017, https://youtu.be/LAWEOwDDt_Y

DEWDROP

- Hyperloop terminal station prototype
- Circular guidance and Operating System

PLATFORM

- 3,600 passengers per hour
- Every gate will manage 180 people per hour

INTEGRATION

- Easily built into the existing infrastructure
- Convenient to build within the city

Hyperloop Transportation Technologies station concept

The following images illustrate how the HTT system could look in the United Arab Emirates.

TRANSPOD

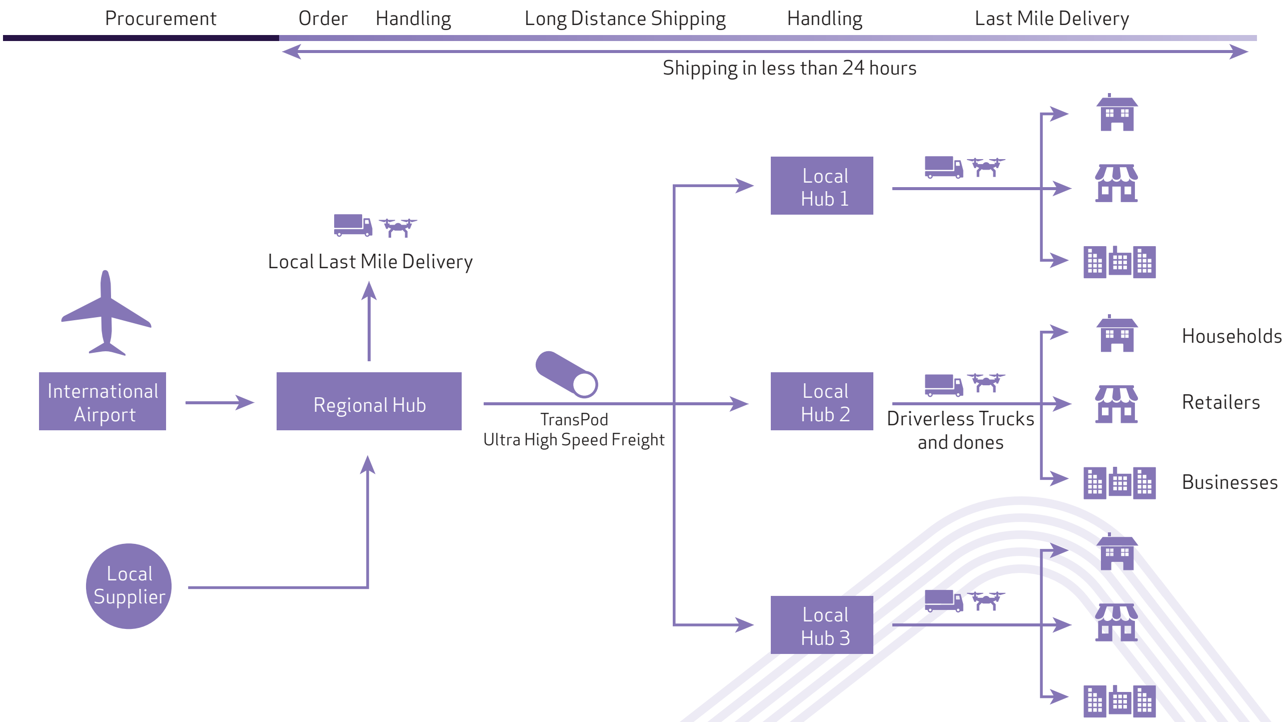
Transpod have produced the following images showing the concept design for infrastructure and vehicles, and have produced a video showing how a future station could look.[10]

Transpod aerospace vehicles are designed to carry passengers between cities at ultra-high-speeds. Faster than airline travel, the Transpod tube system is a comfortable, rapid alternative to highway congestion.

[10] https://transpod.com/en/transpod-system/passenger-transportation/

The following image shows how freight could be loaded onto a hyperloop vehicle:

The diagram below was produced by Transpod to show the role hyperloop could play in a future freight distribution network:



2.5 TEST FACILITIES

This section discusses existing and planned hyperloop test facilities.

VIRGIN HYPERLOOP ONE

VH1 has built a 3.3m diameter, 500m long test track facility, known as 'DevLoop', in Clark County, Nevada.

A video of their latest testing (Phase 3 – December 2017) is available to view online.

With reference to this test, the company stated:

> "Virgin Hyperloop One has also set a historic test speed record of nearly 387 kilometers per hour (240 miles per hour, 107 meters per second) during its third phase of testing at DevLoop, the world's first full-scale hyperloop test site. The company achieved faster speeds and tested a new airlock which helps transition test pods between atmospheric and vacuum conditions during its latest test campaign which was completed on December 15, 2017. All components of the system were successfully tested including:
>
> - the airlock,
> - highly efficient electric motor,
> - advanced controls and power electronics,
> - custom magnetic levitation and guidance,
> - pod suspension, and
> - the vacuum.
>
> The tests were conducted in a tube depressurized down to the equivalent air pressure experienced at 200,000 feet above sea level."

The project team (TSC and HVMC) together with IUK visited the DevLoop facility in May 2018. The visit provided an opportunity to explore that current state of the art in terms of technology and to establish what the team has learnt from testing using DevLoop. It also enabled the project team to see elements of the system which are not made available to the public due to commercial sensitivities, such as the vehicle levitation and propulsion system.

[11] https://www.theverge.com/2017/12/19/16795386/virgin-hyperloop-test-one-top-speed-airlock

SPACE X

Space X, a company owned by Elon Musk, has constructed a section of Hyperloop test track in Hawthorne, California. The tube is approximately 1 mile (1.6km) in length and 6 feet (1.83m) in outer diameter. In January 2017 and August 2017 they hosted global competitions which invited organisations, particularly universities, to develop prototype pod vehicles. The team with the fastest recorded vehicle speed was declared the winner. A video is available that summarises the event in August 2017.[12]

TSC and HVMC visited Edinburgh University to meet with the Hyp-Ed team team who entered the previous Space X competition and will be the UK's sole entry into the next on 22nd July 2018.

Edinburgh University's Hyp-Ed team at the SpaceX Pod Competition, California

OTHER PLANNED TEST FACILITIES

Hyperloop Transportation Technologies (HTT) is working on testing facilities in Toulouse, France in an area known as 'Aerospace Valley'. Construction started in December 2017 of a full scale 1km long 4m diameter tube that will accommodate a full size vehicle, which is also under construction. HTT stated to TSC that this will enable the first tests of a hyperloop system carrying human passengers.

Before the construction of the test track on pylons, which will measure one kilometer long, HTT will initially install a temporary track that will be placed on the ground and will be 300 meters long. Both will enable tests in order to validate the technical concept.

Each of these steel tubes measure 40 meters long and weigh 65 tons.

Transpod, a hyperloop development company based in Canada, is planning a test facility to be built in France later this year. This will be a 3.5km long half scale system and will cost 20M euros. They stated that a full scale 6-10km long route is planned in Canada with construction due to start next year.

[12] https://youtu.be/pm48hdYskt0

3 CONSULTATION

To inform the production of this report, the project team spoke representatives from the following organisations:

Organisation	Reason for Discussion
Hyperloop Transportation Technologies	Hyperloop developer
Transpod	Hyperloop developer
Virgin Hyperloop One	Hyperloop developer
Arup	Engineering consultants, proponents of 'Northern Arc' hyperloop route between Liverpool and Glasgow
PA Consulting	Systems engineers working with Virgin Hyperloop One
Linear Motion	Designers of linear induction motors (LIMs) and proponents of 'Magway' system for moving freight through pipelines
Mole Solutions	Proponents of system for moving freight through pipelines
University of Nottingham - Expert in linear machines for actuation, transportation and high speed launch	Exploring propulsion systems for Hyperloop
Force Engineering	Designers and manufacturers of LIMs
University of Southampton – Institute of Sound and Vibration Research	Expertise in vibration, noise and ride quality for transport systems
Hyp-Ed – University of Edinburgh Hyperloop Team	Proponents of Edinburgh to London hyperloop route, SpaceX pod competition entrants and hyperloop research body
Niche Vehicle Network	Connections to motorsport industry
Motorsport Industry Association (MIA)	Capabilities in rapid vehicle profiling and testing
Beemcar	Proponents of personal rapid transit system, potential comparisons with hyperloop
AECOM	Engineering consultants, proponents of 'Scotland to Wales' hyperloop route that connects Cardiff to Glasgow via London

The above list provided a good introduction but should not be considered exhaustive of all parties that may have an interest in hyperloop. Time and budgetary constraints prevented more extensive consultation, and some organisations failed to respond to the request to make contact.

For example, it would be useful in follow up studies to consult with:

- Further hyperloop developers
- Organisations involved in financing of major infrastructure projects and enterprise companies / investors (e.g. Virgin, who has invested in Hyperloop One)
- Further engineering consultants to explore aspects related to planning and construction, including tunnelling
- Aerospace companies
- Experts in autonomous control systems and vehicle communications technologies
- Safety case experts with background in hyperloop
- Organisations involved in Crossrail and HS2

The results of the consultation discussions have been integrated into all chapters of the report.

4 HYPERLOOP REQUIREMENTS/CHALLENGES

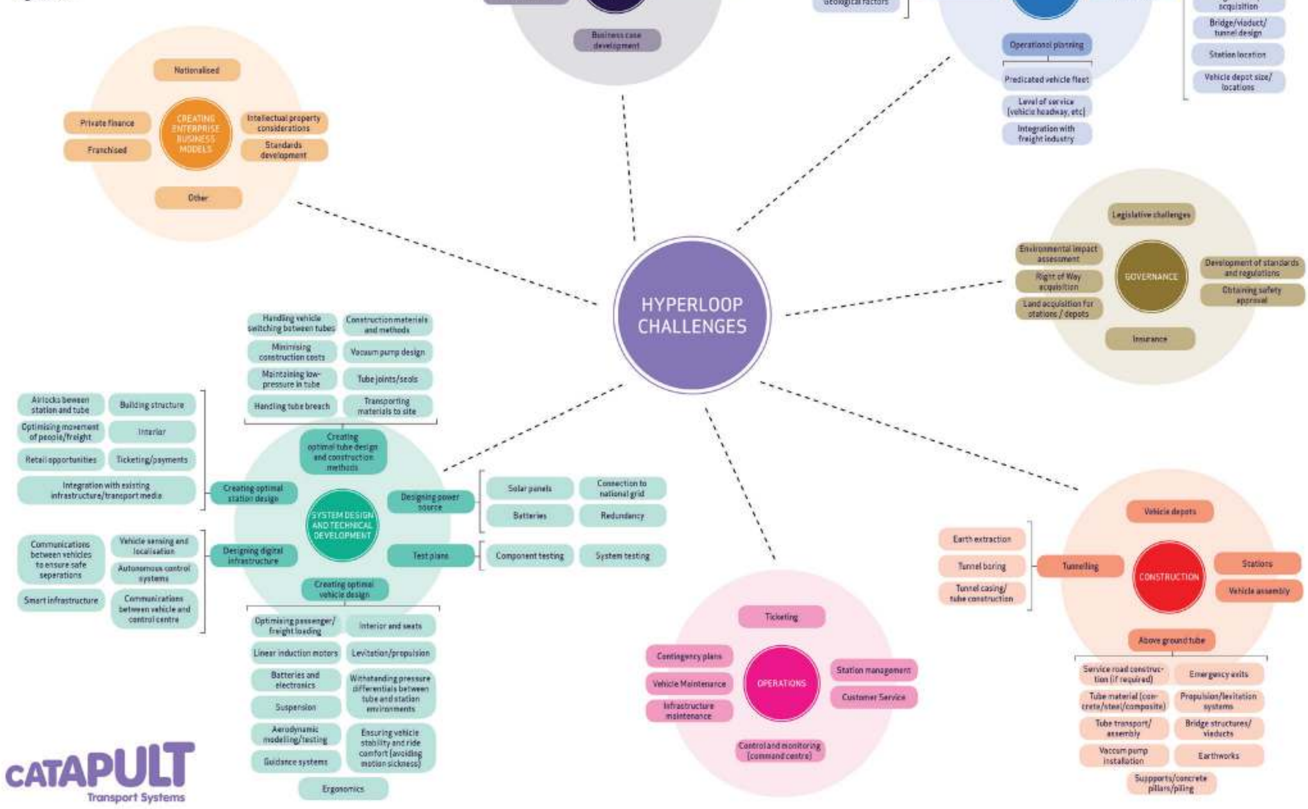
4.1 INTRODUCTION

As part of this study, the requirements and challenges of a theoretical hyperloop system have been investigated so that these can be later mapped onto the capabilities of UK industry. For this purpose, a mind map was prepared which separates components into a number of areas. The mind map is shown as Figure 4-1. Previous iterations of this mind map have been shared during the consultation process, and it has evolved in response. Based on comments received as part of the consultation exercise it is considered a good representation of the needs of a generic hyperloop system, although the details will vary depending on the exact implementation.

The mind map headings have been set out below together with some further explanation of certain aspects.

Mind Map of Hyperloop Challenges

Figure 4-1



4.2 OVERARCHING CAPABILITY NEEDS

'Overarching capability needs' refers to capabilities that are fundamental to delivering most aspects of the hyperloop system. This includes management of risks to project delivery. Risks will not only relate to technology readiness levels but also to manufacturing readiness levels and supply chain readiness levels. During conversations the project team were encouraging the hyperloop developers to outline what they considered to be the biggest risks to delivery, which enabled discussion as to where the UK can help.

Almost all aspects of hyperloop development feed into business case development. A solid business case is essential for securing investment and political support.

Project management skills are fundamental to any large infrastructure project, as are systems engineering skills which can be considered the glue that holds the technical project together.

Human factors considerations need to be considered throughout to ensure the solution is something that people want to use.

4.3 CREATING ENTERPRISING BUSINESS MODELS

This capability area is focussed around securing finance, which could come from a variety of private and public sources. Without financing, infrastructure projects simply cannot happen.

Related to financing is the building of the business case, which forms the basis of investment.

4.4 GOVERNANCE

This capability involves both the private and public sector to ensure the scheme can be advanced through the appropriate channels of governance to be granted permission and deemed acceptable to the public. In the UK this might include environmental impact assessments, Parliamentary White Paper publication to secure consent for a major infrastructure project of national significance, ultimately leading to Royal Assent and an Act of Parliament.

The proposal from AECOM as part of their submission to the Hyperloop One Global Challenge (reproduced at Appendix A) outlined how they envisaged such a mechanism for a UK hyperloop, with a new company set up to oversee delivery:

> **Similar to other recent infrastructure projects, Hyperloop UK Ltd will be a newly formed limited company dedicated to delivering the project. The company will have responsibility for promotion, funding, design, engineering, construction and procurement of an eventual operator. The company will act on behalf of private and public sector partners that are expected to include government departments, private investors, infrastructure providers and commercial developers. Hyperloop UK will have a dedicated team of staff and when needed technical and design advice from consultants to draw on.**

An important aspect is the development of the safety case and obtaining safety approval for a project of this type.

4.5 SYSTEM DESIGN AND TECHNICAL DEVELOPMENT

This category relates to the research and development phase of hyperloop and includes creating optimal vehicle and infrastructure and station design, developing test plans, designing the digital infrastructure and power source.

As this is where hyperloop development is currently focussed, many conversations revolved around the particular challenges in this area.

LEVITATION / PROPULSION

The details of levitation and propulsion are fundamental to the hyperloop system. The technology revolves around linear motors and it seems there is a choice between installing motors on the track compared with on the vehicle. To install them on the track would significantly add to the cost per kilometre, but to install on the vehicle adds significantly to the weight of the vehicle.

ENERGY STORAGE

Even with a low-pressure environment, accelerating a vehicle which could be in the order of 40 tonnes to speeds of around 670mph (300 meters / second) requires a lot of energy. This energy must either be transferred from the infrastructure to the vehicle, or must be stored on the vehicle. To store energy would require a battery array, or some other method of energy storage. Installing batteries would add significantly to the weight of the vehicle, although battery technology is advancing.

THERMAL MANAGEMENT WITHIN VEHICLE

Thermal management was described by some as the most significant technical challenge facing the hyperloop concept. People and equipment within the vehicle will generate heat, and to avoid temperature rising within the vehicle the heat must be transferred somewhere. With little air outside the vehicle to transfer the heat to it will probably need to be stored somewhere within the vehicle, although carrying material that can store heat will add to the weight of the vehicle.

CREATING ROBUST TUBE INFRASTRUCTURE AND MAINTAINING LOW PRESSURE OVER LARGE VOLUME

Another thermal management issue relates to the pipelines and thermal expansion due to heat. Managing tube expansion whilst maintaining the near-vacuum presents a challenge. Atmospheric forces will continuously act on the outside of the tube, which reportedly would equate to around 10,000kg per square kilometre and must be strong enough to resist buckling. The tube will also be subjected to significant internal forces by the vehicle. By it's very nature, hyperloop would be creating the largest vacuum chamber in the world by some margin. The tube could also be subjected to damage related to ground movement, road traffic accidents (if near to a highway) or acts of terrorism.

VEHICLE STABILITY / RIDE QUALITY

Hyperloop developers have confirmed that they are working towards recognised ISO Standards in terms of ride quality. There are no strict 'limits' with respect to ride quality for a particular mode of transport, although there is a process for measuring it and benchmarking against other systems. Hyperloop developers need to decide ahead of time what ride quality they are aiming for and design the system accordingly. It was suggested to TSC that in the rail industry ride quality is falling down the list of priorities. Alongside vibration, designers need to consider noise. This could be challenging for hyperloop with the need for compressors on vehicles and the vehicle speeds involved.

HANDLING TUBE BREACH / SYSTEM RESILIENCE

Hyperloop companies are thinking carefully about tube breach, both in the form of a sudden, catastrophic breach or a smaller breach that results in air entering the tube faster than the vacuum pumps can extract it. It is claimed that solutions are in place and could be tested in simulation, but there is a need to test them in the real world. There is a challenge around how to accelerate vehicles from rest once they have stopped within the tube as a result of power loss. The initial acceleration could be provided from infrastructure at stations, with smaller amounts of power provided along the journey to allow the vehicle to maintain coasting speed, but if the vehicle needed to stop it may be impossible to provide sufficient power to accelerate back up to full speed.

STATION DESIGN

There is limited benefit in creating a system that can move people or freight at extremely high speeds between stations if there are then significant delays at the stations. Station design for a passenger carrying hyperloop will need to focus on efficiency of movement, combined with a high level of customer experience.

The vehicle would probably remain in a low-pressure environment whilst a sealed passenger walkway extends to the vehicle to dock with the vehicle doors. This solution would avoid vehicles being subjected to large pressure differentials.

DIGITAL INFRASTRUCTURE

Digital infrastructure refers to the control systems that understand where vehicles are, where they are needed and ensuring they do not collide. Communications is a key aspect, and there is a challenge associated with maintaining a high degree of reliability for communications links through the shielded nature of hyperloop infrastructure.

DESIGNING POWER SUPPLY

Power supply could include solar panels but it may also be necessary to consider connections to the national grid, and other sources to ensure redundancy.

TEST PLANS

Test plans must be developed to test individual components of the system, but also the whole system working together. One of the main challenges is replicating the full-scale size and length of tube for testing purposes.

CREATING OPTIMAL TUBE / TUNNEL DESIGN

Designing cost effective 'track' infrastructure for the considerable lengths of route being considered (sometimes many hundreds of kilometres) could be amongst the most important requirements for creating a convincing business case for hyperloop.

There are two possibilities; either construct a tube mounted above ground (either on ground or on supporting pillars) or create a tunnel. There are pros and cons of both methods. Above ground tube construction would be cheaper (as much as 10 times cheaper by some estimates) and could present less of an engineering challenge associated with maintaining the low-pressure environment and maintenance, but right of way constraints may require the alignment to curve more than desirable both horizontally and vertically which either negatively impacts on ride quality or necessitates a reduction in vehicle speed (or both). Positive comparisons could be made between hyperloop and high-speed rail, in that if the tube is supported on pillars it does not need to sever the landscape as a railway line does. Farmers could continue to work the land on both sides of and even underneath the hyperloop infrastructure.

An advantage of tunnels is that they can be constructed with a straighter alignment if the geology is acceptable and there is no conflicting subterranean infrastructure, although this is becoming increasingly challenging especially in large cities that have comprehensive metro systems, sewer systems, etc.

Above ground tubes also need to be environmentally acceptable in terms of appearance, noise etc, and will require planning permission and lengthy consultation processes, whereas tunnels are more straight forward from this perspective. Tunnelling needs to take account of the potential impact of any ground movement and noise that is detectable on the surface, but otherwise there is no impact on people at surface level.

As for high speed rail, the construction of an above ground tube will probably require the construction of a service road to transport the equipment to site, which creates additional cost and complications. This has led some hyperloop developers to consider routes alongside existing highways or even along proposed rail corridors, for which service roads will already be needed.

A disadvantage of an above ground tube is that it would be more susceptible to damage either from terrorism or some other accidental cause (e.g. a lorry crashing through a barrier and into the supporting pillar of the hyperloop tube). This can be avoided with tunnelling.

The issue of tunnelling cost is being tackled by 'The Boring Company', an Elon Musk initiative based in the US. They describe on their website[13] methods of reducing the cost of tunnelling:

"First, reduce the tunnel diameter. The current standard for a one-lane tunnel is approximately 28 feet. By placing vehicles on a stabilized electric skate, the diameter can be reduced to less than 14 feet. Reducing the diameter in half reduces tunneling costs by 3-4 times.

Second, increase the speed of the Tunnel Boring Machine (TBM). TBMs are super slow. A snail is effectively 14 times faster than a soft-soil TBM. Our goal is to defeat the snail in a race. Ways to increase TBM speed:

- **Increase TBM power.** The machine's power output can be tripled (while coupled with the appropriate upgrades in cooling systems).
- **Continuously tunnel.** When building a tunnel, current soft-soil machines tunnel for 50% of the time and erect tunnel support structures the other 50%. This is inefficient. Existing technology can be modified to support continuous tunneling activity.
- **Automate the TBM.** While smaller diameter tunneling machines are automated, larger ones currently require multiple human operators. By automating the larger TBMs, both safety and efficiency are increased.
- **Go electric.** Current tunnel operations often include diesel locomotives. These can be replaced by electric vehicles.
- **Tunneling R&D.** In the United States, there is virtually no investment in tunnelling Research and Development (and in many other forms of construction). Thus, the construction industry is one of the only sectors in our economy that has not improved its productivity in the last 50 years."

4.6 PLANNING

Planning of a large scale national infrastructure project can be a long and complex task. It can be broadly split into two questions; where should hyperloop go and where could hyperloop go? The where should hyperloop go question refers to potential demand for such a service linking the particular cities along the route. This is where traditional transport modelling techniques are needed to consider potential number of trips, which includes new trips and abstracted trips from other modes of transport. This can then be translated into a service plan to determine the size of the vehicle fleet required and the level of headway necessary between vehicles.

The 'where could hyperloop go question' refers to constraints and infrastructure costs. Consideration needs to be given to right of way acquisition, detailed surveys and geological analysis. Based on the hyperloop visions presented in ***Section 2***, considerable land areas would be needed within city centre environments for stations, and areas would also be needed for vehicle depot facilities.

[13] https://www.boringcompany.com/faq/

5 STRENGTHS OF UK INDUSTRY IN RELATION TO HYPERLOOP

5.1 INTRODUCTION

This study has investigated some of the UK capabilities with respect the hyperloop challenges. These are presented in this section.

5.2 LINEAR INDUCTION MOTORS

Linear Induction Motors (LIMs) are being considered by hyperloop developers to provide the method of propulsion. The LIM industry can be split into standardised industrial actuation applications and transport applications. Globally there aren't many companies that produce LIM for large scale transport applications, so there could be an opportunity for UK to be global leaders. Existing applications include launching aircraft from carriers and theme park rides.

Force Engineering[14] (FE) are a long established (40 year old) but relatively small company involved in LIM design and manufacturing based in Leicestershire. They hold patents around LIM design in the area of continuous windings. There are around five other companies globally who are also involved, including large players such as General Atomics, Siemens, and GE. There is no major barriers to manufacture of LIMs, but there are subtleties in the design.

FE have proved they can deliver major projects. One example is the baggage handling system at Heathrow Terminal 5, which uses over 6,000 FE motors over a 5-mile track. The motors range from small, low thrust motors for fine control at junctions to active fan cooled, high speed motors to power the carts in the long inter-terminal tunnels. FE's technology is seamlessly integrated into the control architecture of the complete system with the full speed and direction control of the individual carts ensuring overall system integrity and reliability. They are also one of the lead companies providing LIMs for use in roller coasters and theme park rides.

FE still use technical expertise of Prof. Fred Eastham at University of Bath and Prof. Denis Edwards from Sussex University, two long standing UK based experts in this field.

Other applications in transport include any vehicles that use Magnetic Levitation (MagLev). FE were commissioned by a German company to develop low speed MagLev Tram system that has performed 40,000km of testing along a 700m test track. The value of delivering 60 motors for this system is £300k. A full system could be worth around £1M.

Linear Motion Technologies (LMT)[15] are a small UK company which offers consulting in the area of LIMs, and has capabilities in designing and optimising bespoke LIMs for unique applications. LMT are also developing the Magway concept for moving freight, as discussed in ***Section 7*** of this report.

The University of Nottingham have plans is for a £60m LIM test track capable of ~50m/s which would allow verification of a significant range of electromagnetic levitation and transit projects.

[14] http://www.force.co.uk/
[15] http://www.linearmotion.tech/capabilities.html

5.3 BATTERY TECHNOLOGY

Alongside propulsion, battery technology could be fundamental to whether the hyperloop system is successful. This is an area where the UK has strong technical expertise. For example, Williams Advanced Engineering has developed the batteries used by all 40 cars in Formula E races.

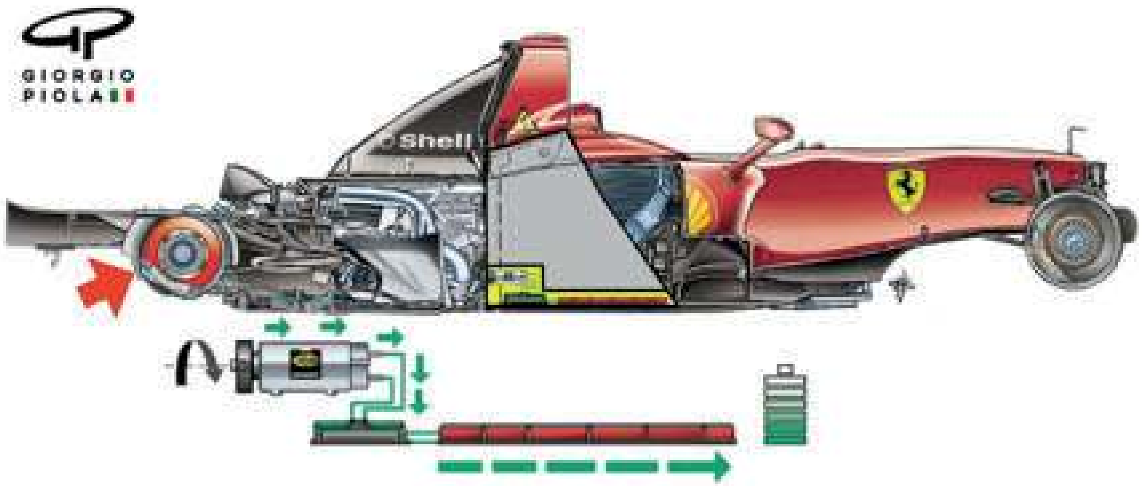
DS Virgin Racing. All vehicles in Formula E are powered by batteries developed by Williams Advanced Engineering

As stated on the FIA Formula E website[16]:

> “The knowledge gained through the tens of thousands of kilometres covered by the cars across the races and testing programmes have given the Williams Advanced Engineering technicians an enormous amount of data and experience in dealing with a situation that was previously unprecedented. While electric cars have been available for over 100 years, never before have they been subjected to the white-hot competitive environment of a single-seater racing series such as Formula E.

[16] http://www.fiaformulae.com/en/news/2017/april/insight-williams-updated-battery/

In addition, the Formula 1 teams were able to develop Kinetic Energy Recovery Systems (KERS), which allowed energy to be stored either in batteries (most teams) or in an electric flywheel (Williams). Interestingly, one hyperloop developer has expressed interest in other forms of energy storage.



Formula 1 Kinetic Energy Recovery System (KERS)

TSC and HVMC spoke to the Motorsport Industry Association (MIA) regarding this project. There are already initiatives led by the MIA to enable the capabilities of UK motorsport to be utilised by industry in areas such as automotive, defence, marine and aerospace. The MIA would be keen to help provide the link between UK motorsport and hyperloop developers.

Battery technology features prominently in the Industrial Strategy Automotive Sector Deal[17] with confirmation of a significant commitment to funding of this technology:

> As a result of the Sector Deal, both government and industry will invest about a quarter of a billion pounds to develop and manufacture electric vehicles. This includes the Faraday Battery Challenge, which will drive the technologies to power electric vehicles in the future, as well as £80 million for a new state-of-the-art automotive battery development facility in Coventry. This investment marks yet another step forward on our journey towards mass producing electric batteries and vehicles here in the UK.

[17] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/673045/automotive-sector-deal-single-pages.pdf

5.4 DIGITAL INFRASTRUCTURE

The UK is investing heavily in the area of connected and autonomous vehicles (CAVs), having set up a specific team within government, the Centre for Connected and Autonomous Vehicles (CCAV), to coordinate activity in this area, and hundreds of millions of pounds of investment is going into research.

The challenge of developing a control system that can understand the location of vehicles, instruct them to proceed to where they are needed and ensure they don't collide with each other would rely on similar technology to that being developed for CAVs. The reliability of communications links is being investigated by projects such as UKCITE, which includes Visteon, Jaguar Land Rover, Highways England, HORIBA MIRA, Huawei Technologies UK, Siemens, Vodafone and Warwick Manufacturing Group (WMG). The UK Autodrive consortium is developing a fleet of autonomous pods that will be deployed in Milton Keynes and will need to communicate with a central control centre. These principles are already being applied at Heathrow Airport, with the PRT system that has been transporting passengers between the business car park and Terminal 5 since 2011.

Another area that is developing relevant technology is the rail industry. A programme termed the 'Digital Railway' is underway that aims to transform train control technology to increase capacity, reduce delays, enhance safety and drive down costs. The focus is on digital signalling.

5.5 NOISE, VIBRATION AND RIDE QUALITY

It was suggested to TSC that British Rail previously developed considerable expertise in the area of noise, vibration and ride quality related to the rail industry, although this has become fragmented following privatisation. A new legislative / regulatory framework for hyperloop could consider how rail operates.

There is a rule of thumb around deceleration events (emergency stop). It's permittable for this to enable a standing passenger to fall over, but not for a seated person to leave a seat. The hyperloop system would need to decide whether standing is permitted and the types of seat restraints that are used, if any.

UK organisations could potentially play a role in turning knowledge into a regulatory framework for hyperloop, and could help with modelling such systems.

Other countries with expertise include those experienced in delivering high speed rail, such as France, Germany, Japan, China, although the UK are world leaders in the development of standards.

It was suggested that there are limited facilities for testing human response to vibration (full sized people shakers).

The UK hosts an annual conference on Human Response to Vibration.[18] The University of Southampton has unique facilities for simulating measured or predicted ride environments. Few others involved in standardisation and regulation have practical experience of exposure to known motions, experience of their effects on comfort and passenger activities, or knowledge of the research literature. It was suggested that there is a tendency for engineers to propose standards based solely on engineering principles, forgetting that additional understanding is required of how motion affects people.

[18] https://www.cranfield.ac.uk/events/events-2017/52nd-uk-conference-on-human-response-to-vibration

5.6 STATION DESIGN

The UK builds on a long history of transport architecture with large historic transport interchanges that act as centres of the community rather than just somewhere to catch a train or bus. A good example that demonstrates the UK's capability is St Pancras station in London.

The development of Crossrail has required the design and construction of ten new stations with a combination of under and above ground implementation. This will be relevant expertise that could be utilised by hyperloop developers.

It is noted that UK architects and engineers have already started to undertake work on hyperloop. For example, PriestmannGoode has designed the initial concept for HTT. [19] Ryder, an architecture firm based in Newcastle, were involved in the 'Northern Arc' Hyperloop One Global Challenge submission, and the London office of AECOM developed concept station designs for the 'Wales to Scotland' route, details of which can be found at Appendix A.

There will be a need to address the significant engineering challenges around pressure differentials, for which the aviation industry in the UK has significant capability.

Efficient and safe movement of people will also be critical. The UK is advanced in the field of pedestrian modelling, with would leading UK organisations such as Legion, Space Syntax, Hydrock, etc developing pedestrian modelling tools.

St Pancras Station – Example of a high-quality interchange design

[19] http://www.priestmangoode.com/project/hyperloop-transportation-technologies-initial-concept/

Elizabeth Line (Crossrail) project has developed significant relevant UK capability

5.7 TUNNELLING

As discussed in ***Section 4***, cost effective tunnelling could be a crucial element in developing a business case for hyperloop as it has advantages over above ground tube construction and may present the only option in some areas. The UK is currently in the process of planning or delivering several major tunnelling projects including:

- **Crossrail.** Described as Europe's largest construction project, since 2009 over 15,000 men and women have worked on the project and over 100 million working hours have been completed. Over 1,000 apprenticeships have been delivered.

Eight tunnel boring machines bored 42 kilometres of new 6.2m diameter rail tunnels under London. The tunnels weave their way through the city's underground landscape, within close proximity to existing railways and beneath some of the most historic buildings in London.

The video titled '*Crossrail tunnelling: Drone's eye view of Crossrail's completed rail tunnels*'[20] provides an indication of the scale of Crossrail.

- **Northern Line Extension.** Two 3.2km tunnels were created between Battersea and Kennington were completed in April 2017.
- **Thames Tideway Tunnel.** In November 2017 construction work started on a 25km interception, storage and transfer tunnel running up to 66m below the River Thames.
- **River Humber Gas Pipeline Replacement.** A 5km tunnel will be built under the river to accommodate a high-pressure gas pipeline.
- **HS2.** The proposed HS2 network includes up to 62km of twin bore tunnels, 6.3km of single bore tunnels and 9.6km of twin cell cut and cover tunnels.

[20] https://www.youtube.com/watch?time_continue=148&v=2e-PW3QIJQY

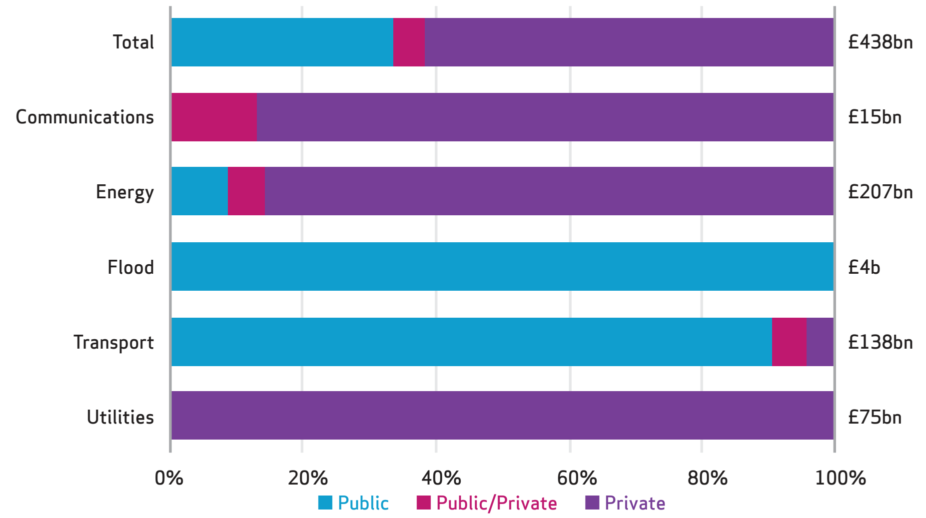
5.8 ENTERPRISING BUSINESS MODELS

There are two broad ways to finance infrastructure; public finance or private finance. With London being one of the leading financial centres globally, the UK is well placed to assist in the raising of private finance. The diagram below shows the scale and breakdown of infrastructure funding during the 2016/17 financial year:

Related to the financing is the need to develop a strong business case. The UK hawws developed a world-leading transport appraisal tool known as WebTAG (Web-based Transport Appraisal Guidance). This forms the basis for large transport infrastructure appraisal.

Building the business case also relates closely to the planning of the infrastructure. Engineering and design decisions can hugely impact the cost estiwmates, for example in hyperloop; whether to incorporate motors into the track or the vehicle, whether to build above or below ground, which materials to use, etc. Likewise, choosing the optimal first route will be crucial in developing the business case. These are areas where engineering consulting firms can assist, and the UK is well represented in this area with a major presence of companies such as AECOM, ARUP, Atkins, Mott MacDonald, etc.

Choice of finance in the national Infrastructure and Construction Pipeline from 2016/17



■ Source: Institute for Government analysis of IPA, National Infrastructure Delivery Plan, Funding and Finance Supplement, 2016.

5.9 SAFETY CASE PREPARATION

VH1 is engaged in deep discussions to develop an EU safety case, which will be accepted beyond the EU. A significant proportion of the EU expertise in safety case development is UK based. It was estimated that around 40% of safety case will be produced by UK experts.

5.10 PROJECT / RISK MANAGEMENT AND SYSTEMS ENGINEERING

TSC are aware that UK-based organisations have experienced success in engaging with hyperloop developers in the field of project management and risk mitigation strategies. This is closely related to systems engineering, a field in which UK organisations have considerable expertise.

6 UK HYPERLOOP DEVELOPMENT?

6.1 INTRODUCTION

An important consideration in how to engage with the hyperloop concept is the decision as to whether to try to construct testing facilities, or indeed a full scale commercial route, in the UK.

6.2 UK HYPERLOOP DEVELOPMENT?

The advantage of developing testing facilities in the UK is that it could create a hub of research and development activity around the facility. Testing facilities in the UK could aim to emulate the types of facilities that have been developed in California, or under construction in Toulouse, or could aim to focus on developing parts of the system that those facilities may be unable to address. The mind map provided in ***Section 4*** provides a starting point for discussion around the challenges to be addressed.

When considering construction of a full-scale, operational hyperloop system comparisons could be made with Crossrail. According to the Crossrail website, 96% of contracts awarded by Crossrail were to companies within the UK. This demonstrates the major advantage of major infrastructure to the local rather than the global supply chain. It is unlikely to be different for hyperloop in that the majority of construction work for tunnelling, tube construction, structures, installation of equipment etc would be undertaken by the incumbent construction organisations, and raw materials sourced as economically as possible.

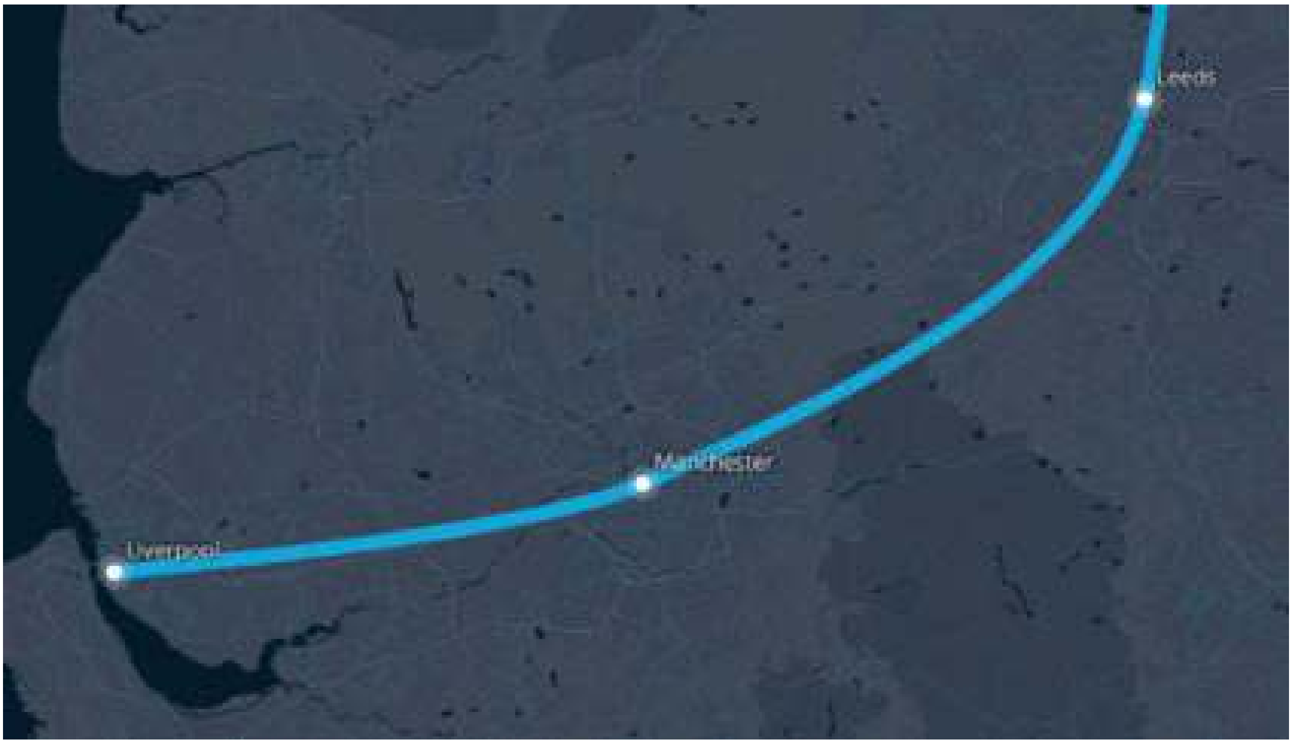
Some doubt the logic of building a hyperloop in the UK based on geography and other factors, but it should be noted that two of the ten winning Hyperloop One Global Challenge routes were in the UK (and a third in the top 20).

COUNTRY	No. TOP 10 ROUTES	No. ROUTES PLACED 11-21	No. ROUTES PLACED 22-34
USA	4	3	4
UK	2	1	0
India	2	0	3
Canada	1	0	2
Mexico	1	0	0
Australia	0	1	0
Estonia / Finland	0	1	0
Spain / Morocco	0	1	0
Corsica / Sardinia	0	1	0
Germany	0	1	0
Israel	0	1	0
Netherlands	0	1	0
China	0	0	1
Poland	0	0	1
South Korea	0	0	1

Hyperloop One Global Challenge results by country

Route submissions included aspects of commercial viability and delivery and were judged by an international panel of experts. On this evidence, the UK ranks highly for hyperloop potential. In addition, the UK has recent relevant experience and engineering capability in planning and delivering large infrastructure projects, with examples including HS1, HS2, the Northern Line extension and Crossrail 1 and 2.

Various UK routes were suggested to the project team during the consultation exercise, including a route proposed by a hyperloop developer for connecting Liverpool, Manchester and Leeds, connecting the airports of Liverpool and Manchester to create a combined three runway hub airport for the north. This represents the southern section of the 'Northern Arc' route which was successful in VH1's Global Challenge competition and it was suggested that such a route could energise the Northern Powerhouse.



It was proposed that a 'proof of operations' test facility between Liverpool and Manchester could be the starting point, that could ultimately evolve into a full system.

Other route possibilities suggested include London to Birmingham. This is an obvious route connecting the UK's two largest cities, which has justified investment in HS2 and for which Royal Assent has been awarded. It was calculated by a large engineering consultant that hyperloop development could be undertaken for approximately two-thirds the cost of HS2, although the caveat is that it's unclear why high-speed rail often is more expensive than planned, and hyperloop could likewise end up costing more than predicted.

It was suggested that the shortest credible route in the most benign geological conditions for which the econometrics could work (for which there would sufficient demand) could be Oxford to Cambridge, which like London to Birmingham also competes with a planned rail route in the form of East-West rail.

An airside link between Heathrow and Gatwick airports could offer advantages over other options being considered in terms of airport expansion. With a hyperloop transfer time of ~10mins, Heathrow and Gatwick could be considered a single hub airport. In response to the question *"Is hyperloop something that can ever be built in the UK",* VH1 chairman Sir Richard Branson recently stated [21]:

> **Most definitely it could be built in the UK, and it would end up transporting people far quicker, in far greater numbers, with far greater convenience than any other train network in the UK. Let me give you one example of a dream for the future in Britain. That would be connecting Stanstead, Gatwick and Heathrow by Hyperloop so there would only be 10 to 12 minutes between Stanstead and Heathrow and six minutes between Heathrow and Gatwick, so effectively it becomes one airport. Dubai are building a new airport 60 miles from the old airport and they are incredibly excited by the idea that you can get on hyperloop at one airport and you could whisk through so you miss the two hour journey getting to the airport and then you miss the two hours at the airport going through the rigmarole to get to your gate.**

In light of the pressures facing airport capacity and the huge investment decisions currently being considered to address this problem, an in-depth study of how hyperloop connectivity could benefit the UK aviation industry could be worthwhile.

As suggested by former transport minister Steve Norris[22], Hyperloop could play a part in helping to rebalance the UK economy by enabling commuters to live further from their work, thus taking the pressure off housing in the South East. It should also be noted that indications suggest hyperloop construction costs may compare favourably to high speed rail costs.

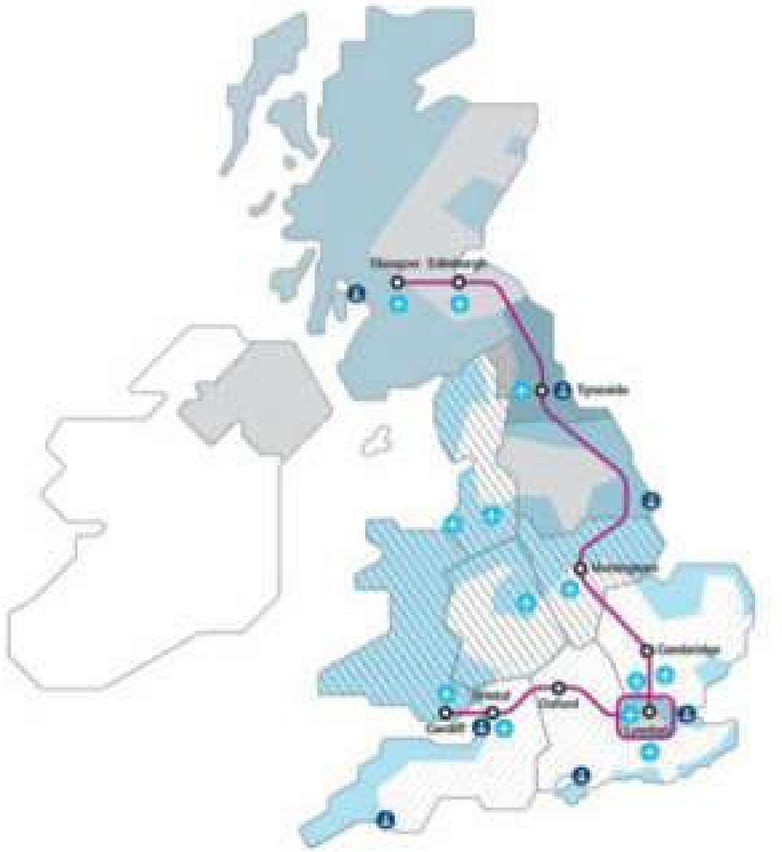
[21] https://www.bbc.co.uk/programmes/b0b42pdb#playt=0h24m27s
[22] http://www.cityam.com/284220/hyperloop-train-leaving-station-and-uk-must

6.3 HYPERLOOP ONE GLOBAL CHALLENGE: UK COMPETITION ENTRIES

This section summarises the UK entries to the Hyperloop One Global Challenge competition.

WALES TO SCOTLAND

The 'Wales to Scotland' route outlined by AECOM in their submission to the Hyperloop One Global Challenge highlights a number of benefits in linking the airports and sea ports along the route. It also provides the connection between Oxford to Cambridge (via London) as a part of the route.



The first Hyperloop UK corridor will connect economically disparate regions

Key		Unemployment
	Hyperloop route	Above 7.0%
	Terminal	5.5%-6.9%
	National Airports	4.0%-5.4%
	Historic port sites	Below 4.0%
		Employment Hotspots over 10%

AECOM | Hyperloop UK

Extract from AECOM submission to Hyperloop One Global Challenge

AECOM included costs of the above route within the proposal at (Page 20, Appendix A).

EDINBURGH TO LONDON

The team representing the University of Edinburgh, Hyp-Ed, proposed a route connecting London to Edinburgh via Birmingham.

This was one of the two winning UK routes:

Extract from Hyp-Ed submission to Hyperloop One Global Challenge

Within the submission[23], it is stated that by creating a number of 'portals', the reach of the route could be expanded so that more than half of the UK population is within a 60 minute drive of a hyperloop station.

Extract from Hyp-Ed submission to Hyperloop One Global Challenge

[23] https://static1.squarespace.com/static/5a0b00baace864b50ecccd8e/t/5a6213c1652dead6876a8d92/1516377049859/HYPED+the+UK+Spine+Economic+Case.pdf

GLASGOW TO LIVERPOOL

The other winning UK route was the 'Northern Arc' route, proposed by a consortium which included Ryder and Arup.

Northern Arc route, proposed by Ryder and Arup for the Hyperloop One Global Challenge

As stated on Ryder's website :[24]

> **The Northern Arc route covers Liverpool, Manchester, Leeds, Newcastle, Edinburgh and Glasgow, aims to create a coordinated, government backed, deliverable proposal which will connect Scotland with the Northern Powerhouse partners to create a super region and showcase the north of England as a global leader of transport innovation.**

[24] http://www.ryderarchitecture.com/insights/news/pioneering-northern-arc-route-revealed.htm

7 FREIGHT PIPELINES AND THE WIDER 'GUIDED TRANSPORT' LANDSCAPE

7.1 INTRODUCTION

This section considers other innovate forms of transport for which the development of solutions could ultimately benefit hyperloop development.

7.2 FREIGHT PIPELINES – "HYPERLOOP LITE?"

Freight pipelines could be described as "Hyperloop Lite" in that they could be:

- **Smaller in scale.** Pipelines could be constructed at much smaller diameter to accommodate freight only. Tunnelling costs increase proportionally with the square of the tunnel diameter, so reducing the diameter ensures a more affordable scheme, and there is greater cost certainty at smaller scale from installation of pipelines for other purposes, e.g. oil, gas, etc.
- **Slower in speed.** Freight does necessarily need to move at supersonic speeds. If it moved faster and more reliably than it does on other modes, that would offer an advantage. There is no need to create a near-vacuum for the movement of freight-carrying vehicles.
- **Easier to create a safety case for.** There is no 'life support' mechanisms needed, as there is for carrying human passengers.

Freight pipelines could, however, help to develop many aspects of the system that ultimately is needed for full-scale hyperloop development, including methods of propulsion, operational control of vehicles, automation of freight loading and unloading, etc.

Freight pipelines might offer a nearer term global opportunity that acts as a stepping stone towards hyperloop, and is able to be commercialised and exported as a technology far sooner. TSC understand from discussion with Mole Solutions, a UK Based organisation developing this technology, that enthusiasm for the concept in certain countries is considerable. For example, China is particularly keen on the concept with a number of major cities, including Xiong'an (the 'new' Beijing), Shanghai, Wuhan and Nanjing keen to develop systems. Xiong'an has already commissioned a system to be built. India, Singapore and the USA are also examining the development of the concept.

Further details on freight pipelines is provided at ***Appendix B.***

7.3 PERSONAL / GROUP RAPID TRANSIT

In a similar manner to freight pipelines potentially offering a nearer term opportunity than hyperloop for freight, personal or group rapid transit schemes may provide a comparative opportunity for passenger transport, which again helps to develop relevant technologies and build UK capabilities. Hyperloop, as described in ***Section 2***, is effectively is a form of high speed group rapid transit. Further details on PRT and GRT is provided at ***Appendix C.***

8 MAPPING OF HYPERLOOP CHALLENGES ONTO CAPABILITIES OF UK SUPPLY CHAIN

8.1 INTRODUCTION

This section considers other innovate forms of transport for which the development of solutions could ultimately benefit hyperloop development.

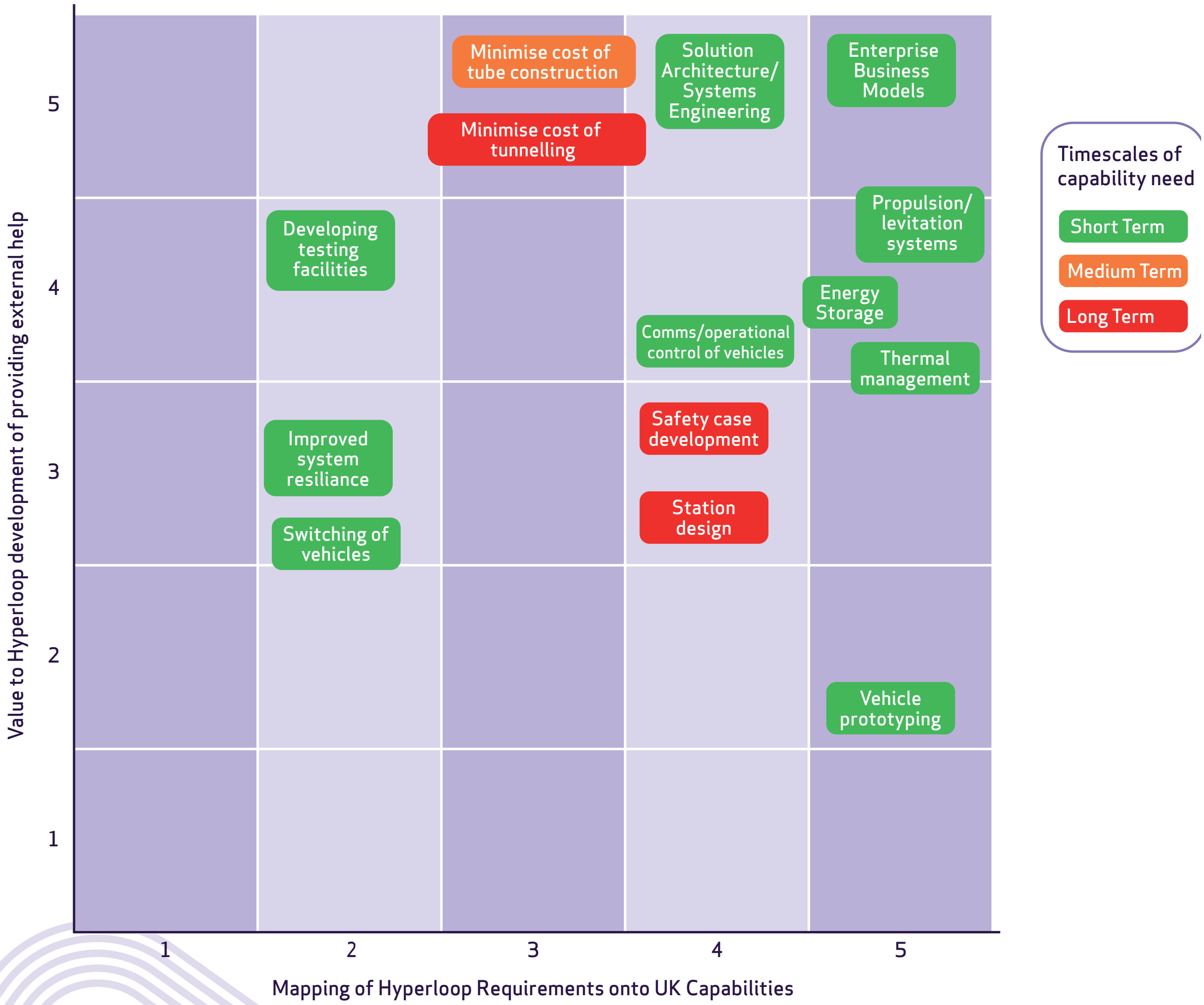
8.2 SCORING MECHANISMS

Prioritisation of potential investment areas was undertaken by first considering the key challenge areas facing hyperloop developers. A simple scale of 1-5 was used for the main challenges discussed in previous sections of this report, with 5 being of most value to hyperloop development and 1 being least value (although still of value otherwise it wouldn't be included).

It was not considered possible to attribute meaningful financial numbers to these values due to the uncertainty of the final system and lack of data, therefore it is only possible to compare the items relative to each other. It is worth considering the main point, however, that infrastructure is the large value item, and may equate to orders of magnitude more value than the vehicle fleet.

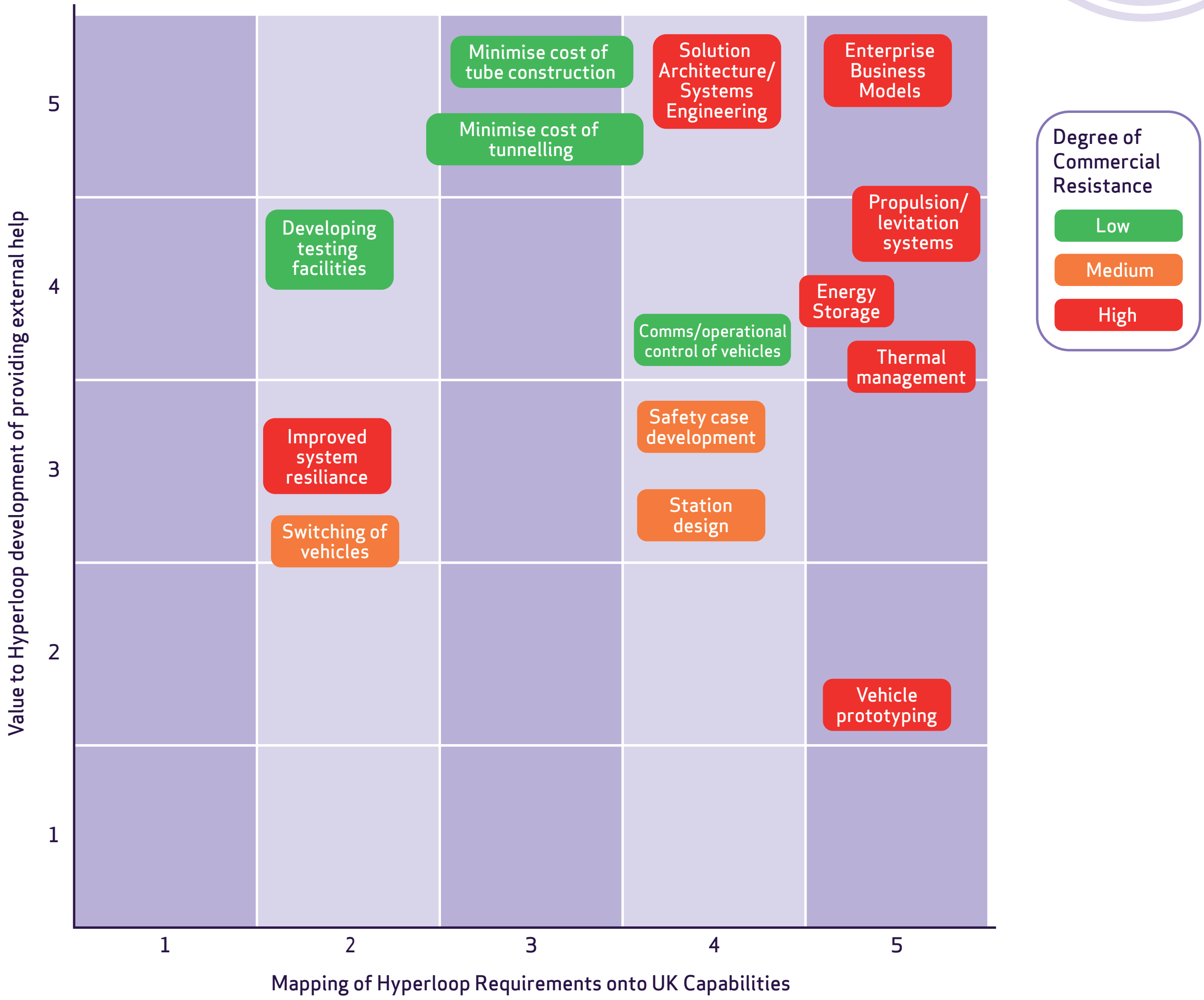
A score was then applied based on the extent to which the UK has capability to assist, relative to other countries. If the UK is a world leader in a particular field, this scores highly. Again, a scale of 1-5 was used.

In Figure 7-1, a third piece of information was included. Each challenge area was colour coded according to whether it is a short, medium or longer term requirement. Short term can indicatively be considered as 0-2 years, medium term is 2-5 years and longer term is 5+ years (although this will vary depending on the ambitions of the hyperloop developer). Figure 7-1 is shown as follows:



On this basis it may be useful to consider in more detail how the UK can assist in areas such as Enterprise Business Models, Solution Architecture, Propulsion / Energy Storage / Thermal Management and Communications technology. In the slightly longer term (or maybe in the short term with a view of creating the business case) minimising the cost of infrastructure will be of huge importance.

There is a further piece of information which is of relevance, which is the extent to which the hyperloop developers are seeking assistance with each aspect, or whether they are developing solutions in house with a view of owning and managing the IP. This has been termed degree of commercial resistance, and has been represented in green / orange / red in Figure 7.2. It is based on what TSC / HVMC were able to detect during discussions.



The above indication of 'commercial resistance' should be treated with caution as hyperloop companies were not asked explicitly about this, rather it was the impression TSC and HVMC received based on discussions.

9 CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

This project has not attempted to assess the technical feasibility of hyperloop. However, from the information gathered it appears some key system design decisions are yet to be finalised, and discussions suggest that there are technical areas where further development is needed to optimise the candidate solutions. This includes energy storage, thermal management, propulsion and connectivity. Other areas that would assist hyperloop developers include creating enterprise business models and helping to minimise infrastructure costs.

Enabling the supply chain to engage with hyperloop development overseas is challenging. UK capabilities would need to be clearly preferable to those of the local supply chain to win contracts. However, it is understood that UK arms of multi-national companies are actively involved in pursuing large contracts for hyperloop construction. It has been suggested that top level Government support could assist in helping to support the potentially large contracts that could be available. In addition, the UK has specific expertise that could assist with hyperloop development, such as world leading manufacturers of linear induction motors and suppliers to the motorsport industry. Such expertise could undoubtedly help to optimise aspects of the hyperloop system.

If a hyperloop testing facility were to be constructed in the UK it could create a hub of activity and ensure expertise is developed in the UK, and the UK supply chain is favoured. There would also be secondary benefits in that technology developed for hyperloop would also be valuable in other sectors. An example could be improving the efficiency and reducing the cost of tunnelling, which would be of benefit to many subterranean infrastructure projects.

Applications of hyperloop could assist with other major infrastructure challenges. For example, linking airports with hyperloop connections could provide an alternative to airport expansion. Linking cities could avoid the need for new road and rail links. Hyperloop could play a part in helping to rebalance the UK economy by enabling commuters to live further from their work, thus reducing the pressure on housing in the South East. It should also be noted that indications suggest hyperloop construction costs may compare favourably to high speed rail costs.

Freight pipelines and personal rapid transit systems are applications that use similar types of technology to that needed for a hyperloop and could be more deliverable in the short term. These types of systems could take advantage of the hyperloop publicity and excitement and could act as stepping stones towards hyperloop deployment.

9.2 RECOMMENDATIONS

The following Government initiatives are recommended based on the findings of this study:

1	Launch a UK event to bring hyperloop developers and interested parties from the UK supply chain together. This could develop into an annual conference which would demonstrate UK interest.
2	Coordinate with UK industry to offer a joined-up offering of UK capabilities to hyperloop developers, with focus on those areas identified in this report. This could provide greater impact than small companies attempting to sell their services individually. Top level Government support should be available for supporting the UK supply chain in this activity.
3	Undertake an independent deep dive into the technical and economic feasibility of hyperloop. This would better inform the decision as to whether to construct large scale testing facilities in the UK, and potential timescales for likely hyperloop deployment which is crucial in considering hyperloop alongside other transport solutions.
4	Undertake a review into the potential opportunities and economic benefits presented by hyperloop. This should include how linking certain airports with hyperloop could help with airport capacity issues and how it could impact on the housing market. Investing in hyperloop could save the need for investment in other types of infrastructure.
5	Undertake an investigation into the feasibility and business case surrounding freight pipelines, with a view of using public finance to help develop testing facilities and enable commercial deployment and export.
6	Undertake an investigation into the feasibility and business case surrounding personal and group rapid transit schemes and innovative new modes that is based on similar technology.

APPENDIX A: AECOM SUBMISSION TO HYPERLOOP ONE GLOBAL CHALLENGE

For further information please visit:

https://s3-eu-west-1.amazonaws.com/media.ts.catapult/wp-content/uploads/2018/09/26144421/Appendix-A.pdf

APPENDIX B: FREIGHT PIPELINES COMPARISONS

For further information please visit:

https://s3-eu-west-1.amazonaws.com/media.ts.catapult/wp-content/uploads/2018/09/26144415/00601_Hyperloop-Report_Appendix_B.pdf

APPENDIX C: PERSONAL RAPID TRANSIT

For further information please visit:

https://s3-eu-west-1.amazonaws.com/media.ts.catapult/wp-content/uploads/2018/09/26144417/00601_Hyperloop-Report_Appendix_C.pdf

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