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# Main report: Hyperloop in The Netherlands

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# Table of content

# Management summary

**Main conclusion**
The development of a hyperloop test facility in The Netherlands contributes to R&D and innovation related to Smart Mobility. It offers opportunities in strengthening the Dutch innovation and production ecosystem (with a first-mover position) and benefits in terms of jobs and contribution to social challenges. Our advice to the government is to build a partly publicly financed full scale, 3 m diameter, test track in The Netherlands. The test track could start with a relatively low budget 3 km facility. Once this test track has been proven successful, it could be extended to a longer one and possibly even become part of a commercial track. But those decisions will have to be taken at a later point in time when more information about the development of the technology and costs is available. The 3 km facility will not be dedicated to one technology or company and as such enables the partnership with multiple hyperloop companies and aim for a joint public-private investment, certification and standardization process.

**Background**
The Netherlands is one of the leading countries in the development and implementation of new and innovative mobility concepts. Concepts such as Autonomous Driving, mobility services, sensors for road control, safety and maintenance, and world class (Smart Mobility) testing facilities are becoming standard solutions in Dutch mobility. The ambition of the Ministry of Infrastructure and Environment is to further strengthen and broaden this position. A hyperloop system (in which passengers and cargo travel in a pod through a near-vacuum tube at sub-sonic speed) could potentially contribute to this goal.

Currently, several hyperloop companies are looking for opportunities to realize a test track. Two of these, Hyperloop One (USA) and Hardt (NL), have approached the Dutch government to discuss a partnership for such a facility. Hardt is looking for a 1 - 3 km test facility, while Hyperloop One is aiming at a 15 km test facility that could be extended to 50 km. In order to compare the different requests, this report investigates 6 scenarios for test tracks (see Table 1). Additionally, this report also gives a short outlook for a first potential commercial track.

This report is the result of an analysis that allows the Dutch government to start the decision-making process on whether or not to invest and/or build a hyperloop test track. The analysis addresses (1) the maturity of the technology, (2) the possible spatial reservation/implementation of a test and a potential commercial track, (3) costs, benefits and added value for The Netherlands, and (4) governance/partnership models for a test (and possibly commercial) phase of a hyperloop system in The Netherlands.

Table 1. Overview of the various scenarios for test tracks

| | Scenario 1 | Scenario 2 | Scenario 3a’ | Scenario 3a | Scenario 3b | Scenario 3c |
|---|---|---|---|---|---|---|
| **Enterprise** | Hyperloop One | Hardt | Any interested hyperloop enterprise | Any interested hyperloop enterprise | Hyperloop One & Hardt | Hyperloop One & Hardt |
| **Type of facility** | Test | Test | Test | Test | Test | Test |
| **Single tube length** | 15 km | 3 km | 3 km | 10 km | 15 km + 3 km | 15 km + 3 km |
| **Number of switches** | 4 | 2 | 2 | 2 | 4 + 2 | 4 + 2 |
| **Type of transport** | People | People | People | People | People | People |
| **Number of test facilities** | 1 | 1 | 1 | 1 | 2 | 2 |
| **Number of test locations** | 1 | 1 | 1 | 1 | 1 | 2 |
| **Tube configuration** | Double | Single | Single | Single | 3 km single + 15 km double | 3 km single + 15 km double |
| **Tube diameter** | 5 m | 5 m | 3 m | 5 m | 5 m | 5 m |
| **Number of airlocks** | 4 | 2 | 1 | 1 (like 3a’ costs according to scenario 2) | 4 + 2 | 4 + 2 |
| **Number of enterprises involved in testing** | 1 | 1 | >1 | >1 | >1; 1 per tube | >1; 1 or more per location |
| **Number of pods** | 2 full-size (60 pax) | 2 test 1 full-size (50 pax) | 4 test 2 full-size (50 pax) | 4 test 2 full-size (50 pax) | 2 test 1 full (50 pax) 2 full (60 pax) | 2 test 1 full (50 pax) 2 full (60 pax) |

**A public investment in the test track creates competitiveness, jobs and revenues**
The main reason for the advice for a partly public investment is that it could, in the test phase (with a running period of 5 years), involve a labor volume of up to 400 FTE per year; around 30 dedicated staff for the facility and 370 jobs for highly innovative companies including staff of Hyperloop One or Hardt. This would be as a result of having a test track. In addition, we expect a maximum gross production impulse (spread over 5 years) in scenario 3a’ in the order of 59% of total CAPEX costs[1] (with respective gross value added or GDP contribution of around 25% of total CAPEX costs).

The added value of the proposed test track is that it can be used to improve technologies, e.g. as developed by Hyperloop One and Hardt, from Technology Readiness Level (TRL) 4-6 to TRL 7/8[2]. These are average values, since some elements, such as high speed switches, are currently at TRL level 2. It is expected that Hyperloop One will be able to test higher TRL technologies than Hardt, as they have a more elaborate testing facility in the USA. We suggest trying to get the testing (and further development of these technologies) to be done in The Netherlands and create a knowledge infrastructure around this technology. When the testing at the 3 km facility starts, the certification process will also start and the certification procedures will be developed simultaneously. For testing and certification for commercial passenger transport at velocities above 1000 km/h to achieve a TRL 9 level, the minimum track length is 40 km. Since a 40 km test track requires a large investment, it would be most efficient to build it along an economically interesting potential first commercial route, e.g. Schiphol-Lelystad Airport (57 km). On a track of 40 km and upwards, the focus will be on the development of the regulatory standards and framework to govern hyperloop-specific operations. Once certification is completed, it can be used as a commercial track.

[1] This concerns total CAPEX costs including pods.
[2] The definition of the TRL levels is given in Appendix C. The effort needed to advance a single level often increases towards higher TRL levels.

It is important to note that The Netherlands has an excellent track record in creating an environment for innovation. We foresee that both public and private parties could assist/co-operate in the design, construction and testing, as well as in realizing synergies with other Smart Mobility test facilities. This is in addition to the delivery of safety cases, EU-standardization and EU-certification. The test track would also function as a means to get more insights into costs that could be expected for a commercial system.

**Design of a test track**
Our suggestion for the test track is to start and build a 3 km, single tube, test track in Flevoland. This first step offers a solid competitive and complementary position to the current existing hyperloop test environments, of which the maximum length is 500 m, with the possibility to add curves and switches. It also opens up possibilities for testing at high speeds with lightweight test pods, and to start the certification of hyperloop components.

Even though the specifications do not meet all requests of Hyperloop One (15 km initially, 2 switches and double tube of 5 m diameter) and Hardt (1 km initially, 5 m diameter, single tube, to be expanded to 3 km with 2 switches), the chosen variables will allow both companies to perform the required testing and development of hyperloop elements, and to start the certification process. The test facility will be designed with the ability to be extended to 15 km and more than 40 km for additional testing, and for a possible first commercial route and full certification.

We advise a 3 km test track consisting of a single 3 m diameter tube on 5 m high pylons, with 2 switches and curves. Part of the test track will consist of 2 tubes to enable the testing of the high velocity and low velocity switches (see Figure 1).

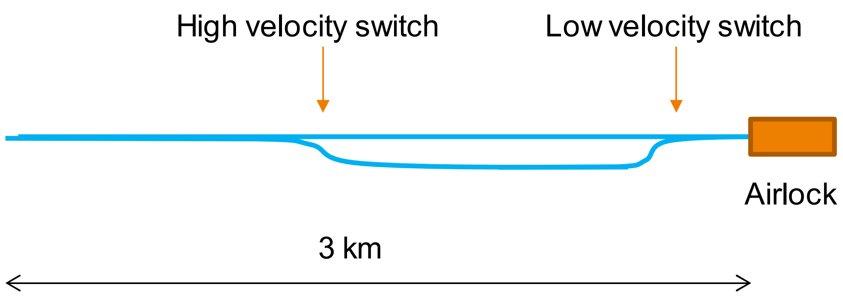


Figure 1. Schematic layout of the proposed 3 km long test track

We expect that each hyperloop party will bring its own pods; a full commercial type pod and two lightweight test pods. The tube will be made of 20 mm thick steel, with pylons every 30 m, and the tube should be accessible to multiple vendors using a magnetic levitation system, at different heights in the tube. Finally, we suggest that, initially, the buildings (offices, storage building, workshops, pumping station) should be well equipped while keeping costs as low as possible, and built in line with cradle-to-cradle principles.

For initial testing purposes, a single tube is sufficient for the main track. Even though both hyperloop parties prefer not to have to share a test track, they do not intend to use an identical system for magnetic levitation and propulsion and also the locations of these systems inside the tube are different. This (likely) gives the possibility for mounting the systems of both companies simultaneously in the same tube. In the end, the realization of a full double tube system from the start is less expensive than adding a parallel tube to a single tube system. However, at this moment the future cost savings do not outweigh the low entry starting costs for a single tube system with which most aspects can be tested, including cost effective production and building methods.

Two switches should be included as this is a novelty compared to the current 30 m (Delft, NL) and 500 m (Nevada, USA) test tracks, and is a very important aspect to be tested from a safety, capacity and technological point of view. The design choices of a high-speed switch will be leading for the selection of the optimal guidance and propulsion systems anticipating a possible commercial track. This is also an aspect that might result in a leading knowledge position of The Netherlands as a hyperloop test location.

The choice for a 3 m diameter tube, made from 20 mm thick steel, is based on the fact that for both the test track and a potential commercial track it is advantageous compared to a 5 m tube (a diameter mainly determined for freight). The advantages of a 3 m tube are the lower costs (road transport of 3 m tubes will be cheaper and easier) and the costs of other components (such as the airlocks and vacuum pumps) will be lower. Other advantages are to be found in spatial implementation and experience with constructing prefab 3 m tubes. Finally, it is expected that when extending the test track to a commercial one, the dominant application would be one of transporting people and possibly ULD-standard boxes from the aviation sector. A 3 m tube with pods transporting around 50 passengers is more than sufficient for supplying this demanded travel capacity.

Therefore, even though both hyperloop parties have indicated a preference for a 5 m tube (also enabling the transport of standard shipping containers), both parties are willing to adapt to customer preferences. A 3 m diameter could be set as a possible EU-standard.

**Costs of a test track**

The total capital expenditure (CAPEX) costs for Scenario 3a' are €119 million (including indirect costs and unforeseen and excluding VAT and pods). The relative costs of the various main components of the test track are provided in Table 2 and are derived from own expertise and benchmark information. It is important to bear in mind that a main focus of the test track is to (further) optimize the hyperloop system and as such will bring important information about possibilities for the reduction of costs of specific hyperloop elements.

Table 2. Relative costs of the main components of a hyperloop test track (Scenario 3a')

| Category | Relative cost |
|---|---|
| Land, Electricity, Pylons and Tube | 24-29% |
| Facilities | 23-28% |
| Vacuum systems, Airlocks, Switches, Motor and Maglev system | 43-53% |

** Given margins in cost estimates the cost categories do not add up to 100%*
*** The cost for facilities are relatively high in the test period due to the fact that, even though the length of the test track is relatively short, full size facilities are needed for storage, workshop, and offices (400 FTE).*

As stated above, we assume that each hyperloop party will bring its own pods. Investments in lightweight pods will add 28-33% to the estimated investments. We present the costs for the pods separately since the number of pods in combination with the length of the test track significantly influences the costs per kilometer. Since several hyperloop components still need to be developed, their costs, and therefore also the total costs, are still uncertain, as is normal for such innovations.

The operational costs (OPEX) for the test track consist mainly of the salaries of about 30 personnel, amenities such as electricity, as well as maintenance. Additionally, a number of about 370 research personnel of multiple partners is expected, who make up the dominant operational expenditure during the test phase. These jobs are associated with the running period of the test facility. Based on average current labor productivity of around €90,000 per year, a potential GDP contribution in the order of €36 million.[3]

**Preferred location and spatial layout**
Based on the spatial analysis, a structure on pylons with a height of 5 meter is preferable and has been used for analysis of all disciplines (e.g. technical status, governance, economy and spatial integration). The Netherlands has a very dense road and water network which could easily lead to spatial clashes with a test track. A construction on pylons makes it easy to avoid spatial clashes with objects and green and grey networks. Little additional work needs to be done to adjust/combine/construct the hyperloop system next to the other networks with this specification/typology. Thus for a 3 km test track accessibility and continuity of the local fabric can be maintained. It is found that pylons of 5 m are sufficient to avoid interaction with roads, since the minimum height to cross a road is 4.6 m. It also allows for a completely horizontal track, which is required for both testing and high-speed transport.

The location analysis included many aspects, such as the current zoning plan (including future projects), soil conditions, land ownership, stakeholders, adjacent projects, legal procedures, planning processes and environmental aspects. Geometrical requirements of the vertical and horizontal alignment and the radii necessary for achieving a curve had an important impact on the feasibility of the spatial implementation of a test track and the choice of location and resulted in the fact that 12 of the 17 locations from a pre-feasibility study were not considered suitable for a test track. Three new locations have been added to the list, which has led to a shortlist of 8 locations. The aspects were analyzed based on (design) research and discussions with key players like the hyperloop parties and the relevant Dutch Provinces.

It was concluded that the Groningen East location was less likely to be amenable for the creation of a successful test facility (on time) because of the proximity of surrounding (rail) infrastructure and possible interfaces that this will create, the fact that the site offers less attractive forms of (local) accessibility, and most importantly in the evaluation, the Schiphol-Lelystad-Groningen corridor seemed more viable than the North-East International corridor towards Germany. For this reason, Groningen East turned out to be less attractive.

When comparing Groningen West and Vogelweg, several positive aspects of the Vogelweg location suggest that this location is more likely to be amenable for the creation of a successful test facility (on time) than the alternative in Groningen West.

Positive findings for the chosen location in Flevoland were the following:

- Several plans are already in place to increase the attractiveness of Flevoland as a commercial and innovation hub. The hyperloop test track would fit in well in this

[3] It is important to note that this will not be a net employment effect because of substitution effects.

future image and branding, as well as with current economic priorities of the Province of Flevoland.

- The area is located in the middle of the country, central to a number of globally renowned research institutes, like NLR, and Technical Universities, as well as between Schiphol Airport and its subsidiary Lelystad Airport, which have the ambition to become an integrated airport.
- Within the search area, there is enough land owned by the national government and province that could be appropriated in a timely manner to build the requested test track of 3 km (potentially extended up to 10 km – 15 km) and other necessary functions (amongst other the test facility center and airlock).
- The orthogonal landscape and road-water network pattern is aligned with the relatively straight alignment required for the test track. This similarity makes for easier implementation.
- The surrounding road network guarantees good access and connections to the site.
- The area is not densely built-up as it consists mainly of agricultural land, which minimizes (collateral) damage, as far as possible. A large part of this area was kept undeveloped as it was the intended site of a new highway, the construction of which has since been deemed unnecessary.
- A lack of environmental/planning/ownership uncertainties, which could affect the timely delivery of the test facility, were also key reasons for choosing this as the location of preference.
- It offers the most potential and the least barriers for a timely delivery of a test route of 3 km to 15 km along with a potential future commercial corridor.

**The Dutch government invests, organizes and facilitates the track to stimulate innovation**

We suggest that the Dutch government, through a Hyperloop Innovation Program, (1) partly invests in this test track (financially as well as by providing land and resources), (2) organizes the EU-certification and (3) facilitates the market development, e.g. by taking away legal boundaries and designing an innovate contracting strategy for partners in a possible extension of the track. This suggestion is based on several examples of important developments that show the importance of the role of government in R&D investments (e.g. the development of smartphones and GPS). Furthermore, the Dutch government should invest in (startup) companies to maximize R&D opportunities.

The test facility consists of a tube for multiple users and a shared test site and facilities. The total CAPEX costs of such a facility are €119 million (including indirect costs and unforeseen and excluding VAT and pods). We expect a maximum gross production impulse (total sum over 5 years) in scenario 3a’ in the order of 59% of total CAPEX costs[4] (with respective gross value added or GDP contribution of around 25% of total CAPEX costs) taking an optimistic perspective where all construction work is executed by Dutch firms and a share of 50% of tube, hyperloop elements and pods required for the test phase are produced in The Netherlands.[5] The other part of the socio-economic benefits is the result of the labor volume involved during the hyperloop testing period. We estimate this to be up to 400 Full Time Equivalent (FTE) per year for a period of up to 5 years.

[4] This concerns total CAPEX costs including pods.

[5] Especially over time, there is a risk that foreign parties develop and manufacture their own technology at home and only come to The Netherlands for testing.

Next to investing, the government should support collaboration and cooperation of public and private parties to stimulate innovation. The aim is to create a better position in innovative mobility and enable the development of a (regional) technology cluster and securing a position in hyperloop technology development. Combining several hyperloop development parties on one site at the same location is likely to contribute most to the Dutch innovation and production ecosystem. This (regional) clustering strengthens relations and networks between Dutch companies, knowledge institutes and other actors through agglomeration mechanisms like sharing and learning. In addition, synergies with other Smart Mobility test facilities in The Netherlands, including Aerospace and airline industry test sites and development clusters and crossovers with, for example, the automotive and IT industry could arise. Productivity gains, both as a result of sharing and learning and R&D investment as such, contribute to the competitive position of The Netherlands and bring potential first-mover advantages when the hyperloop (or spin-off technology) is proven to be ready for commercial adoption.

Finally, the government should commence studying all aspects of a first commercial track, to be able to scale-up if feasible, as part of utilizing the test facility.

**Possibility of a commercial phase**
This analysis also looks into a possible commercial phase of the hyperloop system in The Netherlands. The most likely option would be to extend the test track in order to connect Lelystad Airport to Schiphol. This would require a double tube system of 57 km without stops. Due to the limitations in available space near some cities, and allowable curve radii, it is likely that part of the Schiphol - Lelystad route will require bridges and / or tunnels. A detailed spatial planning of the hyperloop route has to be performed before cost estimates of bridges and tunnels can be made. For that reason the current cost estimates are excluding costs of bridges and tunnels.

The commercial double tube track of 57 km double-tube is about 20 times more expensive than the single tube test track of 3 km excluding the operational costs. Nonetheless, one of the goals of the test track is to come up with break-through cost-cutting measures for constructing and managing a commercial hyperloop track.

Construction of a commercial hyperloop trajectory in The Netherlands will deliver another short term production impulse in the order of 54% of total CAPEX costs[6] - reasoning from upper-limit CAPEX numbers. Once the commercial hyperloop trajectory is realized, we estimate a structural yearly employment effect of around 300 FTE[7], consisting of 100 FTE operational staff and maintenance and 200 FTE in Dutch (manufacturing) industry.

**Next steps**
We suggest starting a ***Hyperloop Innovation Program***, to enable implementation of the no-regret measures mentioned below and accommodate the continuous development and evaluation as mentioned above. The organization of this program should fit the innovative character of the activities. To start up, a small entrepreneurial and flexible Project Organization, based on informal cooperation of public organizations under the responsibility of the Ministry of Infrastructure and Environment, is needed to prepare these next steps and to set up a Hyperloop Certification Authority. This team should be innovative, supported by public organizations and have sufficient mandate from senior

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[6] This concerns total CAPEX costs including pods.
[7] Based on expected number of flight and passengers at Lelystad Airport in 2023.

management to speed up the innovation. Hyperloop ambassadors from the government, market and universities and sponsors from the parent companies should support the team. After deciding to initiate the test track, the spatial procedures require approximately 6 to 12 months.

For the next steps we suggest a combination of no regret measures followed by additional steps to go forward.

No regret measures[8]:

1. Public-private investment in an 'open' test track with an (initial) length of 3 km at the Vogelweg. The aim of the test track is to provide shared test facilities that can be used by all interested parties, such as private companies and universities.
2. Design and implement the certification process and Authority[9].
3. Facilitate private parties in order to establish the first hyperloop test track in the EU, by taking away legal and governance boundaries and by stimulating market development.

The organization regarding the realization and the management of the test track depends on the agreements with hyperloop firms about e.g. the share of public and private finance, and involves multiple options: (1) The government could initiate the realization of the test track and manage the 'open' test facility; (2) A public-private alliance realizes and manages the test track; (3) The realization and the management of the test track is a commercial initiative where the government only has to facilitate a request for a stretch of land of 3 km and a location for the required buildings. To avoid problems regarding state support, a public tender regarding the selection of hyperloop firms could be necessary.

For the additional steps, it is essential to further calculate and continuously evaluate the costs and revenues of further steps, to ensure a maximum return for The Netherlands. The Project Organization should explore relevant aspects, such as:

1. The willingness of hyperloop firms to invest in the test track.
2. The interest of Dutch private companies to take an active part in developing the hyperloop system.
3. Long term perspective for a commercial success.
4. The government as a launching customer, by potentially initiating and co-owning a first commercial route.
5. Maximizing opportunities for start-ups.
6. Optimizing shared test environments, in terms of protection of intellectual property.
7. Facilitate partnerships with other parties in The Netherlands and beyond, that see benefits in using the facility.
8. Circular construction techniques.
9. Government support related to the public investments and the necessity of public tendering and the need for an 'open' exchange of test results.

[8] Compared to the investments required for a full scale commercially exploited hyperloop connection, the relatively small investments necessary for realizing a test track are considered a no regret option.

[9] The Ministry of Infrastructure and Environment will be asked to appoint a legal authority for managing the safety and certification issues: the Certification Authority. This authority will collaborate with hyperloop firms and will develop standards to certify for commercial exploitation.

# 1 Introduction

The ministry of Infrastructure and Environment would like to put The Netherlands in a leading position with regard to the development and implementation of new mobility concepts. The goal is to maintain the strong Dutch position with respect to innovations in mobility, expand attractiveness as a test, production and service providing nation for Smart Mobility, and to contribute to the necessary transition to a sustainable new economy that will allow us to meet the Paris Climate Agreement. The ambition to be a leading nation originates from the already strong mobility position of The Netherlands. The Dutch have vast experience in solving mobility related problems in a densely populated delta and strong powerful main ports with excellent connections to the hinterland and European destinations. Furthermore, the Dutch are known for their knowledge infrastructure and for adopting new technologies.

## 1.1 Emerging mobility challenges

In the next 10 to 20 years, radical transitions will occur in the way we deal with mobility. Breakthroughs are expected on multiple terrains, allowing infrastructure, vehicles, data streams and traveler services to evolve into new concepts like Mobility as a Service. The Netherlands is ready to invest in these innovations because it believes our economy and society at large will benefit from these transitions.

Given the negative impact of the current traffic system on livability and the climate, alternatives for existing modalities are being explored. Particularly for aviation, rail and road transport over long distances there is a need for a system that offers similar or better qualities but with an equal or better travel experience and a lower $CO_2$ footprint and impact on the climate. A hyperloop system could potentially contribute to this goal. A hyperloop system is a transport system in which passengers and cargo can travel in a pod through a near-vacuum tube using a magnetic levitation system. This system allows for speeds over 1000 km/h, while the energy usage is limited due to the reduction of resistance. Maintenance costs are expected to be low due to the lack of friction between components and the fact that the closed tube is not subject to weather conditions.

A hyperloop system allows us to reduce travelling times over land in ways that were not considered possible in the past. The concept of distance might be changed considerably.

Another interesting aspect of the hyperloop is the Silicon Valley approach of creating this novel way of transport: objectives are being set that are challenging and very unlike the current approach of creating mobility infrastructure. Also, the development is being funded by capital investment instead of the traditional, evolutionary manner by existing companies. It is key for the Dutch government to be able to adopt to this innovative approach since it is expected that this will be an important value-creating strategy for solving future mobility challenges.

## 1.2 Testing is essential

To bring the concept further, extensive testing is required. Currently, several hyperloop companies are looking for opportunities to realize a test track. Two of them, Hyperloop One (USA) and Hardt (NL, a spin off from the team of TU Delft students that won an international design competition for a pod), have approached the Dutch government as a partner in such a facility. This interest follows from the strategic geographical location of our nation, the available knowledge and expertise on public transport, mobility, project management of infrastructural projects, technology, Dutch policy on Intellectual Property Rights (IPR), and the familiarity with the high standards of European approval and safety procedures.

The high-quality infrastructure in combination with the positive cooperation between industry, science and government make The Netherlands a very attractive country for innovation, development and application of Smart Mobility. Over the last years, the mobility sector has already invested in new technologies such as intelligent transport systems (ITS), autonomous driving, platooning, IT systems, etc. These new technologies need to be tested in a real life environment.

To get from development to full deployment of a system, a number of steps needs to be taken (see Table 3). The first step is the development and testing of components in the testing phase. In this phase also the certification process will start and certification procedures will be developed. Much of this can be done on a test track with a length between 3 km and 15 km. Finally, on a track of minimum 40 km, certification of the full hyperloop system for passenger transport will take place. This longer track can be upgraded towards a first route of the commercial phase, or even a national or international hyperloop network.

Table 3. Preferred track lengths during the different phases, from development to a full hyperloop network

| Testing Phase | | Commercial Phase | |
|---|---|---|---|
| Development & Testing | Certification | First route | Network |
| 3 - 15 km | | Minimum of 40 km | >> 40 km |

**Economic potential**
The Dutch state has the ambition to further strengthen its international competitive position. A (test track for the) hyperloop can further build on the (strategic) knowledge- and innovation-position of The Netherlands relating to innovative mobility concepts. The Netherlands is already investing in testing facilities, like the Automotive Campus, RDW Test center or SIM Smart Mobility. These contribute to a climate for innovation in The Netherlands, attracting foreign investment and R&D facilities to The Netherlands and thereby contributing to a competitive knowledge position of Dutch businesses.

Provided that an investment in a hyperloop test facility in The Netherlands should be primarily considered an R&D-project, socio-economic benefits arise from strengthening of relations and networks between Dutch companies, knowledge institutes and other actors within the Dutch Smart Mobility and Smart industry innovation system. In addition there will be a production impulse for Dutch manufacturing, engineering and construction firms associated with setting up the hyperloop test facility and first 5 years of testing. Combining several hyperloop development parties on one site at the same location is likely to contribute most to the Dutch innovation and production ecosystem. This clustering strengthens the competitive position of The Netherlands due to spillover effects to productivity growth. This also brings potential first-mover advantages when the hyperloop (or spin-off technology) is proven to be ready for commercial adoption.

Through an investment in a hyperloop test facility, R&D is stimulated and the Dutch innovation system (relations and networks between Dutch companies, knowledge institutes and other actors) is strengthened. Especially agglomeration mechanisms like sharing and learning[10] are not only important for the economic production volume and competitiveness, but are also important mechanisms in stimulating innovation processes.

**Active role of the government**

The involvement of a public partner is essential to realize desired innovation with commercial and societal impact. This insight and vision is for example based on the way in which Mariana Mazzucato describes the importance of the role of government in R&D investments in her book 'The Entrepreneurial State: debunking public vs. private sector myths'. She argues that the creation of new market opportunities is an essential role of government. This has to be done with direct investments in new technology before it is being transferred to the commercial sector. Her argumentation is based on several examples of important developments that would not have happened without governmental investments (in both fundamental and applied research), like smartphones and GPS. Only once the government (NASA, defense) had brought these innovations further as first movers, could companies like Apple and Microsoft develop a commercial application. In short, if The Netherlands wants to make the difference in innovations for new transport modalities, it should be prepared to invest in the transition of applied research and engineering to concrete, commercial applications.

> Mariana Mazzucato is an economist. In her book 'The entrepreneurial state: debunking public vs. private sector myths (2013)' she states the government plays an important role in innovations. Mazzucato emphasizes the importance of an investing and innovating government to gain sustainable economic growth. Public investments are necessary for the development of new technologies and the government is almost the only party capable to invest on the required large scale.
>
> Innovations need financial help in the phase from research towards commercial applications. In the so called 'Valley of Death' private investors ignore the call for financing, because of the large risks. In this phase the government should consider investing in innovation and start-ups. Another option is the government acting as a launching customer, by early adoption of innovative commercial applications.
>
> Moreover real innovations require courage. The government needs a mission to lead the private sector. Innovation needs a government that sees opportunities. And investments only are not enough. The entrepreneurial government focuses also on collaboration and connection of public and private parties to stimulate development.

**Crossovers with other innovative areas**

The hyperloop has several direct technological connections with the existing Dutch Top Sector[11] approach. The development of the hyperloop matches best with technology and R&D in the so-called HTSM-sector, particularly for the automotive, space and aeronautics specializations, which deliver relevant technologies required for the hyperloop. The IT-industry (systems) and logistics (transport innovation) also offer technological connections.

## 1.3 Further desirable research

The Ministry of Infrastructure and Environment is in a serious exchange of thoughts with the interested actors and wants to act quickly, but still has questions that need to be

[10] Centraal Planbureau (2016a). Investeren in infrastructuur. CPB policy Brief, Den Haag / Centraal Planbureau en Planbureau voor de Leefomgeving (2015). Economie van de Stad, CPB, Den Haag.

[11] In The Netherlands, companies, researchers, governments and civil society organizations work together in nine so-called top sectors in which The Netherlands has a strong track record. They are: agriculture and food, creative industries, chemical industry, energy, high tech, horticulture and starting materials, life sciences and health, logistics and water.

addressed. This is why the Ministry has, at the end of 2016, done an explorative research to the feasibility of a test track. The main conclusions of this research were that a test track could offer value for our economy and mobility challenges, but that more detailed research is required to move towards possible decision-making on whether or not to build a test track of 10-15 km that possibly could be expanded to a commercial track of approximately 50 km.

This initial assessment was followed by the current assessment. The need for further research was split up in the following topics:
1. Maturity of the technology, what still has to be clarified and tested before a decision can be made to construct a test track?
2. Spatial implementation for a test- and commercial track.
3. Finance and economics, what is de added value for the Dutch (knowledge) industry and what seem to be realistic costs and benefits of such a test track?
4. Governance and co-funding related questions.

The Ministry of Infrastructure and the Environment (I&M) has appointed the consortium of ARUP, BCI, TNO and VINU to conduct this further research. The final goal is to come to a go-no-go advice on whether the Dutch government should or should not invest in a test track in The Netherlands, including a market perspective for the follow-up with an initial cost estimation and preferred location.

The main results of this research are documented in this public report.  Further analysis of commercially-sensitive information from the hyperloop companies, including answering the above-mentioned sub-questions, is documented in four underlying confidential reports.

# 2 Outline of the research performed

The research has been performed based on research on technology, spatial implementation, governance models and finance and economics. Using scenarios and Innovation Strategies we have delivered a proposal for both a test site and the role the government should take vis-à-vis the hyperloop.

## 2.1 Scenarios and Strategies

6 test track scenarios have been created (see Chapter 7 for details) and by using the pros and cons of each scenario a preferred scenario has been defined. Two of the scenarios are the preferred scenarios of Hyperloop One and Hardt. The other 4 scenarios were defined in close cooperation with the Ministry of Infrastructure and Environment and the two hyperloop parties. Table 10 in Chapter 7 provides a detailed overview of the various specifications of the scenarios.

There is a 7$^{th}$ scenario which concerns a potential commercial track that we selected based on discussions with the Ministry of Infrastructure and Environment and using the first results of the research on spatial integration. See Chapter 7.4 for details.

To help decide on which scenario to choose, it is necessary to decide on the extra objectives with respect to the preferred role of the government. Therefore, we have developed four Innovation Strategies**,** see Table 4 below:

1. <u>Innovation Catalyzer</u>
   The market takes the lead in testing and also takes the initiative for a possible commercial hyperloop network. The government facilitates market parties by thinking, renewing laws and regulations and removing obstacles.
2. <u>Innovation Driver</u>
   The Netherlands is and remains the place with the best test facilities in the world. The hyperloop test facility, to be used by multiple users, seeks cooperation with other well-known testing facilities.
3. <u>Market Shaper</u>
   The government invests in the power of Dutch industry in line with Mazzucato's ideas. The government can achieve this by investing in a test facility together with market parties. In addition, the government aims to initiate a first commercial track for public use.
4. <u>Frontrunner</u>
   The goal is to realize the first hyperloop system in Europe/the world in The Netherlands. The government will make a kick-start by facilitating the development and certification of hyperloop technology, in collaboration with a leading (international) hyperloop company.

Table 4. Innovation Strategies

| Innovation strategy | Role of government | Demands on test facility | Governance model test track |
|---|---|---|---|
| Innovation catalyzer | Facilitator<br>Certifier | Depending on market wishes | Market |
| Innovation driver | Facilitator<br>Certifier<br>Subsidiary test facility | Single shared tube | Government |
| Market shaper | Facilitator<br>Certifier<br>Subsidiary test facility<br>Initiator first commercial track<br>Financer start-ups | Two tubes at same location | Collaboration |
| Netherlands frontrunner | Facilitator<br>Certifier<br>Subsidiary test facility<br>Initiator first commercial track | Single user in his own tube | Monopoly |

Table 4 also provides the governance models corresponding to the Innovation Strategies. The governance models and the role of the government are explained in detail in the separate specific governance report.

Based on the input from the governance report, the findings of technology and the financial and economic analysis a conclusion will be drawn on what scenario fits the various demands and requests best. The technological findings are presented in Chapter 4 and the financial and economic analysis in Chapter 5. The findings for spatial implementation (Chapter 3) are used as input for the preferred locations for the scenario analysis.

## 2.2 The 4 research topics

**Spatial integration: From 17 to 1**
The starting point for the spatial integration analysis was a pre-feasibility analysis, which concluded with 17 potential locations in The Netherlands and the criteria which these locations should meet. This pre-feasibility analysis was taken forward using a multi criteria analysis taking both technological and spatial constraints into account, such as the radii necessary for achieving a curve, the criteria of attractiveness for a potential commercial route for passenger transport, availability of (government owned) land, the speed of potential development of the test-site and the potential for expanding into a commercial corridor. The various criteria are presented in Appendix A.

**Technology approach**
The maturity of the different technologies required for a hyperloop system has been assessed in a literature study, and interviews with experts from Hardt and Hyperloop One. Also site visits to Hardt in Delft and Hyperloop One in the USA have been made. Based on these findings, calculations have been performed to verify the design choices made by these hyperloop parties, such as:

- The dimensioning of the vacuum systems for the tube and the airlocks based on pump down times and leak rates.

- The dimensional stability of the tube due to its own weight, the weight of the pod, the vacuum pressure and the thermal expansion.
- Passenger comfort based on the accelerations of the pod in curves and switches.
- Headway times between the pods in relation to velocity and maximum deceleration during braking.

Finally, each relevant technology has been ranked based on the Technology Readiness Level (TRL) scale, as being used by the European Commission. Based on the findings and the preferences of the hyperloop parties a technical proposal for a first test track has been made.

**Financial and economic approach**
The aim of the financial research was to come up with a cost calculation for the test track compared to the socio-economic benefits of such a test track. Also the costs and benefits of a possible future commercial hyperloop track in The Netherlands were assessed.

The information used for the cost estimate was derived from both public sources and confidential documents received from Hyperloop One and Hardt. These numbers were challenged based on technological insights from our team. There were various moments of contact, including a site visit in the USA. The public sources used are internet, companies delivering hyperloop components or components that are very comparable, colleagues etc.. The research was complicated because of the fact that even though the hyperloop components as such are reasonably standard the dimensions of most of the components are new. On top of this some of the hyperloop components are not yet developed or are being redesigned.

An important task was to split up the hyperloop test track in comparable components, such that all numbers provided by the various parties could be compared. All these numbers (including their uncertainties) have then been applied to both the six test track scenarios and the commercial scenario.

As well as the capital expenditure (CAPEX) the operational costs (OPEX) were also calculated. For these costs we focused on personnel, maintenance and electricity costs.

In the end, investment costs for a hyperloop test facility in The Netherlands have been calculated for six scenarios, the first two based on preferences and initial estimates of Hyperloop One and Hardt.

The benefits of a hyperloop track (test and commercial) were mainly based on socio-economic benefits of the test track, consisting of the number of jobs created (directly and indirectly) and production effects. For the commercial track the revenues of transporting passengers were also taken into account as well as travel time savings. This provides insight into the value of a commercial track and the chances that a commercial track will be realized.

**Governance approach**
The governance issues were investigated by means of a stakeholder analysis, exploratory interviews and an (inter)national benchmark. The results of the research were used for designing and defining governance models for the test and the commercial phase.

Four issues are described: (1) Governance models for the test facility regarding finance, organization and procurement/ public-private competition. Four governance models are linked to innovation strategies (see Table 4); (2) The organization of the certification process and safety issues; (3) Additional activities the government could undertake to stimulate the innovation of hyperloop in The Netherlands; (4) Possible governance models for the commercial phase.

## 2.3 From findings to conclusions

In the next chapters the most important findings for the four research areas are presented. Note that these are (by far) not all the findings. Those are explained in detail in separate reports. Using the findings, the scenarios and the strategies, conclusions are drawn on whether to invest in a test track or not, what it should look like and how to proceed.

# 3 Findings regarding Spatial Integration

## 3.1 Selecting the locations: from 17 to 8: Technical spatial constraints

The location analysis has been based on the earlier executed pre-feasibility study (Nov-Dec 2016). New insights on technical spatial constraints, in particular the geometrical requirements of the vertical and horizontal alignment and the radii necessary for achieving a curve on the basis of the technological analysis, have had an impact on the feasibility of spatial implementation of a test track and the choice of location. This resulted in 12 of the 17 locations from the pre-feasibility study not being considered suitable for a test track. Three new locations have been added to the list, leading to a shortlist of 8 locations. Thus in total, together with the 17 locations of the pre-feasibility study, 20 locations have been analyzed (see Figure 2).


Figure 2. Potential hyperloop locations

## 3.2 From 8 to 3: Multi-Criteria Analysis

By using 14 criteria, the shortlisted 8 locations were reduced to 3. An important criterion was the requirement for a minimum footprint of 10 km by 30 m. The indicative spatial reservation used for the test center facilities is 120 by 190 meters. Other criteria used were Property Ownership, Physical barriers, Social and governmental perception, Energy resourcing, Vibration free & Soil Conditions and the Multifunctional usage of test track infrastructure. All criteria are listed in Appendix A.

## 3.3 From 3 to 2: Schiphol-Lelystad-Groningen

A possible driver for a test track is a potential future expansion towards the construction of a commercial test track. This comes amongst others from the report NL-Next from VNO-NCW, that advised for innovations such as hyperloop to be selected on the basis of the criteria of scaling-up to business case size.

As part of the multi-criteria analysis carried out during the study, it was concluded that of the two Groningen locations, the Groningen East location was less likely to be amenable for the creation of a successful test facility (on time). This is for a number of reasons.

The first relates to the proximity of surrounding (rail) infrastructure and possible interfaces that this will create, namely relating to vibrations and settlement/subsidence caused by these vibrations. Secondly, the site offers less attractive forms of (local) accessibility, important during both the construction and operation phase, as well as being more remote from a potential Innovation/Business areas. Finally, and most importantly in the evaluation, it was concluded that Groningen East does not contribute to a national commercial passenger route. The potential for a commercial hyperloop route was taken into account whilst selecting a test track location. The focus was on passenger transport in defining attractive routes and, considering a potential collaboration between Amsterdam Schiphol and Lelystad airport, the Schiphol-Lelystad-Groningen corridor seemed more viable than the North-East International corridor towards Germany. For this reason, Groningen East turned out to be less attractive.

On the basis of the above reasons, the two locations most suitable to carry forward were located in Groningen West and Vogelweg.

## 3.4 From 2 to 1: Feasibility of timely spatial integration

Elements considered in the final spatial analysis were, amongst others, the current zoning plan (including future projects), soil conditions, land ownership, stakeholders, adjacent projects, legal procedures, planning processes, environmental aspects, and energy resourcing. These were analyzed on the basis of (design) research and discussions with key players like the Technology Partners and the Provinces. Based on this analysis it was observed that environmental, planning and ownership uncertainties that could affect the timely delivery of the test facility, were key reasons for choosing the final destination in Flevoland as the preferred location. It offers the most potential and the least barriers for a timely delivery of a test route of 3 km to 15 km along a future commercial corridor.
For the Groningen West area, large parts of the spatial zoning plan contain functional labels, put in place to protect historical and natural heritage. Furthermore the environmental impact assessment[12] procedures and approval of mitigation and compensation measures necessary to build in the areas labeled as ecologically sensitive could take up more than two years which doesn't comply with the desire to build a test track in a short time frame.

[12] In Dutch: milieu effect rapportage (m.e.r.)

### 3.5 Positive findings and risks for the chosen location in Flevoland

The following positive aspects of the Vogelweg location suggest that this location is more likely to be amenable for the creation of a successful test facility (on time) than the alternative in Groningen West:

The following positive aspects have been identified, amongst others:

- Several plans are already in place to increase the commercial attractiveness of Flevoland as a commercial and innovation hub, including Lelystad Airport Businesspark (LAB) and the autonomous vehicle test track initiative. The hyperloop test track could fit in well in this future economic cluster, as well as with the image and branding of Flevoland. The new business park offers an opportunity for opening, for example, a back office for hyperloop off-site.
- The area is in the heart of the country, close to a number of globally-renowned research institutes, as well as between Schiphol Airport and its subsidiary Lelystad Airport that have the ambition to become an integrated airport. The test track would be situated in the proximity of Lelystad airport. The North-East node would be connected to the lower road network structure of Flevoland, the so-called Carré. Towards the South-West, additional research will have to be carried out, but potentially the hyperloop could be connected parallel to the A1-A6-A9 Schiphol-Amsterdam-Almere highway trajectory. The track is connected to the Lelystad Airport Carré of accessibility roads. A hub could potentially be created linking the different modes of transport.
- As the test track would be well connected to an already existing road network (Airport Carré), emergency services could easily access the test track facilities in case of emergency.
- The plans for the Windmill park Zeewolde would offer enough energy resources to power the hyperloop test track. This would mean green sustainable and local energy could be used as a main energy source. In case the hyperloop test track would be built before the realization of the Windmill Park, there is also the option for the test track to make use of the High Voltage Station in Zeewolde or solar energy. Solar panels placed on the exterior of the tube could provide sustainable energy for a part of the energy resourcing necessary for a hyperloop test track.
- The orthogonal landscape and road-water network pattern is aligned with the relatively straight alignment of the test track. This similarity makes implementation easier. The surrounding road network guarantees good accessibility and connections to the site. A large part is still being reserved, kept free and under the ownership of the Province for construction of a highway that was deemed unnecessary decades ago.
- The area is not densely built-up, and mainly consists of agricultural land, which minimizes (collateral) damage as far as spatially possible. This reduces the chances of damaging impacts on both (i) the structure and (ii) the surroundings. Furthermore, in the event that future analyses conclude that there is a need for additional safety zones or additional mitigating measures, there is enough surrounding buffer space in the area to be able to implement these.

The identified risks and potential clashes regarding the spatial conditions are the following:

- The soil conditions in the search area are not optimal, as the soil in that area is subject to subsidence. Foundation piles would be needed to create a stable substructure for construction of the tube supports. Stability is critical as the tubes are likely to have minimal allowable tolerances for displacement. This has already been considered and is regarded as a factor irrespective of the location.

- Even though there are no Natura 2000 locations, there are a few ecological zones in the area of search. Mitigation and/or compensation measures will need to be taken if this land is to be used for the hyperloop test track. This will be the case if the 3 km test track is extended to 10 km and/or 15 km length. This could mean that additional land needs to be appropriated for compensatory planting of, for example, trees[13].
- In the current situation there are several objects in the area of search, including roads that intersect with a hyperloop structure. It will require detailed design interfacing when locating the columns. Furthermore, attention should be paid to the spatial requirements and flight clearance zones of Lelystad Airport.
- There could be clashes regarding logistic planning and environmental impact between the hyperloop project and the projects SAA - A6 highway widening and the Windmill Park Zeewolde. These projects are situated in proximity of each other and are planned to be constructed in the same period as the hyperloop construction. Construction logistics and interfacing between the projects will need attention in advance of the start of the project.
- The residential housing plan Almere-Oosterwold could clash with the plans for a potential commercial route expansion towards Amsterdam.
- There are 6 road crossings. For five crossings, there are no expected problems as the 5 m height of the structure doesn’t clash with the clearance of a road of 4.6m. The width of 30 m between the columns leaves space to allow for adjusting the horizontal road clearance. However, one road is positioned on a slope and the vertical alignment increases here.
- There are three waterways crossing the search area. Their profile, including the banks, is 30 meters wide. Including a 5 m clearance zone outside the slopes, would mean that the total clearance over the water is 40 meters. Considering the structural grid of 30 meters between the columns, there would be a design clash that needs to be resolved, such as a strengthened pipe-section that could stretch 40 meters.

All barriers and potential risks seem solvable, making use of current solutions and known mitigation measures. Hence, the currently-identified risks are based on the conceptual lay out of the hyperloop test track and additional land requirements. In order to identify actual clashes and develop suitable (design) solutions, the design of the structure will need to be developed into a preliminary design. Via an iterative design process (which could be started on short notice), the occurrences and solutions can then be optimized which will minimize risks of clashes during the actual construction phase.

## 3.6 Other findings

Governance planning process:

Specific conditions for each location must be met – the legal conditions and a successful coordination with stakeholders are both crucial. The Dutch government has significant ownership in all locations. For a 3 km test track, a site with 100% Government ownership could be found, depending on the final alignment of the test track. When extending the test track to 10 km - 15 km, the government will most likely not be the sole owner. Therefore anticipating on a future extension of the test track and a potential commercial track, negotiations with current owners of land, surrounding residents, residing companies or other relevant stakeholders, are necessary. This certainly also implies timely consultations and stakeholder cooperation should a commercial track be considered.

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[13] https://www.rijksoverheid.nl/onderwerpen/natuur-en-biodiversiteit/wetgeving-voor-natuurbescherming-in-Nederland. The example mentioned is related to the part about ‘bos compensatie’.

# 4 Findings regarding Technology

The specifications of the different test scenarios (see Chapter 7) are the result of extensive discussions about the hyperloop technologies with the engineers of Hardt and Hyperloop One. These specifications have been verified by calculations and information drawn from literature on the different technologies. For the most relevant hyperloop technologies, the Technological Readiness Level (TRL) has been determined, for both the technology in general and for the knowledge and experience level of the individual hyperloop parties with that specific technology. Based on this ranking, the specific needs for testing and certification have been determined, resulting in a proposal for a low cost test scenario (paragraph 7.3). Several technology findings are presented in the next sections.

## 4.1 Hyperloop components

Hyperloop: maglev in a tube
From a technological point of view the hyperloop systems as proposed by Hardt and Hyperloop One are actually magnetically levitated (maglev) trains travelling inside a vacuum tube. Maglev trains have been developed before, with the Transrapid being the one that has the largest resemblance with the technologies selected by Hardt and Hyperloop One. The Transrapid technology has been certified and implemented in practice on a 30 km long commercial track in Shanghai.

The vacuum tube
The main difference between the Transrapid and the proposed hyperloop systems is the vacuum tube. The required vacuum components, for both the tube and the airlocks, are almost completely available off the shelf, as has been shown by Hyperloop One on their 500 m test track. The baseline is a steel tube with a diameter between 3 m and 5 m and a wall thickness between 2 and 3 cm. The vacuum tube also poses safety related issues that need to be addressed. But no fundamental showstoppers are currently foreseen.

Switching technology
The main new technology that still has to be developed is a switch that can be passed at full speed in all directions. Such a switch is required for the hyperloop concept where a high passenger capacity is realized by using small pods, comparable to a single train section, that travel at intervals of only 10 to 20 seconds[14]. Only with a high speed switch is it possible for a hyperloop network to be realized where pods do not interfere with each other, independent of the destination of the pod. The design of such a switch will be a key criteria for the selection and design of the optimal magnetic guidance and levitation system. This will also dictate the position of the rails inside the tube, where Hyperloop One and Hardt have currently different preferences. Such high speed switches do not yet exist and as such have a TRL level 2. The 3km test facility will allow for testing and development of such a switch in order to bring it to a TRL level 7/8.

Airlocks
Airlocks are devices equipped with gate valves, in order to allow passengers to enter and leave the pod inside the vacuum tube, without the need to vent the entire tube. To enable headways between pods of only 10 to 20 seconds, multiple parallel operating

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[14] Safe travel at such short intervals require IT and safety innovations before it can be used at a commercial trajectory.

airlocks are needed that allow fast and efficient boarding and disembarking of passengers. These airlocks still need to be engineered. This will be based on existing vacuum technologies, so there is only a low technological risk expected. In addition, every 10 km a gate valve is needed for maintenance purposes.

Sidings

Sidings are emergency lanes where pods can be guided to in case of a serious technical failure. A siding consists of a low speed switch and an airlock to allow evacuation of the passengers. In the commercial outlook, a siding is foreseen every 10 km.

## 4.2 Passenger comfort & safety

Passenger comfort

The maximum acceleration and maximum pod velocities in curves are not limited by technology, but by passenger comfort. The aim of both Hyperloop One and Hardt is to offer a passenger comfort level in terms of vibrations and accelerations that is comparable to airplanes. Passenger comfort, in for example trains, have been described extensively in literature and the results can be used as design guidelines. A test track will be needed for verification of the comfort levels in practice. Similar to an airplane, passengers have to be seated during travel and wear a seatbelt for safety in the event of emergency braking.

Safety

A hyperloop system offers very few risks to people outside the tube. For passengers inside the pod, safety measures and redundancy will be implemented similar to airplanes. Valves for fast venting of a tube section, in case of an emergency or security issue, will also be implemented. The means to evacuate passengers from the pod and from the tube still need to be engineered, but seem solvable based on technological similarities with existing metro and train tunnels. All safety measures should be fully certified before commercial passenger transport can start. An important aspect will be the certification of the safety-critical IT infrastructure that controls the complete hyperloop system, including the position, velocity and braking of the pods, and the venting of the tube in case of an emergency or security issue.

## 4.3 Other findings

Technological risks

The positive side of using similar technologies for a hyperloop system as those currently used for a maglev system, is the reduced technological risk. The negative side is that both Hardt and Hyperloop One tend to do all the development work themselves, while much of it has been done before by the companies behind the Transrapid development (Siemens and ThyssenKrupp). Cooperation might be beneficial here, and potentially could speed up the hyperloop development and reduce the development risks and costs.

Intellectual property risks

A potential risk are the numerous existing patents, both on maglev technologies and on hyperloop concepts and components, filed by different companies other than Hardt and Hyperloop One. These patents could result in conflicts, or in the selection of second-best solutions in order to circumvent existing patents.

Technology Readiness Levels

The main purpose of a 3 to 15 km long test track would be to get the hyperloop technologies from Technology Readiness Level (TRL) 4 to 6, up to TRL 7 or 8. It is most likely that Hyperloop One will start at TRL 6 or 7 due to the existing availability of a 500 m test track (see Figure 3). Hardt will most likely start at TRL 4 or 5 due to limited testing capabilities in the 30 m test tube at the campus of the TU Delft (Figure 4). In order to get to the final TRL 9 for the full system, a much longer test track of at least 40 km is required, depending on the maximum accelerations and decelerations of the pod. TRL 9 will need to be achieved before commercial operations can start.

Figure 3. The 500 m long test tube of Hyperloop One in the Nevada dessert.


Figure 4. The 30 m test tube of Hardt at the campus of the TU-Delft.

# 5 Findings regarding Finance and Economics

### 5.1 Comparison Hyperloop One & Hardt data compared to our research

For an analysis of the costs of a hyperloop system, we received information from both Hyperloop One and Hardt which we benchmarked with our own sources. Since we cannot reveal any of the cost breakdown information received from the hyperloop parties, we will focus on where our own research leads to significantly different cost estimates and how we can explain these differences.

The main differences between the data provided and are our research were found for the following four cost components:
- Cost of the tubes
- Cost of the switches
- Cost of the hyperloop motor
- Costs of the pods

There is about a 60-80% difference in the cost of the tubes provided by Hyperloop One and Hardt (lower) and our research (higher). We typically found that, in The Netherlands, the cost of the logistics involved in getting a prefabricated 5 m diameter tube segment on site is much more expensive than the data provided allows for.

For the cost estimates for the switches Hyperloop One and Hardt used a comparable methodology. Hyperloop One estimates the cost of a switch to be 3 times the costs of a normal piece of track (but provides cost estimates for 6 times), whereas Hardt and our research find that 2 times the costs of a normal piece of track should be sufficient. This results in significant cost differences.

The cost of the hyperloop linear motor is an important cost driver for the total system. Here we have done research to find other similar suppliers and compared the costs to what is known about existing maglev transportation systems. Hyperloop One and Hardt are developing their own systems and their data suggests their motors are about half the cost of what we could find from other independent sources. Their motors are still in development so it is difficult, if not to say impossible, to judge whether their estimates or our challenge of those costs is correct. Therefore for the cost of the linear motor we report a range in the relative cost tables in this document.

Finally, the costs of the pods show a huge difference in price between the various sources. The estimates of Hyperloop One (low) and Hardt (high) differ with a factor 3. Our own estimate is based on the average of the relative costs for a Transrapid train and an Airbus plane. In the discussion of our findings with Hyperloop One, they admitted that a comparison with the cost of a Transrapid train is valid. This leads to an estimated value for the costs of a pod that is about the sum of the initial cost estimates of Hyperloop One and Hardt.

There is additionally a cost difference for land and facilities, which is due to the fact that the hyperloop parties did not take (some of) the relevant cost elements into account. Other cost estimates were either in line with our estimates, absent or too small to affect the overall analysis. An overview of the cost components of a hyperloop system can be found in Appendix B.

Important to note is that for all cost estimates, an uncertainty of between 10%-60% should be taken into account. This is primarily due to the fact that the technical specifications are yet to be determined, many hyperloop system elements need to be custom-made and actual prices therefore do not yet exist.

## 5.2 Comparison of scenarios

We find it difficult to justify the overall costs associated with the 5 scenarios initially assessed (5 m diameter tube, 3 - 15 km, etc., see Chapter 7) when compared to the potential benefits of implementing a hyperloop test track in The Netherlands. We therefore looked for alternatives that meet most, if not all, of the requirements of Hyperloop One and Hardt, while at the same time minimizing costs. We found that the most savings potential can be realized for the following main cost drivers:

- Reducing the tube's inner diameter from 5 m to 3 m; This is a reduction in both the material needed (40%) as well the cost of manufacturing and transport (around 50%).
- Choosing a single tube with switches instead of a double tube with switches. This provides the same testing scenarios at 20-30% lower costs.
- Reducing the 10 - 15 km length of the test track to a 3 km track. A 10 - 15 km track is a lot more expensive than a shorter track, whilst it doesn't significantly increase the testing possibilities. A 40 km track is the expected minimum for full speed testing with passengers.

We incorporated these adjustments into an alternative scenario (Scenario 3a') and this reduced total CAPEX costs for this so-called Scenario 3a' to €119 million (including indirect costs and unforeseen and excluding VAT and pods). Table 5 shows the relative cost components for this scenario.

Table 5. Relative costs of the main components of a hyperloop test track

| Category | Relative cost |
|---|---|
| Land, Electricity, Pylons and Tube | 24-29% |
| Facilities | 23-28% |
| Vacuum systems, Airlocks, Switches, Motor and Maglev system | 43-53% |

** Given margins in cost estimates the cost categories do not add up to 100%*

Investments in lightweight pods will add 28 - 33% to the estimated costs. We present the costs for the pods separately since the number of pods in combination with the length of the test track significantly influence the costs per kilometer.

The operational costs (OPEX) for the test track consist mainly of the salary of about 30 personnel, amenities such as electricity, and maintenance. Additionally, approximately 370 research personnel from multiple partners are expected, making up the dominant operational expenditure during the test phase.

## 5.3 Socio-economic benefits of a hyperloop test facility in The Netherlands

Knowledge, R&D and technology are important factors for economic growth and competitiveness. The Dutch government could facilitate this process in various ways: 1) by creating the right conditions for innovation; 2) by actively solving market failures (by e.g. reducing investment risks) and creating market opportunities aimed at economic transformation and long term economic growth. In the case of the latter, when innovation is not only focused on R&D, but also on economic transformation and the export of knowledge and products, new opportunities and spillovers between sectors could arise. According to Mazzucato, this broader perspective of an entrepreneurial government offers more added value for a country's economy. Once the government co-invests in strengthening the country's innovation system by means of adapting the production system around new technologies and supporting knowledge institutions to strengthen their knowledge position, production advantages and a renowned knowledge position will arise and lead to first-mover advantages (e.g. leading in development and standardization).

Provided that an investment in a hyperloop test facility in The Netherlands could be primarily considered an R&D-project, socio-economic benefits are likely to arise from strengthening of relations and networks between Dutch companies, knowledge institutes and other actors within the Dutch Smart Mobility and Smart industry innovation system. In addition there will be a limited production impulse for Dutch manufacturing, engineering and construction firms associated with setting up the hyperloop test facility and the first 5 years of testing. Combining several hyperloop development parties on one site at the same location is likely to contribute most to the Dutch innovation and production ecosystem. This clustering strengthens the competitive position of The Netherlands due to spillover effects to productivity growth. This also brings potential first-mover advantages when the hyperloop (or spin-off technology) is proven to be ready for commercial adoption. Even though not every innovation will be a guaranteed success, investments in a hyperloop test facility can surely contribute to an attractive investment climate.

We expect a maximum gross production impulse (total sum over 5 years) in scenario 3a' in the order of 59% of total CAPEX costs[15] (with respective gross value added or GDP contribution of around 25% of total CAPEX costs) taking an optimistic perspective where all construction work is executed by Dutch firms and a share of 50% of tube, hyperloop elements and pods required for the test phase are produced in The Netherlands.[16] The other part of the socio-economic benefits is the result of the jobs involved during the hyperloop testing period. We estimate this to be a labor volume of up to 400 FTE per year (370 from both hyperloop parties and 30 dedicated staff for the test facility) for a period of 5 years. This will lead to a positive impulse in terms of employment and spending in the local economy.

Based on our own calculations of energy requirements of different components of the system, all energy provided by potential solar panels on the tube will be used for maintaining the vacuum in the tube. Taking into account that a PV-panel is not an essential part of the hyperloop system and the fact the solar energy could be generated on the same location independently from the presence of the tube, we don't consider this to be of substantial importance when making a decision about the testing facility. However, the tube could form a great asset for testing solar panel innovations and as such contribute to building an innovative eco system around the test facility.

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[15] This concerns total CAPEX costs including pods.

[16] Especially over time, there is a risk that foreign parties develop and manufacture their own technology at home and only come to The Netherlands for testing.

## 5.4 Commercial phase

In addition to the socio-economic analysis of a hyperloop test facility we have briefly looked into a potential commercial phase of the hyperloop system in The Netherlands. For a commercial hyperloop network, specific elements of the hyperloop system that do not yet exist are needed, such as a high-speed switch. As an outlook to a possible commercial phase, we analyzed the proposed Schiphol - Lelystad Airport track. For this specific point-to-point track, no high speed switches are needed, but their value will be manifested once more destinations in The Netherlands or abroad would be connected. The Schiphol - Lelystad Airport track would be a 57 km double tube track, based on the 3 m diameter design from the test phase. There will be a station on either side that contains airlocks[17], and there would only be need for switches for the sorting platforms at each end) [18]. The relative costs for the low-cost commercial phase are presented in Table 6.

Table 6. Relative costs for low cost commercial phase comprising 57 km double tube track and two stations[19]

| Category | Relative cost |
|---|---|
| Land, Electricity, Pylons and Tube | 37-43% |
| Facilities | 2% |
| Vacuum systems, Airlocks, Switches, Motor and Maglev system, Sidings | 32-41% |
| Stations | 20-23% |

Additional investments in pods for 50-60 passengers will add 26-30% to these investment costs. We expect the total system to be about 20 times the cost of the test track from scenario 3a'. There are a few opportunities for cost reduction in the commercial phase compared to the specifications that were analyzed in the relative cost break down above. These concern design choices regarding the station and the pylons, and effective research to create a hyperloop motor on the lower end of the current cost estimate.

## 5.5 Operational costs and benefits from the commercial phase

The operational costs breakdown for the commercial phase is split into four main categories. The costs are mainly driven by the number of trips the pods would make. This is beneficial to the exploitation of the track since the costs of the track scale very well with the number of passengers. In Table 7 we present the relative operational costs.

Table 7. Relative costs for the commercial phase

| OPEX cost elements | Relative weight |
|---|---|
| Personnel and office space | 12% |
| Energy | 18% |
| Maintenance | 58% |
| Ticketing | 12% |

Maintenance costs would make up the largest part of operational costs during the commercial phase. These are in the current cost estimate assumed to be in line with

[17] For clarification, it needs to be mentioned that the airlocks will be part of the station design and are no longer a separate element in the motor and maglev system category.

[18] The switches that are needed for certification reasons on a track >40km (e.g. to test switches at full speed) are not included in the cost calculations for the commercial track, nor are the costs for a station larger than needed to handle the expected passenger capacity on the track Schiphol - Lelystad.

[19] These costs exclude costs for tunnels, bridges, etc.

maintenance costs per passenger kilometer of European high speed rail connections but could potentially turn out to be lower, as magnetic levitation comes with lower drag, and lower wear and tear compared to regular train systems.

We identify four categories of travelers and have come up with estimates for the number of travelers that could be expected[20] (see Table 8). For each of the categories, we have come up with estimates for the number of travelers to be expected in 2023, based on 10,000 flights at Lelystad Airport and existing commuter and other domestic person movements on the trajectory Lelystad-Schiphol. Considering the 5-year test phase that hyperloop parties currently foresee, as well as estimated developments at Lelystad Airport, 2023 is a hypothetical first year in which a commercial hyperloop trajectory could be opened.

Table 8. Traveler categories and numbers

| Traveler category | Annual one-way tickets |
|---|---|
| Transit passengers using Lelystad Airport as an extra terminal for Schiphol Airport | 308,000 |
| Existing car drivers (both passengers and commuters) between Schiphol and Lelystad Airport changing to the hyperloop for parking cost savings or convenience | 1,368,000 |
| Passengers leaving from Lelystad Airport with a logical public transport route via Schiphol | 616,000 |
| Existing public transport users between Schiphol and Lelystad area for which the hyperloop track results in significant travel time savings | 912,000 |

Ticket sales[21] based on these passenger numbers in 2023 result in annual revenues that are 1.3 times the operational costs.

## 5.6 Socio-economic benefits of a commercial hyperloop track between Schiphol-Lelystad airport

Construction of a commercial hyperloop trajectory in The Netherlands would deliver another short-term production impulse. Following the same assumptions as for the test phase, that 50% of the required tube, hyperloop elements and additional pods will be produced in The Netherlands, and add-up to local construction and engineering works, the gross production effect could be in the order of 54% of total CAPEX costs[22] - reasoning from upper-limit CAPEX numbers to build a 57 km track and all additional facilities. In a commercial phase, structural economic effects are to be expected from yearly maintenance as gross production effect in the same order as the relative weight of maintenance in total OPEX.

Together with permanent hyperloop operation and control staff, we expect a structural employment effect to be in the order of 100 FTE. This is the direct highly skilled employment generated by a hyperloop connection. Other employment effects of around 200 FTE can be expected from structural (production) orders for Dutch companies, such as pods, hyperloop elements and second order effects (parking, retail, catering, etc.). Overall, we estimate an employment effect of around 300 FTE. We, however, stress that this is a rather ad hoc estimate.

[20] Important to note that these numbers will increase over time and not be a fact from the first day of operation of the hyperloop.
[21] Ticket prices are excluding VAT and we assumed a discount for category 1 and 4 given the fact that either the airlines will buy tickets in large quantities and daily commuters will most likely use season tickets.
[22] This concerns total CAPEX costs including pods.

# 6 Findings regarding Governance

## 6.1 The test track

Linked to the strategies and the scenarios, we defined four promising governance[23] models for the test track: market, public, collaboration and monopoly. Each of these governance models is directly linked to one specific strategy. Table 9 contains an overview of the four identified governance models with specific characteristics regarding finance and funding, management and the procurement strategy/public-private competition of the test track. The role of the Dutch government in the development and exploitation of the test track depends on the chosen governance model as presented in Table 9.

Table 9. Governance models for the test track

| Model test track | Market | Public | Collaboration | Monopoly[HL1] |
|---|---|---|---|---|
| Strategy | Innovation Catalyzer | Innovation Driver | Market Shaper | Front Runner |
| Scenario (see Chapter 7) | - | 3a (open tube) | 3 | 1, 2 |
| For example | DevLoop, Nevada | CERN, Switzerland | Automotive Campus, The Netherlands | - |
| Finance and funding | Private funding | Public funding | Private and public funding | Private funding |
| Management | Private company | Public organizations | Public Private Partnership | Private company |
| Procurement strategy | None (public initiative) | None (usage fee) | Tenders before and after the test phase | Innovation-partnership (tender before the test phase) |

The presented governance models show the bandwidth of different possibilities and as such support the thought process of the Dutch government. The final choice, however, will be dependent on further discussions/negotiations with the hyperloop parties.

Before making a final choice for a governance model, it is necessary to gain understanding of: (1) the willingness of hyperloop firms to invest in the test track; (2) the interest of Dutch private companies to take an active part in developing and funding the hyperloop system; (3) the willingness of hyperloop companies to share test facilities, related to the protection of intellectual property; (4) the feasibility of an initial commercial track; (5) issues regarding government support (state aid) and the necessity of public tendering.

## 6.2 Safety and certification

The safety and certification process has to completely be initiated and developed from a clean sheet. In the initial development phases, the safety and certification process has to focus on the safety of testing. In the pilot phase focus will have to shift to the safety and

[23] 'Governance' is defined as all issues concerning collaboration, market competition, finance and funding, safety and certification that need to be organized to meet the goals of the project.

security aspects of the hyperloop system, as another stepping stone towards certification for the commercial exploitation of a first tube. It is the role of the Ministry of Infrastructure and Environment to make sure that the hyperloop system falls under a legal authority which is under their responsibility. Moreover, the Ministry needs to appoint and instruct an authority for managing the certification and safety issues. This Certification Authority needs to collaborate closely with test applicants and other partners for gaining the required expertise for the assessment of the safety and security. Based on the knowledge and expertise gained, certification for the commercial exploitation will have to be developed. To limit the team size of the Certification Authority, only the core technical expertise, such as aeronautics, railway, vacuum and civil engineering is represented within the team. Other expertise would be acquired on a consultancy basis.

The Certification Authority would also monitor that the safety of involved partners and surroundings is guaranteed during testing. Only if that is the case, can they give permission to perform tests. Parallel responsibility for each of the partners to manage (in close collaboration with the Certification Authority) the safety and possible certification of components and systems remains in place. The described mechanism as part of the legal framework needs to be: (i) applying for a test, (ii) assessments of safety and security, (iii) granting permission by the Certification Authority, (iv) responsibility of the applicant during execution of the test and (v) assessment/evaluation and possible adaptation of safety and certification procedure.

## 6.3 Additional activities of the government

We suggest starting a Hyperloop Innovation Program in The Netherlands. This program would consist of projects around the test track and the possible future commercial track, the independent Certification Authority and additionally of activities facilitating private-company and public innovation in development of the hyperloop system. This could, for example, be done by taking away legal and other boundaries and stimulating market development. Furthermore, the government could, depending on the chosen strategy, initiate a first commercial track as a launching customer and invest in related startups. A small, entrepreneurial Project Organization within the Dutch government should be appointed to manage such a Hyperloop Innovation Program.

## 6.4 Governance in the commercial phase

We have distinguished six possible governance models for a commercial phase, ranging from a full public monopoly to a fully market-led initiative. These models differ in terms of the distribution of risks and control between the government and private companies. The six models are compared on the basis of distinctive criteria, arising from the benchmark: system integration, market competition, public control, public risks, flexibility and support level. At this moment there is no need yet to analyze or make choices regarding the governance model in the commercial phase.

# 7 Scenarios and strategies

In total 7 scenarios have been compared: 6 test tracks and 1 commercial track. The specifics of each test scenario are given in Table 10. In section 4, an overview of the proposed first commercial track (Scenario 7) is described.

Table 10. Overview of the various scenarios for test tracks

| | Scenario 1 | Scenario 2 | Scenario 3a' | Scenario 3a | Scenario 3b | Scenario 3c |
|---|---|---|---|---|---|---|
| **Enterprise** | Hyperloop One | Hardt | Any interested hyperloop enterprise | Any interested hyperloop enterprise | Hyperloop One & Hardt | Hyperloop One & Hardt |
| **Type of facility** | Test | Test | Test | Test | Test | Test |
| **Single tube length** | 15 km | 3 km | 3 km | 10 km | 15 km + 3 km | 15 km + 3 km |
| **Number of switches** | 4 | 2 | 2 | 2 | 4 + 2 | 4 + 2 |
| **Type of transport** | People | People | People | People | People | People |
| **Number of test facilities** | 1 | 1 | 1 | 1 | 2 | 2 |
| **Number of test locations** | 1 | 1 | 1 | 1 | 1 | 2 |
| **Tube configuration** | Double | Single | Single | Single | 3 km single + 15 km double | 3 km single + 15 km double |
| **Tube diameter** | 5 m | 5 m | 3 m | 5 m | 5 m | 5 m |
| **Number of airlocks** | 4 | 2 | 1 | 1 (like 3a' costs according to scenario 2) | 4 + 2 | 4 + 2 |
| **Number of enterprises involved in testing** | 1 | 1 | >1 | >1 | >1; 1 per tube | >1; 1 or more per location |
| **Number of pods** | 2 full-size (60 pax) | 2 test 1 full-size (50 pax) | 4 test 2 full-size (50 pax) | 4 test 2 full-size (50 pax) | 2 test 1 full (50 pax) 2 full (60 pax) | 2 test 1 full (50 pax) 2 full (60 pax) |

## 7.1 Preferences Hyperloop One and Hardt

During discussions with Hardt and Hyperloop One, their preferences have been identified. The most important preferences were:

- They both prefer a 5 m tube diameter in order for them to be able to test for maximal future conditions anticipating also transportation of containers. The minimum size given by Hyperloop One was 4 m, by Hardt it was 3 m. Both parties are willing to adapt to customer preferences, and they could both potentially agree on a 3 m tube (a size optimized for transporting passengers).
- They both prefer to have their own testing environment. However, the magnetic levitation constellation foreseen by both parties does not require different tubes.
- Hardt prefers to start with a 1 km track extending to a 3 km track in time.
- Hyperloop One prefers to start with a 15 km track extending to a 50 km double tube test track and commercial track in time.
- Both require multiple switches.
- Both want to test with pods for 50-60 passengers.

See Table 10 (Scenario 1 and 2) for an overview of their preferences.

## 7.2 Other scenarios for a test track

Different scenarios (i.e. 3a, 3b and 3c) have been designed in order to enable comparison of costs, preferences of parties involved and spatial integration. We varied aspects such as length of the track, number of switches and whether a tube is open for testing for all parties or that a specific tube per party is made available. The most important findings are:

- Costs increase almost linear per km of track
- The number of switches influences the price significantly
- A track up to 15 km limits the number of possible locations significantly

Based on input from our findings on governance, technology and costs estimates, we conclude that Scenario 3a' would best fit the Netherlands:

- An open test track accessible for various interested hyperloop parties to fit the ambition of The Netherlands to create an open innovation infrastructure.
- A single tube of 3 km, with 2 km parallel tube between two switches, with one airlock:
  - This will save costs significantly.
  - Hyperloop One and Hardt are most likely able to make use of the same tube.
  - With this we might be able to set a de facto European standard.
  - Limit the number of switches, since it will reduce costs significantly. The design of the switches (in order how to incorporate them to test what specifically) needs further discussions with parties involved.
  - Limit the number of airlocks to one.
  - Use special lightweight pods in order to be able to test at high speed by using high acceleration scenarios.

## 7.3 Scenario 3a': a low-cost alternative

Mainly based on the finding that scenarios 3a to 3c are still expensive, a 6$^{th}$ scenario has been designed in which the tube diameter was reduced to 3 m and the track length reduced to 3 km. The other variables are similar to scenario 3a. The total costs of this 3a' scenario compared to the original 3a scenario are about a factor 4 less.

The impact of these changes is as follows:

- Shortening the length of the test facility to 3 km requires some adaptations of the tests in order to be able to achieve the maximum design velocity between 1,000 and 1,100 km/h. At that speed, most of the different test types should be feasible as presented in Table 11. It shows that all tests can be done in a tube with a length of between 3 km and 15 km, apart from full speed passenger pods and full operational testing. For the latter two a tube length of at least 40 km is required. The certification process will start with a 3 - 15 km test tube, but requires at least 40 km for finalization. Note that all certification aspects still have to be agreed upon by a not yet existing Certification Authority.

Table 11. Overview of test that can be performed for different lengths of the test track. For some tests the required acceleration and deceleration rates are given.

| | 1 km | 3 km | 10 km | 15 km | 55 km |
|---|---|---|---|---|---|
| **Vacuum performance** | X | X | X | X | X |
| **Full speed with dedicated pod** | | 3.0 g | 0.9 g | 0.6 g | 0.2 g |
| **Full speed with passenger pod** | | | | | X |
| **Safety systems** | X | X | X | X | X |
| **Airlock** | X | X | X | X | X |
| **Low speed switch** | X | X | X | X | X |
| **High speed switch with dedicated pod** | | 4.5 g | 1.0 g | 0.7 g | 0.2 g |
| **High speed turn with dedicated pod** | | X | X | X | X |
| **Multiple pods** | | X | X | X | X |
| **Traffic management system** | X | X | X | X | X |
| **Proof of operations certification** | | | | | X |

- Even though both hyperloop parties have indicated a preference for a 5 m tube (based their ideal scenarios without any cost constraints and also enabling the transport of standard shipping containers), both parties are willing to adapt to customer preferences.
- The acceptance of a hyperloop system by the public will depend on the visual impact on the landscape. The smaller the tube, the better.
- The main reason for choosing a large 5 m tube diameter would be to enable transport of standard sea containers, which require a pod diameter of at least 3.56 m. It would make sense, however, to use smaller containers for goods that require high-speed transport. Several ULD-standard boxes from aviation for example require a pod diameter of only 2.2 m, with fits well inside a 3 m diameter tube.
- A tube with an external diameter up to 3.4 m can be transported by road with relative ease. This enables the manufacturing of complete sections, including the tracks for levitation, the linear motor for propulsion and all other wiring and electronics, pre-tested ready for integration. This could reduce the costs of the infrastructure, and speed up the on-site integration process.
- When required to go underground via a tunnel, the costs of the tunneling will be significantly lower for smaller diameters. When a tunnel is positioned near a station, where the velocity of the pod is limited, the tube diameter could be even smaller than 3 m, accepting a higher blockage ratio.
- By limiting the diameter of the tube, the hyperloop parties will be forced to come up with innovative solutions in order to get the best possible utilization of the available infrastructure. An example could be an aerodynamic pod shape that allows to use a larger pod with the same air drag in the small tube.
- A smaller tube will result in less passengers per pod length, potentially limiting the maximum number of passengers that can be transported. On the other hand, smaller pods, that can be connected to each other, depending on the capacity needs, might add valuable flexibility to the hyperloop system.

The spatial layout for this scenario is a combination of input received by Hardt and Hyperloop One, and consists of a 3 km test facility with two switches. The total width of this layout is approximately 15 m (see Figure 1).

Important to note is that the proposed test track should be seen as a first step test track that is able to start with the lowest cost possible and can start as soon as possible without losing too many test options. Once this 3 km test track has been proven successful, it could be extended to a longer one and possibly even become part of a commercial track. But those decisions will only have to be taken at a later point in time when more information about the development of the technology and costs is available.

## 7.4 Commercial scenario

For the commercial scenario it has already been proposed that it should be part of the route Schiphol-Lelystad-Groningen. The track between Lelystad and Schiphol Airport (57 km) could become a possible first commercial line. An overview of the various aspects of this scenario is presented in Table 12 below. Note that the relative costs of the various main parts of this track are given in the finance chapter (paragraph 5.4).

Table 12. Specifications of the commercial track

| Enterprise | Any interested hyperloop enterprise |
|---|---|
| Type of facility | Commercial |
| Single tube length | 57 km |
| Number of switches | 0 |
| Total tube length incl. switches | 2 x 57 km |
| Type of transport | Passengers |
| Number of stations | 2 |
| Diameter | 3 m |
| Number of airlocks | Included in stations and sidings |
| Number of sidings | 12 |
| Number of gate valves | 10 |
| Number of pods | 37 |

## 7.5 Pros and cons of the various Innovation Strategies

The costs, benefits and appreciation by the market parties for each of the Innovation Strategies have been rated. This is summarized in Table 13.

Table 13. Pros and cons of the four Innovation Strategies on costs, revenues and appreciation

| Strategy | Test phase | | | | | | | | | Commercial phase |
|---|---|---|---|---|---|---|---|---|---|---|
| | Cost | | | Revenues | | | Appreciation | | | |
| | Totals | Public | Private | BC | Gross prod. | Added value | H-1 | Hardt | Uni's | Government investments |
| Innovation catalyzer | + to ++++ | 0 | 100% | - | + | + | -- | -- | -- | No |
| Innovation driver | +++ | 100% | 0 | 0 | + to ++ | + to ++ | 0 | ++ | ++ | No |
| Market shaper | +++++ | 50% | 50% | <0 | ++ | ++ | + | 0 | + | Possible |
| Front runner | ++++ | 5% | 90% | <0 | ++ | ++ | ++ | -- | -- | Schiphol-Lelystad |

*Legend:*
**) ranging from + → low costs to +++++ → very high costs*
***) + → limited contribution to gross product, ++ → higher contribution to gross product*
****) + → limited contribution to added value, ++ → higher contribution to added value*

*****) -- → very negative, - → negative, 0 → neutral, + → positive, ++ → very positive*

From Table 13 it can be concluded that the strategies “Innovation Catalyzer” and “Front Runner” will not result in investments in hyperloop technology in The Netherlands and economic effects, since private companies are not willing and/or able to invest the full required budgets themselves. Also there is significant risk for the government in committing to a commercial phase. The strategies “Innovation Driver” and “Market Shaper” have the largest potential to attract private investments, limit investment from the government and realize the economic potential of hyperloop in the test phase and in the commercial phase.

Taking into consideration that one of the objectives of the government is to increase the value of the Dutch Smart Mobility knowledge industry, the appreciation (see Table 13) of Hardt and the universities is important. This leads to a choice between Innovation Driver and Market Shaper, or a combination of the two.

Being a first mover (see Figure 5) supports the connection of The Netherlands with a possible future European network and creates the opportunity for the local cluster of hyperloop technology development and manufacturing companies to become the leading producers and exporters of proven technology. However, there remains a risk, especially over time, that foreign parties develop and manufacture their own technology at home and only come to The Netherlands for testing. This will result in a lower long-term economic effect for The Netherlands, as testing and certifying contract research is expected to generate lower turnover.

| **“BV The Netherlands”** | **Developing companies** |
|---|---|
| Advantages:<br>- Determining the standard (acquiring knowledge position)<br>- Ensures that The Netherlands will be connected to an European hyperloop network<br>- Binding R&D frontrunners to The Netherlands → growing up to a development hub<br>- “Bring in the Dutch” – effect | Advantages:<br>- Technology leader<br>- Acquiring good market position<br>- Income from licenses |
| Disadvantages:<br>- Development ends and The Netherlands remains empty handed<br>- “First time” - effect → relatively high investment costs | Disadvantages:<br>- Sunk costs through not using technology<br>- Imitation by free-riders |

Figure 5. Pros and cons of being a first-mover

# 8 Conclusions

## 8.1 Combination of Market Shaper and Innovation Driver

In Section 7.5 (see Figure 5) we concluded that the most favorable Innovation Strategy is a combination of Market Shaper and Innovation Driver. With that strategy, the combination of the benefits for The Netherlands, the costs for the Government and the appreciation from the hyperloop interested parties is best met.

The aim is to create a better position in innovative mobility and enable the development of a (regional) technology cluster and securing a position in hyperloop technology development. Part of managing the (construction of the) test facility should be to realize synergies with other Smart Mobility Test Facilities in The Netherlands, including Aerospace and airline industries test sites and development clusters. This combination of activities of the Dutch government provides the largest economic benefits.

However, we do acknowledge that based on further negotiations with the hyperloop parties or budgetary constraints, the government might decide to go for an Innovation Strategy for which the governmental investment is (near to) zero: the Innovation Catalyzer or Front Runner. If that is the case, the choice between these two is mainly based on the governmental role in implementing the commercial phase.

We suggest that the Dutch government, through a Hyperloop Innovation Program, (1) partly invests in the test track (financially as well as by providing land and resources), (2) organizes the EU-certification and (3) facilitates the market development, e.g. by taking away legal boundaries and designing an innovative contracting strategy for partners in a possible extension of the track. Also the Dutch government could invest, when this leads to sufficient economic benefits, in startup companies, e.g. under the condition that it shares in profits gained at the (test-)track and/or that Dutch companies share also (e.g. in intellectual property rights). And, finally, the government could initiate, if feasible, a (study into a) first commercial track.

## 8.2 Start with a 3 km test track

Based on Table 13 we conclude that scenario 3a is best fit for the choice for the combination of Market Shaper and Innovation Driver. In Chapter 6 it was already concluded that there is a lower cost alternative for the scenario which we call scenario 3a' (see Table 10). This scenario is about 4 times cheaper than scenario 3a.

We advise to use this scenario and organize the development of testing facilities in The Netherlands in a staged approach (which might result in a commercial track). Important is working step by step. In Chapter 9, these steps are being described.

## 8.3 Build the test track in Flevoland

The search for a location suitable for a hyperloop test track to be built in an as short as possible time-frame, via a quick scan of 20 locations in the Netherlands, and the analysis of a shortlist of 8 locations, resulted in a recommended location at the Vogelweg (see Figure 6). This location offers opportunities regarding the lay-out of the current landscape, land ownership, accessibility of the site, the possible connection to other innovative businesses in the surrounding area and the potential expansion into a commercial passenger corridor. Identified uncertainties, clashes and environmental requirements and issues in this location seem solvable when addressed and mitigated in the design and stakeholder engagement strategy.


Figure 6. Search area (15 km) for 3 km test track in Flevoland

The aim should be to enable the development of a (regional) technology cluster and explore synergies between this facility and other Smart Mobility test facilities. We expect that this combination of activities of the Dutch government provides the largest economic benefits. Even though both hyperloop parties prefer not to have to share a test track, most chosen variables will allow both companies to perform the required testing and development of hyperloop elements.

## 8.4 First commercial track: Schiphol-Airport to Lelystad-Airport

In our analysis we also looked into a possible commercial phase of the hyperloop in The Netherlands, including identifying the pros and cons of extending the test track into a commercial hyperloop system. For testing and certification of commercial passenger transport at velocities above 1000 km/h to achieve a TRL 9 level, the minimum track length required is 40 km. Since the construction of a 40 km test track requires a large investment, it would be most efficient to build it along an economically interesting potential first commercial route, e.g. Schiphol-Lelystad Airport (57 km).

This would be a double tube system of 57 km, with no stops. Due to the limitations in available space near some cities, and allowable curve radii, it is likely that part of the Schiphol - Lelystad route will require bridges and/or tunnels. A detailed spatial planning of the hyperloop route would need to be performed before cost estimates of bridges and tunnels could be made. For that reason, the current costs estimates are excluding costs of bridges and tunnels. Two stations would be required.

The commercial double tube track of 57 km is about 20 times more expensive than the single tube test track of 3 km excluding the operational costs. Nonetheless, one of the goals of the test track would also be to come up with break-through cost-cutting measures for constructing and managing a commercial hyperloop track.

Construction of a commercial hyperloop trajectory in The Netherlands will deliver a short term production impulse in the order of 54% of total CAPEX costs[24] - reasoning from upper-limit CAPEX numbers. Overall, we estimate an employment effect of around 300 FTE.

[24] This concerns total CAPEX costs including pods.

# 9 First steps

## 9.1 Hyperloop Innovation Program in The Netherlands

We suggest starting a Hyperloop Innovation Program in The Netherlands, including activities and projects that support, facilitate and drive innovation. A programmatic approach would support the development of hyperloop innovations. A step by step approach is required.

To start, a small, entrepreneurial and flexible Project Organization, based on informal cooperation of public organizations under the responsibility of the Ministry of Infrastructure and Environment, is needed. The Project Organization needs commitment from the public organizations concerned and sufficient mandate to speed up the innovation.

The Project Organization should consist of a project team, an expert team, ambassadors and patrons. The project team would implement the activities described in the next paragraph. An expert team would support the project team. This team should consist of experts regarding participation, public support, market development, contracting, technology, safety, certification, finance, economics, governance and legal issues. The project team would also need to be supported by a group of selected patrons and three hyperloop-ambassadors. The patrons should be managers and 'supporters' from the governmental organizations that are involved, who are able to assist the Project Organization by paving the way and implement the necessary changes within the organizations, by using their strength, position and network. The hyperloop-ambassadors, coming from private companies and social organizations, would need to be externally and socially oriented and have an excellent network in the world of business, research institutions and government. They can act as the figureheads of innovations around hyperloop because of their ability to execute 'new thinking' and their speed and thoroughness of action. They would support the project team with market development, by setting up contacts and arranging meetings between public and private parties, and be able to connect people and organizations and boost innovation.

## 9.2 First steps

For the first steps we suggest that only no-regret measures are taken and that detailed research continues in the Innovation Program. We distinguish the following no-regret measures:

1. Public-private investment in a test track with an (initial) length of 3 km at the Vogelweg[25]. The aim of the test track is to provide shared test facilities that can be used by all interested parties, such as private companies and universities.
2. Design and implement the certification process and authority[26].
3. Facilitate private parties in order to establish the first hyperloop test track in the EU, by taking away legal and governance boundaries and by stimulating market development.

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[25] Compared to the investments required for a full scale commercially exploited hyperloop connection, the relatively small investments necessary for realizing a test track are considered a no regret option.

[26] The Ministry of Infrastructure and Environment will be asked to appoint a legal authority for managing the safety and certification issues: the Certification Authority. This authority will collaborate with hyperloop firms and will develop standards to certify for commercial exploitation.

During these first steps, it is essential to further calculate and continuously evaluate the costs and revenues of further steps, to ensure a maximum return for The Netherlands. The Project Organization should explore relevant aspects, such as:

1. The willingness of hyperloop firms to invest in the test track.
2. The interest of Dutch private companies to take an active part in developing the hyperloop system.
3. Long term perspective for a commercial success.
4. The government as a launching customer, by potentially initiating and co-owning a first commercial route.
5. Maximizing opportunities for start-ups.
6. Optimizing shared test environments, in terms of protection of intellectual property.
7. Facilitate partnerships with other parties in The Netherlands and beyond, that see benefits in using the facility.
8. Circular construction techniques.
9. Government support, related to the public investments and the necessity of public tendering and the need for an 'open' exchange of test results.

We want to stress that quick decision-making is required. There are many countries moving forward to gain a 'first-mover position'. Our advice assumes that The Netherlands wants to be leading in hyperloop innovations in Europe on a first-mover basis.

In the next steps to be taken, decisions should be made regarding studying (and preparing) further investment in the extension towards a 15 km test track and a first commercial track, e.g. Schiphol-Lelystad.

## 9.3 Realization of the test track

The organization needed regarding the realization and the management of the test track depends on the agreements with hyperloop firms about, for example, the share of public and private finance, and includes multiple options: (1) The government could initiate the realization of the test track and manage the 'open' test facility; (2) A public-private alliance realizes and manages the test track; (3) The realization and the management of the test track is a commercial initiative where the government only has to facilitate a request for a stretch of land of 3 km and a location for the required buildings. To avoid problems regarding state support, a public tender regarding the selection of hyperloop firms could be necessary.

The realization of the test track could be appointed as a project within the MIRT-program. The MIRT-approach has the advantage of giving a framework for decision-making regarding financial public contributions. The disadvantages are the lack of flexibility in the procedures and the long period necessary for decision-making. If possible, we suggest that the hyperloop test track becomes a pilot project within the MIRT, in terms of the approach regarding innovation projects. This is only feasible if sufficient flexibility is guaranteed. If not, a custom-fit approach should be chosen for the development of the test track.

Spatial planning procedures for the test track will require about 6-12 months. This period is required for a regular procedure according a "provinciaal inpassingsplan" or "bestemmingsplan / omgevingsvergunning". Another option, with the same duration, is to ask for a so-called exception for the "bestemmingsplan". This exception is valid for 10 years. In both cases a proper preparation and willingness of all stakeholders is absolutely necessary to meet the planning.

The government needs to ensure availability of the required land for the test track. Depending on the exact location and spatial integration, a substantial part of the land necessary for the 3 km test track at the Vogelweg is owned by the government. If necessary, we suggest to gain the use of land owned by private parties by exploring willingness amongst landowners to arrange a right in rem[27] or a lease of their land. Especially in Flevoland landowners are expected to be prepared to cooperate if the conditions are fruitful. Nevertheless, land expropriation is an option, but these procedures can take much more time, up to two years, because a so-called "Royal Decree[28]" has to be taken. In a permanent situation, acquiring land ownership (if necessary by expropriation) is the best option though. It is also possible that part of the land owned by the government is currently leased[29] by private parties, mostly farmers. If this is the case it is expected that the tenants will cooperate if they can be compensated with suitable land nearby, so the land they lease can be used for the test track.

[27] In Dutch: zakelijk recht
[28] In Dutch: Koninklijk Besluit
[29] In Dutch: gepacht

# Appendix A: Spatial Criteria

The initial overview of locations was tested along the following 14 criteria agreed within early meetings with the Client. This paragraph outlines a description of these criteria.

Reservation footprint
The location should allow for a large scale test site with a track length of 10 km. The indicative spatial reservation taken into account for the width of a test track is 30 meters. The indicative spatial reservation for the test center facilities is 120 by 190 meters.

Property Ownership
Realization speed can be significantly increased if the land on which the test track is realized is owned by the government. A large variety of different (private) owners on the other hand, could significantly slow down the realization process. This criterion gives an indication on how the location scores on this spectrum.

Barriers
This criterion gives an indication on the amount of physical barriers that are present on the location. Given that the hyperloop has to travel in a nearly straight line, these barriers have a large impact on the feasibility of the test track. Examples of barriers are viaducts, waterways, road exits, and Natura 2000 areas.

Height differences
Due to the criterion of a nearly straight line, significant variations in ground level height can increase costs for leveling of the surface or implementation of jacks. Necessary design solutions could slow down the realization process.

Commercial expansion possibilities
A potential driver for a test track is a potential future expansion towards a commercial test track. This can already be taken into account in the test track by putting it on a commercially attractive route regionally, nationally and internationally. This criterion gives an indication on the extent to which the location in question is on a commercially attractive route.

Social and governmental perception
Public and government perception can be an important driver (or showstopper) in the realization process of a test track. This criterion gives an indication on the political situation on that location.

Vibration free
External vibrations should be kept to a minimum. This criterion gives insight in how much external vibrations are present at the location in question.

Soil Conditions
Soil conditions have an impact on the construction speed, the risk on settlements, and the selected foundations for the supporting structure. This criterion gives an indication of the suitability of the soil for the realization of the track.

Multifunctional usage of test track infrastructure
Depending on the local infrastructure demands, the infrastructure for a test track could potentially be used in combination with future infrastructure projects, which can increase the financial feasibility of the test track. This can be done in two main ways:

- Adding facilities for a hyperloop tube on a project planned for construction
- Giving the track a new function for when the test track is no longer required.

The tube can be taken out and a new function can be introduced (like a tram of rail line) In this way, even if the test track is not expanded towards a commercial track, the realized infrastructure still has value. This could make the financing of a test track more realistic. This criterion gives an indication of projects already being planned for construction and the compatibility with a hyperloop test track.

Combination possibilities with existing infrastructure
There is a possibility to combine the test track with existing infrastructure. This criterion describes the possibility of achieving this.

Construction speed (phasing)
This criterion gives an indication of the realization speed of the hyperloop test track.

Building cost
This criterion gives an indication of the building cost of the hyperloop test track.

Vertical and horizontal alignment
This criterion describes whether the location provides enough space for the implementation of the test track.

Structural flexibility
Several structural typology options could be used for the test track. It can be done above ground level, on ground level, shallow buried, and below ground level as a tunnel. On some locations only one of these options is feasible, where on others several options are feasible. This criterion gives an indication on the design flexibility regarding different structural options that is present for the location in question.

# Appendix B: Cost elements hyperloop

Cost elements of hyperloop system that are taken into account in the cost calculations

| **Primary costs** |
|---|
| - Land |
| - Preparation of land |
| - Electricity |
| **Facilities test site** |
| - Offices and test houses |
| - Workshop and storage |
| - Infrastructure |
| **Support structure** |
| - Support structure |
| **Hyperloop elements** |
| - Tube |
| - Vacuum pumps |
| - Gate valves |
| - Motor and maglev |
| - Airlock |
| - Switch |
| - Pod |
| - Siding |
| - Station |

# Appendix C: Technology Readiness Levels

The Technology Readiness Levels (TRL) as given in the Horizon 2020 Work Programme 2016-2017, Annex G, of the European Commission.

| TRL | Description |
|---|---|
| **TRL 1.** | basic principles observed |
| **TRL 2.** | technology concept formulated |
| **TRL 3.** | experimental proof of concept |
| **TRL 4.** | technology validated in lab |
| **TRL 5.** | technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies) |
| **TRL 6.** | technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies) |
| **TRL 7.** | system prototype demonstration in operational environment |
| **TRL 8.** | system complete and qualified |
| **TRL 9.** | actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space) |