14. Identifying disruptive innovations in transport: the case of the Hyperloop[1]

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1. INTRODUCTION

Innovations in transport modes and services enable people to travel more kilometres for work or leisure (Walton, 2006) compared with even a decade ago (except for the COVID-19 pandemic years). However, current motorized transport modes are either using fossil fuels directly or using electricity mainly generated by such fuels. This contributes to global CO_2 emissions, one of the leading causes of adverse climate change. Transport research, as well as practice, has focused on innovating cleaner and safer transport modes that can positively contribute to people's lives and health and cover their mobility needs while avoiding further negative impacts on climate by the transport sector. Undoubtedly, this calls for outside-the-box thinking and being innovative.

Innovations can be categorized into incremental or disruptive.[2] Incremental innovations are generally improvements to existing products and services. They have a limited impact on society, whereas disruptive innovations have a high impact on society or even disrupt the current market and offer many new technological features (Hopp et al., 2018b; Kylliäinen, 2019). An example of an incremental innovation in transport could be the addition of winglets at the tip of an aircraft's wings, which reduces fuel consumption by 2–5 per cent (Takenaka et al., 2008) and thus leads to a small improvement in aircraft emissions. But some innovations have disruptive impacts, such as container shipping (more than 60 years ago), which allowed for large-scale production and distribution of goods globally (Levinson, 2006; Notteboom and Rodrigue, 2008). Another example is Netflix, which started as a simple mail-order company but grew up to put Blockbuster out of business due to its convincing business model, and utilization of internet and online streaming technology for delivering media content (Hopp et al., 2018a).

Disruptive innovations involve unexpected trends in innovation pathways and often require new areas of research and development (R&D), the creation of new ways of production, and new markets. They can lead to sectoral transformations and the displacement of incumbent companies (Christensen et al., 2015).

Since disruptions often bring many changes to society, they can be challenging if citizens and governments are unprepared (Chen, 2018). This could leave policymakers, people and even businesses exposed to hard choices and even lead to closures of long-running businesses. Thus, it is crucial to grasp what makes an innovation disruptive in the transport domain.

To the best of our knowledge there are limited studies in the transport domain that focus on how innovations in transport can become disruptive and what are the underlying conditions and requirements for disruptions to occur. Therefore the focus of this study is to examine the disruption phenomenon in the context of transport and introduce a method for identifying the disruptive potentials of innovations in the transport sector. For this purpose, we have developed a framework that can help transport planners and researchers assess if a given innovation can be potentially disruptive.

We will further apply this framework to discuss the case of the Hyperloop to see if it could be a disruptive innovation in the transport sector in the coming decades. The Hyperloop has been chosen as a case study for our framework since there is a heated debate among academics and practitioners on how disruptive this new mode will be for the current transport sector.

The Hyperloop is poised to offer several societal advantages and appealing features such as ultra-high speeds (1200 km/hr) using only electricity (i.e. fewer emissions), much-reduced noise or vibration due to technical novelties (Mitropoulos et al., 2021), and being weatherproof (Dudnikov, 2017). Together, these attributes can be considered significant changes from the existing modes in the transport sector. Some even call it the 'fifth mode of transport' (Jacob et al., 2017; Armağan, 2020).

There are claims that the Hyperloop will reshape future travel and be a competitive mode to high-speed trains (HSTs) and air travel (Jia et al., 2019; Armağan, 2020; Mitropoulos et al., 2021). But the critics argue that the Hyperloop's construction costs would be very high and its effectiveness in increasing the overall welfare of society is doubtful (Hansen, 2020).

We emphasize that our goal in this chapter is not to forecast if and when an innovation (such as the Hyperloop) will be disruptive. Instead, we aim to explore when innovations could be potentially disruptive.

2. AN OVERVIEW OF THE LITERATURE

Disruptive Innovations

Many authors have tried to explain what disruptive innovations are and describe the nature of these innovations (for instance, see Marsden and

Docherty, 2013; Hopp et al., 2018b; Si and Chen, 2020; Petzold et al., 2019; Martínez-Vergara and Valls-Pasola, 2021). However, in this chapter we use the definition provided by Christensen et al. (2018): disruptive innovations are those products or services that initially start at the bottom of the market with simple applications. They are normally less expensive and more accessible than the incumbent products or services. Eventually the simple, cheap and accessible product or service manages to aggressively move upmarket and force the incumbents out of the market or even put them out of business.

Tait and Wield (2021) point to the importance of policymakers paying extra attention towards disruptive innovations, since such innovations offer 'potential gains for a national economy that hosts the next generation of disruptive innovations' (Tait and Wield, 2021, p. 316).[3] The authors refer to the policies put in place by the UK government to support these innovations by implementing support systems, measuring the success or failure of policy initiatives that support disruptive innovations, and offering a regulatory system that enables the adoption of the innovative technology (Tait and Wield, 2021).

Finally, Millar et al. (2018) identify an important gap in the literature, namely research that addresses 'the impact of disruptive technology [innovation] on macro-systems such as societies or ecosystems, or on specific strategies and instruments to leverage, mitigate, or ameliorate systemic disruption'(p. 256). Therefore, the impact of disruptive innovations in the transport sector is of significant importance and needs to be carefully examined and researched to reveal the full potentials (or even threats) to society.

The Hyperloop: An Innovation with Great Potential and Challenges

The academic discussions on this innovative mode in the transport sector have recently intensified, with 95 per cent of published studies dated after 2016 (Mitropoulos et al., 2021). The original idea of the Hyperloop, where a pod travels at high speed through a vacuum tube, dates back to the early 20th century when Robert Goddard designed magnetic floating trains that in vacuum tubes could reach 400 km/hr (Salter, 1972; van Goeverden et al., 2018).

The discussions about the Hyperloop were revived after the publication of a white paper on the Hyperloop by Elon Musk and his group of engineers at SpaceX company in 2013 (SpaceX, 2013). In his 'Hyperloop Alpha' white paper, Musk provided some technical and economic features for a possible 'fifth mode of transport' (SpaceX, 2013). To demonstrate the potential of the Hyperloop, Musk chooses the example of the journey between Los Angeles and San Francisco, a roughly 610 km trip (each way) that by his estimate 7.4 million passengers take every year. Using the Hyperloop, the travel time would be slashed from 75 minutes by air travel (airport to airport) to 35 minutes by the Hyperloop (station to station), with a $20 (€15.3 in the year 2013) ticket cost. The $6 billion[4] (€4.6B in 2013) capital investments would be repaid in 20 years, assuming 40 pods operating every 2 minutes and each pod carrying 28 passengers (SpaceX, 2013; Rajendran and Harper, 2020).

The Hyperloop is designed to offer services for passengers and freight, possibly mixed, in tubes that are expected to be around 3.3 metres in diameter. However, most Hyperloop proposals indicate that pods carry only passengers or only freight, using the same tubes and infrastructure, since this would be beneficial from an operational perspective (Doppelbauer, 2013; van Goeverden et al., 2018).

Van Goeverden et al. (2018) conclude that the Hyperloop could have positive societal impacts by increasing accessibility to points of interest and job markets, and further it could be environmentally beneficial (e.g. less energy consumption, no emissions of greenhouse gases (GHGs), and much-reduced noise), if the promised technical and safety features are fulfilled. However, unlike Musk, they indicate that the drawback for the Hyperloop is that the construction and operational costs do not suggest a strong financial performance. The Hyperloop requires a revenue of more than €0.30 per passenger-km to cover the annual costs for operations and amortization of line infrastructure capital investments[5] compared to €0.17 per passenger-km for high-speed rail and €0.18 per passenger-km for air travel for a distance of 600 km (van Goeverden et al., 2018).

On the issue of construction costs, there are more recent studies that provide different estimates. For instance, in a relatively recent feasibility study conducted for Transport Canada, Stubbin et al. (2020) estimate construction costs of $56.4M (€49.0M in the year 2020) per km for a distance of 500 km in Canada. They further provide a range of estimates from other feasibility studies, varying between $37.8M (€32.9M) and $52.6M (€45.7M) per km for Stockholm to Helsinki (500 km), Abu Dhabi to Dubai (150 km), and Toronto to Windsor (350 km). These cost estimates all tend to contradict the appraisal of Musk (SpaceX, 2013), which was around $19M (€16.5M) per km for the Los Angeles to San Francisco line.

We will use the Hyperloop as a case from the transport sector when applying our disruptive innovation framework. Applying the framework to the Hyperloop provides an opportunity to debate its disruptive potential based on those above-mentioned (potential) societal advantages and possible financial difficulties.

3. CONCEPTUAL FRAMEWORK FOR DISRUPTIVE INNOVATIONS

Bower and Christensen (1995) investigated why the leaders of companies, which lead the market, often failed to react or respond to a challenge arising from a technological change or innovation that was initiated by new entrant(s) with far less resources (Bower and Christensen, 1995; Christensen et al., 2015; Hopp et al., 2018b).

Initially, Christensen and his colleagues investigated how 'disruptive technologies' are developed, but later Christensen and Raynor (2003) switched to the term 'disruptive innovations' since there are cases where the technological part of the innovation is limited. However, there are other reasons why innovation can still be disruptive. For instance, the business model and the enabling value network can be highly influential in bringing disruptive innovation to the market (Hopp et al., 2018a). In later publications, Christensen et al. (2018) provide more detailed features and characteristics of disruptive innovations. They explain that disruptive innovations '… are NOT breakthrough technologies that make good products better; rather, they are innovations that make products and services more accessible and affordable, thereby making them available to a larger population' (Christensen et al., 2018).

We will now introduce our framework, which applies Christensen's theory to the transport sector. While other frameworks, such as the 'innovation feasibility' framework of Feitelson and Salomon (2004) (see Annema, Chapter 6 in this volume), the 'sociotechnical transition pathways' of Geels and Schot (2010), and several others as introduced in Part I of this book, have already explained how innovations are adopted in the transport sector, few studies address the disruptive aspects of innovations. The Disruptive Innovations Theory of Christensen seems to help shed light on how some innovations become disruptive.

As described by Christensen et al. (2015), disruption begins when an entrant firm with fewer resources challenges incumbent(s) who have considerable resources and revenues. Incumbents, however, try to improve their products and services for their most demanding and profitable clients. Incumbents tend to ignore or pay less attention to the needs of others (i.e. non-consumers, or the low end of the market). Entrants try to target those overlooked segments, and gain a foothold among them by offering suitable functionalities, usually at a lower price. Incumbents do not respond appropriately to these moves by entrants. Then entrants grow and claim some of the incumbents' mainstream customers while keeping those features that made them successful. The disruption is completed when (or if) the mainstream customers start adopting the entrants' products on a large scale.

This chapter puts Christensen's theory into practice with the help of a conceptual framework (see Figure 14.1). The conceptual framework aims to help researchers explore if a given innovation can potentially disrupt the market/sector (or not). The framework guides the researcher to consider different types of enablers that may help the innovation to be disruptive. These innovation enablers are categorized into supply related enablers and demand related enablers, as elaborated upon later in this section. Once these innovation enablers have been investigated, the researcher or the market analyst can gain a better outlook on the disruptive potential of the innovation under study.

The proposed conceptual framework starts by identifying the innovation. This framework can address diverse types of innovations in transport such as transport modes (e.g. the Hyperloop, flying car), transport services (e.g. Mobility as a Service (MaaS); see Veeneman, Chapter 12 in this volume), or technologies that can impact the way people may travel (e.g. Virtual Reality (VR), which might reduce the need to travel).

In the first part of the framework, the basic characteristics of the innovation are determined. The following questions could be helpful: what does the innovation do? Who will use this innovation (i.e. which user segments)? What are the investment costs? What are the operational costs? What are the key drivers and barriers of the innovation? What are the environmental impacts of the innovation?

The next two parts of the conceptual framework form its core, containing the two main types of innovation enablers: the *supply related innovation enablers* and the *demand related innovation enablers*. We explain these two in detail below.

The Supply Related Innovation Enablers

The second part of the framework focuses on the supply related *enablers*, and includes three essential enablers of an innovation which can make it a potentially disruptive innovation. They are called[6] 1) 'enabling technology', 2) 'business model' and 3) 'coherent value network'. Table 14.1 explains what is meant by each of these three innovation enablers.

According to Christensen, the three innovation enablers should be in place in order to make disruptive innovations available to consumers or users (Christensen et al., 2015, 2018). These enablers can be seen as the key ingredients that allow the innovating firm to supply (i.e. make available) the innovation to customers in collaboration with a network of partners and distributors. If the supply related enablers of an innovation are not in place, then it would be hard to make the innovation widely available to the public in a short time scale (i.e. few years).

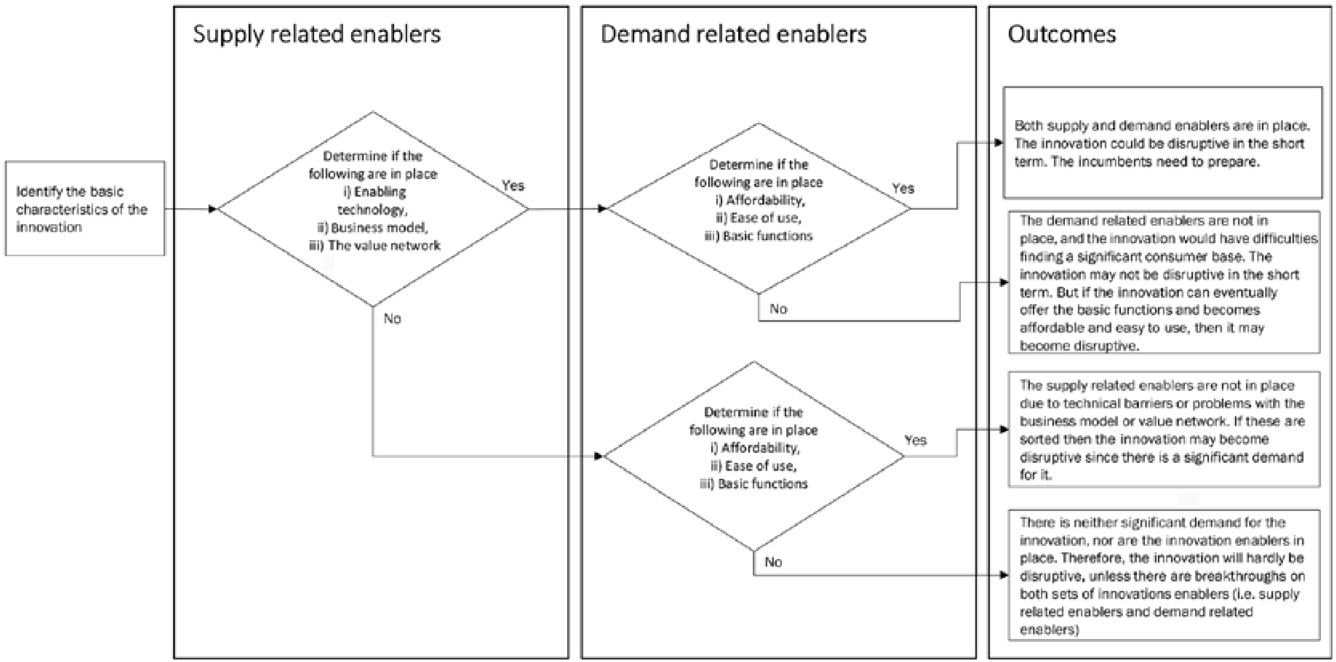

Figure 14.1 Conceptual framework for exploring the disruptive potential of an innovation

Table 14.1 The three supply related innovation enablers and their description

Supply related innovation enablers	Description
Enabling technology	An enabling technology that makes a product or a service more affordable and accessible to a broader population
Business model	A business model that targets new customers, non-consumers (who previously did not buy products or services in a given market) or low-end consumers (the less profitable customers)
Coherent value network	A network in which suppliers, partners, distributors and customers are each better off when the disruptive technology prospers

The first supply related enabler is the actual technology behind the innovation. This refers to the mechanism that enables the innovation to function. If the 'enabling technology' for a given innovation is not yet ready or mature (i.e. is still at lower TRL levels[7]) that means the technology (behind the innovation) is in its infancy or early conceptual phase (e.g. below TRL level 3 or 4). The technology exists only in labs or simulation environments (at these TRL levels). The prototypes or working models of the innovation[8] need to be built and tested. The safety features also need to be checked and verified.

The second supply related enabler is the business model for the innovation. Suppose the innovation's business model does not indicate a positive financial performance for the innovation; this means that the innovation is not yet feasible (financially) and requires (substantial) investment to take off. The cost of building the infrastructure for some innovations, or building the IT platforms for an innovative service, may be simply too high to amortize the capital costs for investors in a time frame set by them.

The third supply related enabler is the coherent value network. Often, the innovators are not independently able to bring the end product or service (i.e. the core of the innovation) to the users/customers. The firm needs suppliers of parts or raw materials, and it also needs distributors and partner companies who can help with the logistics. Without these networks of companies, the innovating firm will have difficulties in getting its product or service to its clients, and the innovation will probably not disrupt the market.

The Demand Related Innovation Enablers

The innovation must have features that will increase the utility of consumers by using or adopting it. Therefore, the needs and requirements of the consumer on the demand side are very important and are investigated as the third part of the conceptual framework. The demand related enablers include three ele-

Table 14.2 Demand related enablers for a potentially disruptive passenger mode or service

Demand related innovation enablers	Description for passenger transport mode or service
Affordability	Travel costs are comparable to, or lower than, those of the existing modes or services
Ease of use	Availability, comfort and accessibility of the mode or service is attainable by consumers
Basic functions	The mode or service can be used safely by the travellers The travel time when using the innovative mode or service will be comparable to, or lower than, that when using existing modes or services

Table 14.3 Demand related enablers for a potentially disruptive freight mode or service

Demand related innovation enablers	Description for freight transport mode or service
Affordability	Shipping costs are comparable to, or lower than, those of existing modes or services
Ease of use	Loading/unloading locations are accessible for shippers There is a suitable network connection so that the freight can be distributed smoothly
Basic functions	The mode or service can be used reliably, with a shipping speed that is comparable to, or higher than, that of existing modes and services

ments,[9] namely: 1) 'affordability', 2) 'ease of use' and 3) 'basic functions' of the product or service offered by the innovation. These elements in the demand related innovation enablers should be in place so that innovations can find a substantial consumer base and potentially gain a foothold among consumers and even attract non-consumers or the lower end of the market. This part is also essential for making an innovation potentially disruptive.

In Tables 14.2 and 14.3, the elements of demand related enablers are listed and further translated into specific key criteria for a potentially disruptive passenger and freight transport mode (or service), respectively.

The last (fourth) part of the framework provides a series of outcomes, informing the user of the framework about the status of the innovation and what changes are needed to enable a disruptive entry to the market. The two sets of innovation enablers can generate four different outcomes. Based on each of these four outcomes, the framework provides guidance regarding the disruptiveness of the innovation.

In the next section, we will apply the above-mentioned conceptual framework for the case of the Hyperloop and discuss the disruptiveness potential of this mode of transport.

4. APPLYING THE CONCEPTUAL FRAMEWORK FOR THE CASE OF THE HYPERLOOP

To make a fair judgement on the disruptiveness potential of the Hyperloop, one needs to implement a full-scale and up-to-date technical and financial feasibility study of a Hyperloop system in a potential corridor or a network of corridors to obtain a better picture of the Hyperloop's impact on the transport sector. We have not yet conducted such a comprehensive assessment. However, we rely on recent technical and economic feasibility studies, which will be the sources for our case study.

The first step of our conceptual framework is to identify the basic characteristics of the Hyperloop. The literature review article by Mitropoulos et al. (2021) is a solid point of departure in determining these basic features of the Hyperloop. The paper offers answers to the questions we proposed at the start of section 3. The authors list various studies conducted in different regions of the world (Europe, Asia and America) and address multiple technical aspects of the Hyperloop, for instance the pod, the power systems, the infrastructure, levitation, propulsion, and transport engineering and planning aspects.

For the second step of the framework, we reflect on the supply related enablers of the Hyperloop (as discussed in section 3), which are the following: 1) the enabling technology, 2) the business model for the Hyperloop and 3) the coherent value network that needs to be created for the Hyperloop.

The Enabling Technology Needed for the Hyperloop

The Hyperloop is, on many levels, a highly advanced piece of technology that needs to be studied at multiple levels (van Goeverden et al., 2018):

- pod technology
- levitation and propulsion technology
- the infrastructures (i.e. the tubes, the pylons, stations, high-speed switches)
- the vacuum environment
- the stations and loading and unloading of passengers and cargo to the pods
- the safety and regulatory processes and guidelines
- communication, traffic monitoring and control systems.

Based on the discussion provided by van Goeverden et al. (2018), Stubbin et al. (2020), Rajendran and Harper (2020) and Mitropoulos et al. (2021), among other authors, the technical features of the Hyperloop are in the 'design' or 'define' phase or 'in the very early stages of development'. Much more data needs to be gathered from different pilots or test environments (where actual-size pods are put on test tracks, in tubes) to make a definite conclusion on the technological readiness of the Hyperloop.

There are uncertainties about the pods' comfort level, including in relation to seat and thermal comfort, amount of walking space within the pods, and vibration and noise levels at such high speeds. Amenities such as WiFi connection, luggage compartments and lavatories are also essential for the Hyperloop's competitiveness with air travel or HSTs. There are also issues about maximum thrust forces and acceleration or deceleration that can be applied on pods with passengers onboard, which must be tested (Mitropoulos et al., 2021).

Assuming all these technical barriers and uncertainties are solved, the Hyperloop could provide a 'good alternative' to air travel for 'medium to long-distance travel' (van Goeverden et al., 2018).

The Business Model for the Hyperloop

Since there are not yet any commercially available Hyperloop lines, there is no market in place to allow us to assess the current business model for the Hyperloop. However, according to Christensen's theory, a business model of disruptive innovation needs to target non-consumers or new customers from the low end of the market. The low end of the market is where the disruption of the market often occurs (Christensen et al., 2018).

The developers of the Hyperloop expect it to capture some part of the market for air travel and HST, or even disrupt these markets. Hence, the Hyperloop business model needs to be comparable with these two incumbent modes in terms of capital investments, operational costs and revenues. That is why some studies, including those by van Goeverden et al. (2018), Rana (2020) and Rajendran and Harper (2020), compare financial indicators of these two modes with that of the Hyperloop.

The business model of the Hyperloop, if it wants to be disruptive and capture a significant market share from other modes, needs to cover the operational and overhead costs and repay the capital costs over a period of time. At the same time, the travel costs for the passengers and the freight fares per ton-km needs to be competitive with the existing modes so that reasonable modal shifts can be observed over time.

The study by van Goeverden et al. (2018) estimated that the travel time for a 600 km distance would be 40 minutes for the Hyperloop, compared to 98 minutes for air travel and 139 minutes by HST. The energy consumption per passenger would be 3.3 times less for the Hyperloop and HST than for air travel, and similarly, the GHG emissions[10] would also be three times less. This means that there would be passengers who would be willing to pay a premium to travel on the Hyperloop for reasons of either speed or low emissions (or both), which means the Hyperloop could have higher ticket prices than its competitors. However, asking for a premium ticket price for the Hyperloop would make it impossible to capture the low end of the market.

Stubbin et al. (2020) have reviewed the feasibility studies[11] of several Hyperloop projects and collected the capital costs of different potential corridors. The capital costs for infrastructure are in the range[12] of $37.8M to $56.4M per km (in 2020 $) in these feasibility studies (Stubbin et al., 2020), €33.5M[13] per km in the article by van Goeverden et al. (2018), and €38.9M per km in the article by Maja et al. (2020). Here, the type of soil where the pylons for the tubes need to be built and the geography of the corridor play a significant role in making estimates of capital costs. Based on the corridor's terrain, the tubes may need bridges or tunnels, which would increase the costs per km and would be highly challenging from a safety point of view.

In addition to the capital costs, the operational and overhead costs also need to be covered by the Hyperloop revenues. Providing estimations for these costs is extremely difficult since it depends on the demand size, the frequency of pods, the time saving per corridor and the freight capacity that could be handled in a corridor. Yet, a few studies have provided helpful revenue estimates translated into ticket costs. Based on certain assumptions regarding the indicators that we just mentioned for the operating costs, van Goeverden et al. (2018) has estimated that €0.30 per passenger-km would at least mean the project would break even. Stubbin et al. (2020) have used the example of MagLev trains as a gauge for the Hyperloop and estimated a unit ticket price of $0.26 to $0.28 per person-km. Maja et al. (2020) calculated that it is possible to envision a Hyperloop service between Rome and Milan with a ticket price of €0.23 per passenger-km if the project is allowed to amortize its capital costs over 44 years.

These price estimates per passenger-km are often comparable to or higher than legacy air carriers and certainly higher than the low-cost air carriers. These ticket cost estimates make the Hyperloop affordable for the high end of the market rather than the lower end, which means it is unlikely that the innovation will be disruptive.

The Value Network that Needs to Be Created for the Hyperloop

Several private Hyperloop developers such as Hyperloop Transportation Technology (HTT), Hyperloop Italia, Virgin Hyperloop One, Zeleros Hyperloop (UPV), Delft Hyperloop, DGW Hyperloop, and The Boring Company are actively studying, experimenting with and testing different concepts and technological hurdles of Hyperloop.

The European Hyperloop Centre is a not-for-profit and open innovation initiative in the Netherlands. It is a public–private partnership between a provincial body and two Dutch Ministries,[14] and a group of private companies trying to support the R&D on Hyperloop transportation.

The formation of several private companies and public–private partnerships as well as various publicly funded feasibility studies on the Hyperloop signal increasing interest for the Hyperloop. However, hurdles remain regarding both technical matters, such as the promised speeds and the acceleration and deceleration challenges, and safety and health aspects, all of which need to be overcome. There needs to be much more industrial collaboration from different stakeholders to overcome the technical and safety barriers. These collaborations are essential to acquire the approval of regulators that will allow the Hyperloop to be put into public use.

Next to technical challenges, there are some legal challenges regarding the land, both private and publicly owned, that needs to be acquired (i.e. right of way) for building the Hyperloop infrastructure (Stubbin et al., 2020). There are plausible concerns about the visual pollution caused by the tubes placed over pylons in urban and suburban areas, which might lead to resistance from citizens. Therefore, in addition to technical collaboration, there needs to be stakeholder collaboration on legal and societal issues for the Hyperloop to be built in urban and suburban areas. Without the collaborations among stakeholders, the network of suppliers and regulatory authorities, it is unlikely that even a technically ready Hyperloop would be allowed to operate.

As a next step in assessing the conceptual disruptive innovation framework, we focus on the demand related enablers of the Hyperloop. This part looks from the user's perspective. In the following subsections, we discuss if the Hyperloop is affordable, easy to use, and has the basic functions a mode needs for passengers and cargo movements.

Affordability

According to Christensen, disruptive innovations need to address the low end of the market (Christensen et al., 2015). But there are examples of innovations that were initially expensive and eventually disrupted the mobility market, for instance the car following mass production by the Ford company. In the car example, the price of a car was too high for the lower end of the market, but Ford managed to reduce the cost significantly so that it was no longer a luxury product for the very rich. Ford managed to make cars accessible to broader sectors of the market, and with added competition from other carmakers and economics of scale, the car eventually became available to the middle classes.

As discussed in the business model section, previous research and feasibility studies have put the Hyperloop ticket price at between $0.26 and $0.36 (€0.23

to €0.31 in the year 2022) per person-km to break even. Air travel is expected to be a strong competitor for the Hyperloop. We have taken the average cost of a one-way plane ticket from many connections (ranging from 350 km to 1200 km) in different parts of the world (i.e. developed and developing countries). We arrived at prices between $0.06 and $0.12 (€0.05 to €0.10 in the year 2022) per passenger-km for the low-cost carriers and between $0.11 and $0.35 (€0.09 to €0.24 in the year 2022) per passenger-km for the legacy carriers (for a one-way economy class seat). However, many legacy carriers sell their return tickets (for many connections) with a price only 10 to 30 per cent higher than their one-way tickets. Hence, the travel cost per passenger-km for a return ticket would be between $0.05 and $0.18 (€0.04 to €0.16 in the year 2022) per passenger-km for the legacy carriers. The price for HST tickets, depending on the distance and the location, is in the same order of magnitude as air travel. Van Goeverden et al. (2018) put the HST price at $0.20 and air travel at $0.21 per passenger-km, which is in line with our observation of the current situation (in 2021).

The conclusion is that given the current travel cost estimations for the Hyperloop, it would not compete with air travel or HST, purely based on costs.

Ease of Use

When assessing the 'ease of use' of a transport mode we consider three attributes, namely 1) availability, 2) comfort and 3) accessibility, that are highly relevant to travellers when selecting a travel mode.

Comfort

Walker (2018) has defined a few criteria for passengers' comfort in the Hyperloop, which include acceleration/deceleration, seat comfort, thermal comfort, crowdedness, psychological distress, noise, motion sickness and access to facilities.

To ensure passenger comfort, maximum acceleration and deceleration needs to be strictly limited to 0.1G and 0.3G, respectively. However, motion sickness, which can be anticipated with the presence of lateral gravity when travelling around bends and curves at high speeds, is yet to be studied (Walker, 2018).

Given the experience with MagLev trains, Hyperloop passengers are less likely to sense much noise or feel much vibration since the driving mechanism for pods is relatively similar, except pods travel in a more controlled vacuum environment (Walker, 2018). However, the actual noise and vibration levels need to be demonstrated at speeds of 1200 km/hr, which has not yet been achieved either in practice or in the test phases.

Another important comfort factor is that passengers will not be able to enjoy the view of the surroundings while travelling in the tube. This may need to be compensated by onboard amenities such as video or visual features in the Hyperloop pods.

Although Elon Musk did not include lavatory facilities in his design, it seems essential for trips longer than 10 minutes. Therefore, to compete with air travel and HST, the Hyperloop pods need to be equipped with lavatories. Additionally, the passenger compartment needs to be easily walkable with enough luggage room, especially for trips of medium to long distance.

Given what has been said above, it is clear that the level of comfort for the Hyperloop is not yet certain. Further data from test cases and pilots are required so that there is enough evidence to make a sound analysis of the comfort levels.

Availability

Various feasibility studies (e.g. Stubbin et al., 2020; NOACA et al., 2019; Rajendran and Harper, 2020) assume that the number of pods travelling on a given corridor (e.g. 600 km) per hour would be anything from 15 to 40, or even 50, with a passenger capacity of 28 to 44 and an operation time of 15 to 18 hours per day. SpaceX has estimated the frequency of pods to be one pod per 2 minutes, and van Goeverden et al. (2018) have used a frequency of one pod per 5 minutes. Maja et al. (2020) have used two scenarios of 4 minutes in peak times and 8 minutes in non-peak times.

Given all these estimates, we can conclude that the Hyperloop would have a robust competitive edge when it comes to availability, since HST and air travel, even for busy point-to-point destinations, cannot compete with such high frequencies. However, the Hyperloop and HST are bound to the corridors built for them and do not have the flexibility available to air travel. No corridor or infrastructure other than the airport itself is required for air travel, and air travel therefore wins in terms of availability for less densely populated areas.

Accessibility

If we define accessibility in terms of passengers boarding or disembarking the pods, then the Hyperloop seems to be comparable to HST and would therefore be a relatively passenger-friendly mode (Walker, 2018; Jia et al., 2019). Reaching the pods at the station would be relatively quick, requiring less screening and waiting times than air travel. Therefore, the time lost in Hyperloop stations is thought to be somewhat less than air travel (Jia et al., 2019).

If the accessibility of passengers is defined in terms of accessing the station itself, then the Hyperloop would be similar to air travel, given that the Hyperloop stations would most likely be positioned on the outskirts of cities, with good access/egress connections. Assuming that the Hyperloop stations could be located in or near urban centres, they would be more accessible than airports and comparable to trains. Spatial design topics play an important role in determining the optimal location for the Hyperloop stations and whether the Hyperloop stations should be built underground or above ground with tubes connecting them.

Given some safety concerns due to the vacuum environment and the high speeds of the pods, the Hyperloop stations might need a special design to allow the vacuumed and normal pressure areas to be split (Mitropoulos et al., 2021) and might have to be located outside of built-up areas (Jia et al., 2019).

In conclusion, boarding the Hyperloop would, at best, be similar to HST in terms of waiting time at the station and accessing the station. But it would be similar to air travel should passengers have to go to the outskirts of cities to get to the stations, which would require good access/egress links. Therefore, the Hyperloop would not be much better or worse than the incumbent modes in terms of accessibility.

We emphasize that there are many socio-economic factors involved in choosing the location of the Hyperloop stations. These factors include accessing workplaces in the metropolitan areas, increased land value, increased economic activities and enhanced accessibility to other metropolises. Therefore the optimal choice of location for a Hyperloop station, and its consequential impacts, requires detailed research.

The Hyperloop could be an instrumental mode in making two metropolitan areas accessible to each other. The high frequency of pods is an important advantage of the Hyperloop over HST and local air travel. The high capacity offered by pods travelling at high frequencies (e.g. every 2 to 5 minutes) between two metropolitan areas would give the Hyperloop an unmatchable edge in connecting two places, increasing the accessibility of people wanting to reach those areas that are linked to the Hyperloop network. This might also generate new trips, for instance people working in Paris but deciding to live in Rotterdam.

Basic Functions

A fundamental goal of transport modes is to move people (and cargo) safely at an acceptable cost, in relative comfort, and within a reasonable travel time (Mokhtarian, 2019). We call these 'basic functions' of a transport mode. Comfort and cost have already been discussed in previous sections, and here we focus on the other two basic functions: safety and travel time. To be commercially successful, the Hyperloop needs to be safe and preferably have lower or similar travel times compared to the existing travel modes.

Safety

Around a third of previous research on the Hyperloop has paid some attention to safety issues (Mitropoulos et al., 2021). This volume of research reflects the level of concern about the safety of the Hyperloop.

Since the Hyperloop aims to travel at very high speeds in tubes, it needs to overcome many technical challenges before it can be considered safe by regulators for public use. The near-vacuum operating environment, the frequent pressurization and depressurization of pods, air cracks and fire hazards in pods and tubes, and emergency exits in different parts of the corridor (in tunnels, over bridges, over water), are among the topics which should be addressed for safety (Gkoumas and Christou, 2020). Therefore, Hansen (2020) considers ‘safety constraints’ to be the ‘most serious barrier’ to ‘successful commercial operations’ (p. 817).

Hyperloop developers are promising that the highest safety standards and stringent regulations are being pursued in the design of the systems. However, these claims remain to be substantiated during the pilot phases. Statistically, the Hyperloop needs to be at least as safe as air travel, given that air travel would be one of the main competitors of the Hyperloop. The safety record of air travel is well documented by the International Air Transport Association (IATA), which has recorded 1.3 to 1.7 accidents per 1 million flights (IATA, 2022). These statistics would be the benchmark during the initial and pilot phases of the Hyperloop.

Assessing and proving the safety of a novel concept like Hyperloop can be deemed a difficult challenge. The mapping of risks and hazards in the state-of-the-art literature (e.g. railway, aviation, automotive) is often done on the basis of statistics. Although the Hyperloop concept consists of many subsystems which have been proven to be safe in various existing applications (e.g. magnetic levitation, airlocks, vacuum systems), the statistics on the risks and hazards of these components rely on the application context. Moreover, when dealing with such a novel concept, an additional set of complications is induced by the lack of existing application-specific norms or standards (Arup et al., 2017).

In order to assess the safety of Hyperloop in its early development stages, in the absence of application-specific norms/standards and/or statistics, novel and potentially tailored approaches may have to be designed. These approaches should accommodate interactive discussions between the applicant and the assessor on notions such as, for example, acceptable risk (Arup et al., 2017).

In this chapter we will not go deeply into the safety aspects and concerns of the Hyperloop; we refer readers to Gkoumas and Christou (2020) for a deeper discussion regarding the safety aspects of the Hyperloop.

Travel time

Travel time is another essential aspect for any transport mode, not just disruptive ones. Due to the levitation of pods and reduced air resistance in the tubes, the pods are poised to travel at very high speeds, thereby drastically reducing travel times over short to medium distances compared to incumbent modes. If these promised low travel times are realized in the real world, the Hyperloop can claim to have a significant advantage over its competitor modes, that is, air travel and HST.

The perception of time or the value of time (VOT) is not consistent among different user groups, such as commuters, business travellers and leisure travellers (Horowitz, 1978). Establishing the VOT and willingness to pay for such low travel times among different segments of the Hyperloop users requires further research (Mitropoulos et al., 2021).

BAK Economics AG (2020) has discussed the time aspects for the Hyperloop and concludes that even considering the access/egress time and the time needed for the security screening, the boarding process and baggage handling, the Hyperloop will still be considerably faster than competing modes, and will probably have a significant impact on the Basel–Paris corridor of 415 km, which was taken as an example. Furthermore, the Hyperloop is poised to have a winning edge over air freight in the high-speed cargo market, which accounts for 2 per cent of total ton-miles but covers 40 per cent of total freight value (BAK Economics AG, 2020).

In the two years preceding the writing of this chapter in 2022, many business trips have been scrapped and replaced by online meetings due to the COVID-19 pandemic. Going forward, many business travellers will likely continue to reduce their amount of travel compared to before the pandemic. Some researchers claim that this reduced work-related travel may stay for the long term (at least for high-income individuals), even after the pandemic is over (Brough et al., 2021). This would cause severe doubts as to the travel demand for the Hyperloop, and would weaken one of the best advantages that the Hyperloop has to offer in comparison to its competitor modes.

5. DISCUSSING UNCERTAINTIES REGARDING THE HYPERLOOP

The conceptual disruptive innovation framework provides a tool to explore different criteria of innovations and swiftly check if an innovation (mainly in the transport sector) has the potential to be disruptive or not and under which conditions.

We used the case of the Hyperloop to validate the framework and to see if the Hyperloop could potentially disrupt the transport sector. The findings of recent research on the Hyperloop was used as input for our assessment.

Table 14.4 Index for determining the disruptiveness of each element

Highly unlikely to be disruptive	Unlikely to be disruptive	Neutral	Likely to be disruptive	Highly likely to be disruptive
– –	–	0	+	+ +

Tables 14.5 and 14.6 provide a summary of the two central components of the framework (i.e. the supply related enablers and the demand related enablers), which will guide us to the outcome of the framework. An index for determining the disruptiveness of each element discussed in these tables is given in Table 14.4.

Framework Outcome

Based on the above discussions, one can conclude that some supply related enablers for the Hyperloop are in place, some are uncertain, and some are not in place. Similarly, some demand related enablers for the Hyperloop are present, and some are yet to be proven. Therefore, given the current level of uncertainty, it would be challenging to consider the Hyperloop as a disruptive mode of transport in the short term. This finding is based on what has been revealed by the currently available academic literature on Hyperloop assessment and by independent feasibility studies. However, the future may look different for the Hyperloop given other circumstances. Next, we offer some possible future developments that could help the Hyperloop disrupt the transport sector or conversely make the Hyperloop uncompetitive in the future.

Possible Future Developments

The environmental pull: the need to reduce the carbon footprint of the transport sector

Due to the significant role of the transport sector in total emissions and the increased public sensitivity to climate change, the Hyperloop seems to be an attractive alternative to air travel for policymakers, and could replace many short to medium air trips between metropolitan areas. Aircraft currently use fossil-based fuels, which is highly unsustainable (Upham et al., 2012), and there are growing public concerns, reflected, for instance, by the flight shaming campaign (Flaherty and Holmes, 2020; Mkono, 2020).

There are additional reasons for policymakers to support the Hyperloop developments. Here we name just a few: the uncertainties in oil prices; the Paris Agreement and the follow-up obligations for CO_2 reduction; and the

Table 14.5 Summary of findings for supply related enablers of the Hyperloop

Supply related innovation enablers	Discussion	Potential for disruption	Assumption
Enabling technology	The technical features of the Hyperloop are highly uncertain. Some features are in the 'design' or 'define' phase, and some are in the 'early stages of development'. Therefore it is too early to say if the final product would be more affordable to a broader population than the incumbent modes.	0 (too early to say)	Technologies must be safe and cost-efficient to operate a network of pods.
Business model	Based on different scenarios on infrastructure costs and market size, researchers have generally evaluated that the ticket price of the Hyperloop will be around two times higher than HST and legacy air carriers (three times more costly than low-cost carriers) to cover the capital costs and operational costs. This will make it difficult for the Hyperloop to disrupt the market and target the low end of the market.	– –	Environmental drivers are not the main drivers for extensively adopting a mode (i.e. disruption). The ticket price and willingness-to-pay play a more significant role in determining the business model of the Hyperloop.
Coherent value network	There is a significant interest and excitement among several private parties to further push ahead with the technical development of the Hyperloop. There is also interest from the public sector to assess the potential of the Hyperloop, at least at the level of feasibility studies. Some public–private collaborations are underway, which creates the foundation of a value network. This factor could positively contribute to the Hyperloop's disruptiveness, provided that other aspects (technical and financial) are fulfilled.	+	Private–public collaborations will continue in future.

Table 14.6 Summary of findings for demand related enablers of the Hyperloop

Demand related innovation enablers	Discussion	Potential for disruption	Assumption
Affordability	Given the current estimations, the Hyperloop ticket price would be between \$0.26 and \$0.36 per person-km. In contrast, the low-cost carriers are at \$0.06 to \$0.12 per passenger-km, and the legacy carriers are between \$0.11 and \$0.35 per passenger-km for one-way economy tickets and even less for a return ticket. The Hyperloop could not compete with air travel or HST, purely based on ticket price.	− −	The ticket price for the Hyperloop is determined with the assumption that it only recovers the operational costs and initial capital investments with a discount rate of 2%.
Ease of use	*Availability:* for an established Hyperloop corridor, the frequency of the Hyperloop will be very high and much better than flight and HST frequencies. However, the air carriers are more flexible in choosing destinations and responding to the market demand.	+ (for frequency)	Based on the frequency of one pod per 2 to 5 minutes.
	The Hyperloop, like HST, is bound to the existing tracks, making it difficult for the Hyperloop to be available at many locations, thus limiting its availability.	− (for network availability)	New routes would take a longer time to construct and considerable investment and depend on the demand.
	Comfort: Hyperloop developers claim that it would be a smooth ride, with less noise and vibration. The Hyperloop's comfort level is not yet certain and requires further proofs through test cases and pilots to gather enough evidence to make a sound analysis.	+ (with uncertainty)	Based on the validation of claims made by the Hyperloop developers.

Demand related innovation enablers	Discussion	Potential for disruption	Assumption
Ease of use (continued)	*Accessibility:* the Hyperloop would be (at best) similar to HST in terms of waiting time at the station and travelling to the station; otherwise, reaching a Hyperloop station would be similar to going to airports on the outskirts of cities, which require good access/egress links. Therefore, the Hyperloop would not be much better or worse in terms of accessibility than incumbent modes.	+	Based on screening at the Hyperloop stations not being intensive.
Basic functions	*Safety:* this is highly debated in the literature, and many technical and safety challenges are yet to be overcome. This factor provides the highest level of uncertainty for Hyperloop's deployment and possible disruption in the coming years.	0 (for safety)	High level of uncertainty for Hyperloop's deployment.
	Travel Time: if the promised speeds are fulfilled, the Hyperloop will have a significant advantage over its competitors. This creates potential disruption capabilities for the Hyperloop, assuming that there is sufficient demand for fast travel after the pandemic.	+ + (for travel time)	The Hyperloop can reach speeds of 1200 km/hr (as promised)

increasingly available electricity from renewable sources, which is more easily used in land-based transport than in air transport.

The need to reduce the carbon footprint of the transport sector may allow policymakers to justify spending public resources on the infrastructure costs of the Hyperloop. This would have a reinforcing effect on efforts to fast-track technological developments of the Hyperloop and to attract additional investment from the private sector, in order to overcome the technical and safety challenges.

There is the possibility that policymakers will opt for imposing environmental tax levies on the aviation sector, to force the aviation sector to innovate and reduce emissions and also to support the cleaner competing modes, such as the Hyperloop or HST. This would again be an advantage for the Hyperloop. However, considering the costs of tickets, it seems that without substantial increases in the price of flying, it will be challenging for the Hyperloop to compete and become disruptive.

Breakthrough in aviation emissions problem

There is also the possibility that the aviation sector might make a breakthrough in flying without the need for fossil fuels, by replacing them with electro-fuel and liquid hydrogen (Åkerman et al., 2021) or any other innovative technology. This scenario would create a very high entry barrier for the Hyperloop, given the high capital investment costs compared to air transport, which already has a lot of infrastructure (local and international airports) in place.

Breakthrough in reducing the Hyperloop costs

Currently, the most influential factor in determining the high ticket cost of the Hyperloop seems to be the capital investments needed for building the infrastructure (van Goeverden et al., 2018; Hansen, 2020). If there are breakthroughs in significantly reducing the infrastructure costs and building cost-efficient pods and operating systems, the disruptive potential of the Hyperloop may increase.

Furthermore, the reduced infrastructure costs would enable more countries to invest and collaborate in developing an international Hyperloop network (e.g. Amsterdam–Frankfurt–Brussels–Paris network). This scenario would work as a catalyst in fast-tracking the Hyperloop's entry into the market.

6. CONCLUSIONS

This chapter introduces a conceptual framework to explore disruptive innovation in the transport sector. The framework is based on the Disruptive Innovation Theory of Christensen and could further help transport researchers and practitioners to put this theory into practice.

The framework is then applied to the case of the Hyperloop as a potentially disruptive mode. The supply related enablers of the Hyperloop – namely, the Hyperloop technology, business model and value network – are explored, along with the demand related enablers of the Hyperloop. Further, the demand related aspects – namely, affordability, availability, comfort, accessibility, safety and travel time – are discussed. This is done based on recent literature and feasibility studies on the Hyperloop.

The outcome of the conceptual framework is that it is unlikely that the Hyperloop will be disruptive in the short term (i.e. the coming decade), given the arguments provided in the discussion section and the current uncertainties on the technological readiness and safety issues. Moreover, the current estimated ticket costs for the Hyperloop would be acceptable only to the high-income groups of society. Therefore, policymakers could find it hard to justify the infrastructure costs to only benefit this small segment of society instead of investing in projects with more comprehensive and overall benefits for society as a whole.

Finally, we argue that the need to reduce the carbon footprint of the transport sector combined with possible breakthroughs in reducing the Hyperloop's infrastructure expenses (and subsequently reducing travel costs) may be helpful for the realization and potential disruption of the transport sector.

NOTES

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2. In the innovation literature, there is another category of innovations, called radical innovations. Radical innovations also point to novel ideas or products and technological breakthroughs. However, there are some conceptual and fundamental differences between disruptive innovations and radical innovations. They are created by different mechanisms and the response of incumbent firms or organizations towards these two types of innovation should be different. We refer the interested reader to Hopp et al. (2018a) and Hopp et al. (2018b). In this chapter we focus on disruptive innovations and base our work on the literature related to such innovations.
3. Some of the potential gains are listed as creating new business models, value chains and transforming or propelling the sector (in which the disruption has occurred) to a leading position (Tait and Wield, 2021).
4. All the prices given in this chapter are in US Dollars ($) or Euros (€) unless otherwise mentioned.

5. Also assuming pods with a capacity of 28 passengers and a frequency of 12 pods/hr each direction with at least a 15 hr/day operating time.
6. These terms are taken from Christensen's theory of Disruptive Innovations (Christensen et al., 2018).
7. TRL levels refer to the technology readiness levels explained by Mankins (1995).
8. In case of transport, this could be either a mode, a service or a new technical tool.
9. These terms are taken from Christensen's theory of Disruptive Innovations (Christensen et al., 2018).
10. If the electricity for the Hyperloop or HST comes from renewable sources then the GHG emission saving would be much larger compared to air travel.
11. These studies have been conducted by different commercial sector consultancy companies including, among others, SpaceX, KPMG, TEMS and Virgin Hyperloop.
12. There is a low estimate of $19M per km by SpaceX (2013), which seems to be an outlier, given the rest of the feasibility studies – see section 2.
13. Given that 50 per cent of the 600 km corridor has solid soil, 40 per cent weak soil and 10 per cent consists of tunnels.
14. The Ministry of Economic Affairs and Climate Policy, the Ministry of Infrastructure and Water Management, and the Province of Groningen.

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