Assessment of Potential Commercial Corridors for Hyperloop Systems

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ASSESSMENT of POTENTIAL COMMERCIAL CORRIDORS for HYPERLOOP SYSTEMS

Design of a methodology to select and classify the most suitable corridors for the implementation of a first commercial hyperloop line for passengers

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Abstract
This study aims at developing a methodology to select and rank the most attractive corridors for the implementation of first commercial vacuum-tube train (or hyperloop) lines for passengers, in complement to traditional tools and methodologies.
From a list of the most populated cities all over the world, a first selection of possible transport connections is made, considering that a first commercial vacuum-tube train line has to be viable and safe and therefore cannot require the construction of a tunnel or cross a conflict area.
Then, an evaluation of all selected corridors is performed on the basis of defined classification criteria. Important parameters characterizing the potential of a corridor are identified during the research: the number of air passengers on the corridor, the nature of the competitive transport infrastructure, the GDP per kilometre and the topography along the route. Some other minor criteria are also used, in order to elaborate a robust tool which can be a good help for investors and decision makers.
All selected corridors are ranked, resulting in a short list of the 250 most attractive corridors for the implementation of first commercial lines.
This study presents a proposal for the ranking of the most promising corridors. In order to validate and refine its results, it should be followed by proper feasibility studies on the highest ranked corridors including ridership calculations, sensitivity analyses, etc.

Keywords
Vacuum-tube train, hyperloop, transport economics, methodology

1 Introduction

In a context where the world population increases rapidly and travels a lot more than before, resulting in a “hyper-mobility” (Crozet (2016)), transport systems are key. Besides, the concerns about a man-caused climate change put the sustainability of our mobility models in question. Indeed, if the Humanity continues to increase its daily mobility with current technologies, it will inevitably conflict with its goal to globally reduce greenhouse gas emissions as agreed in the Paris Agreement signed at the end of the COP 21 in 2015 in Paris, France.

That is the reason why engineers, scientists, investors and business men all over the planet are imagining “greener” transport solutions that allow the humanity to continue increasing its mobility without putting the survival of the planet and its own existence into danger. The most disruptive solution is the vacuum-tube train, named hyperloop by Elon Musk in 2013 (Musk (2013)). It consists in capsules propelled at very high speed (up to 1,220 km/h) by electromagnetic systems inside low pressure tubes, so that friction and aerodynamic resistance are practically inexistent (Musk (2013)).

Even if the technical feasibility of this idea is still not guaranteed, several companies have started to work on the concept and conduct first tests on their prototypes (Davies (2017)). Three of them are ahead of the market: TransPod, Hyperloop Transportation Technologies and Virgin Hyperloop One. All three are raising funds and negotiating with public authorities to sound out interest in the market. Given that the opportunities of this technology are great and that the first successful implemented system would bring a big advantage to the company that has imagined and produced it, the evaluation of the most attractive places for the development of the first commercial lines is a decisive step.

As this mode of transportation also innovates in terms of operations, flow, frequency, it is useful to consider new methodologies that would complement traditional ones.

No work currently exists on this topic, so TransPod and IKOS consulting conducted a study which aims at defining the basis of a methodology for selecting and classifying the most attractive corridors for the implementation of the first commercial hyperloop line for passengers.

This paper reviews the existing methodologies, then presents the criteria chosen for this new multi-criteria analysis, details the process and the results, and concludes on explaining the limitations of such methodology, and the way forward.

2 Appropriateness of conventional methodologies to compare corridors for the implementation of a new commercial hyperloop line

2.1 Cost-Benefit Analysis (CBA)

The most usual methodology to assess the feasibility of a large transportation project and compare it with alternate ones is the Cost-Benefit Analysis (CBA). It uses monetized values (measured in monetary units) to compare total incremental benefits with total incremental costs (Transportation Research Board (n.d.)). To ensure the viability of the project on a long-term perspective, costs and benefits are estimated over a long period of time (20 to 30 years for large transportation projects like railways, roads or airports).

This methodology is mostly used to rank suitable alternatives for new or existing commercial transport lines on a defined corridor. It could therefore be an appropriate tool to compare hyperloop with competitive modes of transport on a specific corridor, based on a financial and economic analysis. As a matter of fact, it would take into account the economic benefit of very high speed, diminution of traffic congestion and possible low emissions with the use of clean energy. On the other hand, it would integrate very high investment costs, concerns about safety and reliability as well as land use (which is a very critical point in dense cities).

Theoretically, for the purpose of this study, which is to select and rank corridors for the implementation of the first commercial hyperloop line, the CBA would also be an appropriate methodology. But as the hyperloop technology is still at an early stage of development, the estimation of decisive parameters for the analysis (cost of a kilometre vacuum-tube, passenger demand, hyperloop users' value of time) is associated with a great margin of error. The evaluation of benefits and costs on each corridor would therefore be very imprecise and the analysis wouldn't be a good initial basis for investors and decision makers to determine where to launch the first project of a commercial hyperloop line. However, it would be used at a later stage of decision, once the corridors are selected and the parameters are precisely defined.

2.2 Multi-criteria analysis (MCA)

The Multi-Criteria Analysis (MCA) is another methodology which can be used to make a choice between several alternative projects, based on an algorithm that combines a set of relevant criteria for the choice and their relative "weights". A scale is defined for the evaluation of the relevant criteria. It can be continuous (e.g. if the evaluation score can take every value between 0 and 5) or discrete (e.g. if the evaluation score can only take the values 0, 1, 2, 3, 4 and 5). Each alternative is given a score on each criterion which is then multiplied by the corresponding weight. At the end, all weighted scores are added, resulting in a representative performance for each alternative. The comparison of those performances gives the most suitable alternative. An example of a Multi-Criteria Analysis is given in Table 1.

Table 1: Example of a Multi Criteria Analysis

Criterion	Weight	Alternative 1		Alternative 2		Alternative 3	
		Evaluation score on the criterion	Weighted score on the criterion	Evaluation score on the criterion	Weighted score on the criterion	Evaluation score on the criterion	Weighted score on the criterion
Time before start of commercial service	1	2	2	3	3	5	5
Safety	7	1	7	3	21	4	28
Environmental impact	3	0	0	1	3	2	6
Social benefit	3	5	15	2	6	3	9
Return on investment	5	2	10	5	25	1	5
Sum	19	10	**34**	14	**58**	15	**53**

According to the MCA presented in Table 1, the alternative 2 is the most suitable because it has the highest sum of all weighted scores (though it does not have the highest sum of all raw scores, which illustrates the importance given to the subjectively attributed weights in this methodology).

The MCA seems to be a well appropriate methodology to select and rank corridors for the implementation of the first commercial hyperloop line. Indeed, it does not require monetizing all benefits and costs like the CBA but can be based on assumptions or more intuitive criteria for differentiation between several possible routes. However, as a lot of corridors will be looked at in this study, the choice of criteria, scale and weights have to be made on a coherent, solid and reasoned basis. A sensitivity analysis should also be conducted to fine tune the choice and weight of each criterion.

3 Principles of the methodology for selecting and ranking the most suitable transportation corridors

First, the methodology developed in this study selects the routes where a hyperloop system would be technically feasible, economically viable, reliable and safe. To this end, some requirements are defined to automatically exclude the corridors which are obviously not suitable for the implementation of a hyperloop system (for demographic, economic, geographical or political reasons).

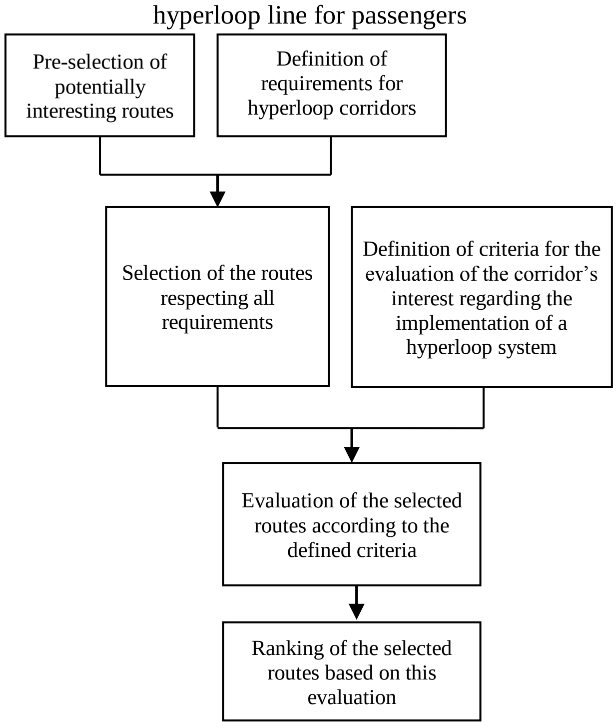
Then, the remaining possible routes are evaluated in a Multi-Criteria Analysis. The ranking of the corridors' interest for the implementation of a hyperloop system are worked out based on the evaluation of specific, scalable and reliable criteria, modulated by margin of error. Each criterion is attributed a conversion method from its initial range of values in its initial unit of measurement to a standardized dimensionless range of values between 0 and 10. The rating 0 indicates a route that is not at all interesting according to the assessment criterion under consideration, whereas the rating 10 is the translation of a most attractive one. After that, criteria are weighted according to their estimate contributions to the attractiveness of a corridor. The more relevant, objective and reliable the criterion is, the greater the weight. Finally, each corridor is rated by summing the weighted ranges of values of each criterion.

The figure 1 illustrates the methodology and its different steps, from the selection of potentially interesting corridors to the ranking of the most suitable ones for the implementation of a first commercial hyperloop line. The following paragraphs get into more detail in the development of the methodology and its application.

4 Selection of the most suitable routes

In the first place, following selection criteria are defined and applied with a view to establishing a list of possible origin and destination points for hyperloop corridors:

Figure 1: Methodology used to select the most interesting corridors to implement a first hyperloop line for passengers



- **Population:** The passenger demand for the use of a hyperloop system has to be high enough. That is why only urban agglomerations with more than 300,000 inhabitants and capital cities with 100,000 to 300,000 inhabitants of countries populated with at least 500,000 inhabitants (this includes Luxembourg City) are considered as possible origin and destination points.
- **Geography:** Crossing a sea or an ocean would drastically higher the infrastructure costs. Only cities connected by land can form an appropriate corridor for a first investment in a hyperloop system.
- **Economy:** Building a hyperloop system requires a huge investment. Low-income economies (GNI per capita lower than $1,006 in 2016) are excluded of the pool of cities.
- **On-going conflicts and tensions**: All of the 28 areas listed by Australian and French Governments as insecure places (war, conflict, high tensions, terrorism, armed groups presence) are excluded.

After this first selection, the number of possible origin and destination points for hyperloop corridors is reduced to 500 by taking the population and the GDP of the country into account (so that countries with high population and high GDP have the most cities in the list). The global distribution of the 500 selected cities can be seen on Figure 2.

Possible connections between those cities are filtered in order to meet the following requirements:

- **Route length:** The hyperloop is a very high speed mode of transport which mostly competes with air and has its greatest interest on middle to long distances. However, due to the huge investment cost, a first connection over 1,500 km would hardly find the funding. Only city pairs that are 300 to 1,500 km apart are considered in this study to form a potential hyperloop corridor. The distance between the selected cities is estimated using the GIS software QGIS 2.18.12 (with the tool “Distance matrix”) with a margin of error under 5%.
- **Geography:** Corridors that require the construction of a new undersea tunnel or a new bridge over the sea or the ocean are not selected for economic reasons.
- **On-going conflicts and tensions:** Corridors that cross insecure areas are excluded.

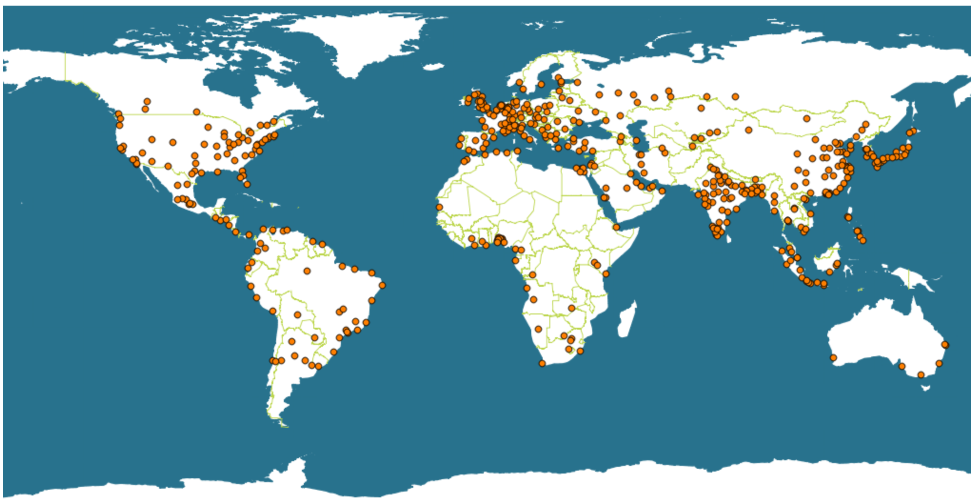


Figure 2: Global distribution of the 500 selected cities

After having performed the selection on the origin and destination points and on their connections, 6,167 corridors remain in the list of the most suitable routes for the implementation of a first commercial hyperloop line. With help of a Multi-Criteria Analysis, they are ranked from the most to the less attractive one.

5 Ranking methodology of the selected corridors

5.1 Criteria used for the evaluation

The following criteria are used to perform the Multi-Criteria Analysis:

- **Air traffic**: Air is the closest transport mode to hyperloop in its characteristics: very high speed, limited number of passengers, high users' value of time. That is why the demand for hyperloop will probably be high where the air traffic is significant. Air transportation being well developed and traceable throughout the world, accurate and reliable data is available [protected source].
- **Average load factor per aircraft:** A saturated air traffic indicates that there is a potential for more passenger demand on very high transport modes. The average load factor is often given with the passenger traffic on a corridor.
- **GDP per kilometre**: The GDP at a national level does not reflect the disparities of wealth and population between two cities of the same country. That is the reason why we use the GDP of metropolitan areas evaluated by McKinsey (Mc Kinsey & Company (2016)) rather than the GDP of countries. Considering the GDPs of origin and destination, it is logic to consider that the higher the sum of their GDPs, the more profitable the hyperloop line will be. Concerning costs, it is assumed in the first place that the construction and exploitation costs are directly proportional to the distance d between origin and destination. The two dimensions (costs and benefits) are summed up in one single indicator that we note C:

$$C = \frac{GDP_{Origin} + GDP_{Destination}}{d} \qquad (1)$$

- **Trip nature:** The higher demand is on domestic trips (connections between two cities of the same country). Domestic corridors will therefore be preferred to international corridors.
- **Route length:** The ideal compromise between a corridor where the very high speed reached by the hyperloop system brings a significant gain of time and a route whose infrastructure costs stay reasonable is evaluated around 600 km route length. The most interesting corridors for the implementation of a first commercial hyperloop line are the ones between 300 and 900 km. Over 900 km, the investment costs are barely sustainable. The distance between the selected cities is estimated using the GIS software QGIS 2.18.12 (with the tool "Distance matrix") with a margin of error under 5%.
- **Natural disasters**: Natural disasters would have a major impact on the hyperloop system. In a document produced by the United Nations, every major city is associated with the number of natural disasters it is exposed to.
- **Topography:** A steep terrain would raise the infrastructure costs and cause too high accelerations for passengers. The data for topography is accessed using Google Earth Pro 7.3.0.3832

- **Available terrestrial transport modes**: Only city pairs connected by air are considered for this study (so that the criterion based on air traffic can actually be evaluated). Terrestrial transport modes, like high-speed rail, highway, and conventional rail can discriminate the corridors by giving an indication on the competitive situation of the mobility market. The less available terrestrial transport modes, the more interesting the corridor. Data on available terrestrial transport modes is reliable and exhaustive, often furnished by the public authorities themselves, as they have an interest and a duty to communicate on such big infrastructure projects.
- **Country's GDP per capita:** Potential users of a hyperloop system are people with a high purchasing power. The United Nations provide a list of the GDP per capita in every country all over the world.
- **Country's ecological performance:** The hyperloop is potentially a clean transport mode, as it does not use any fossil fuel. Countries interested in reducing their greenhouse gas emissions are more likely to invest in this technology. The "ecological performance" of the country is not easily available, that is why only major countries will be evaluated on this criterion based on the GGEI (Global Green Economy Index).

5.2 Scaling of the evaluation criteria

All criteria are expressed in different physical units and cannot be directly added. Therefore, a conversion method to a standardized dimensionless parameter is required for every criterion. At the end, after conversion of the actual value, a number between 0 and 10 is obtained. The rating 0 indicates a route that is not at all interesting according to the assessment criterion under consideration, whereas the rating 10 is the translation of the most attractive power by only taking this criterion under account.

Different mathematical functions are used to convert each parameter into a standardized dimensionless parameter between 0 and 10: discrete, linear, quadratic, logarithmic. The goal by developing those conversion functions is to develop a methodology which can discriminate corridors on relevant criteria directly or indirectly related with costs and benefits for the whole system.

5.3 Weights attributed to the standardized dimensionless parameters

The interdependency between criteria is considered in the attribution of the weights given to the standardized dimensionless parameters. In particular, the GDP per kilometre and the route length are directly related (considering two city pairs with the same cumulated GDP, a longer route between the two cities of the first city pair will result in a lower GDP per kilometre for the first city pair than for the second). That is why the weight attributed to the route length will be adjusted according to the one given to the GDP per kilometre. Similarly, the GDP per kilometre and the country's GDP per capita are intuitively interdependent (metropolitan areas located in a country with a high GDP per capita are more likely to have a higher GDP than cities in a less developed country). This is also taken into account as the weight attributed to the country's GDP per capita is adjusted according to the one given to the GDP per kilometre.

The following weights are attributed to the standardized dimensionless parameters:

Table 2: Weights attributed to the standardized dimensionless parameters

Standardized dimensionless parameter	Corresponding classification criterion	Weight
P_1	Air traffic	8
P_2	Average load factor per aircraft	3
P_3	GDP per kilometre	9
P_4	Trip nature	2
P_5	Route length	2
P_6	Exposure to natural disasters	2
P_7	Topography	6
P_8	Available terrestrial transport modes	8
P_9	Country's GDP per capita	4
P_{10}	Country's ecological performance	2
Total		46

In this evaluation, four criteria are particularly relevant:

- Air traffic
- GDP per kilometre
- Topography
- Available terrestrial transport modes

By integrating the topography and the competitive situation among the most important parameters, the feasibility of the project and the possibility to get the support of both public and private investors are taken into account. Other criteria relative to the countries involved in the project like their GDP per capita and their interest in developing a greener economy are less important elements, as they are changing and subject to a frequent reevaluation.

6 Results

The weighted sum is calculated with Excel, giving a single score to every corridor. Then, corridors are ranked in decreasing order of this score. According to this ranking, the ten most attractive corridors for the implementation of a first commercial hyperloop line are (in that order):

1) Chicago – New York City
2) Houston – Dallas-Fort Worth
3) Sydney – Melbourne
4) Washington, D.C. – New York City
5) Detroit – New York City
6) Montréal – Toronto
7) Orlando – Atlanta
8) Buffalo – New York City
9) Atlanta – New York City
10) Tampa-St. Petersburg – Atlanta

It can be noted that 8 of the 10 most attractive corridors are domestic routes in the United States. Many reasons can explain this:

- Air traffic is very important in the United States.

- The GDP of many American metropolitan areas is very high as the average GDP per capita is one of the highest on the planet.
- Rail passenger traffic is not very developed over the country and there are still no high speed rail lines operating in the United States (but some are planned).
- The east side of the country is relatively flat.

Thus, the United States of America, and particularly its east side, is a great area to implement the first hyperloop line. The main problem though could be the reluctance of the federal state to invest in a massive transport project like this. It would create disparities between the states that will not be easy to compensate in the future without investing massively in developing a national hyperloop network.

It is surprising that no corridor located in the Middle East appears among the 100 best ranked routes. As a matter of fact, countries in this region of the world are willing to develop and diversify their transport infrastructure and possess the financial capacity to do so. A possible reason why no corridor in the Middle East is ranked among the best ones is an undervaluation of the cities' GDP in the Arabian Peninsula. This raises the question of the relevance and the quality of the input data.

7 Discussion

The methodology used for the selection and ranking of the corridors has been designed by hand, with little outside support. It differs from more traditional methodologies used to evaluate large transport projects in the uncertainty of its results and its questionable mathematical basis. Its application has been time-consuming, laborious and error-prone. If this research had to be conducted again, the time spent in collecting the data for the ranking process must be shortened by selecting a lower number of corridors (for example by taking only the 10 most frequented for each country). The great number of corridors may have resulted in mistakes during the transfer of the data from the source to the Excel table where all parameters used for the evaluation were computed.

Another limit to the study is the lack of data on certain classification criteria, such as the GDP of metropolitan areas, for which only one serious source was available and exhaustive. Moreover, the quality of the selected data and the methodology can also be questioned as corridors in the Middle East that intuitively seem attractive for the implementation of a Hyperloop system are not even classified under the top 100.

Some classification criteria are dependent on each other, which raises the question if there was no possibility to combine them in a single indicator. Air traffic, GDP per kilometre and country's GDP per capita to a lesser extent are all linked to the amount of people with a high purchasing power who could be potential hyperloop users. Similarly, the GDP per kilometre depends directly on the route length. But as the conversion function is linear for the GDP per kilometre (the higher the GDP per kilometre the most attractive the corridor, which at constant GDP means: the lower the distance the most attractive the corridor) whereas it is quadratic for the route length (corridors between 300 and 900 km are privileged with an optimum at 600 km), evaluation are interpreted differently for both criteria.

The attribution of a score ranging from 0 to 10 based on a weighted sum results in small differences between consecutive corridors in the ranking. That is why a small change in the conversion method from the initial value in its initial unit of measurement into a standardized dimensionless parameter can totally change the final ranking. Hence, it is more accurate to analyze the ranking by forming groups of corridors with similar scores rather than considering only the first one and leave the rest aside.

The methodology still constitutes a first interesting basis to work on and can be fine-tuned with some more mathematical input. After serious studies have been conducted on the costs and benefits of a vacuum-tube train system, a Cost-Benefit Analysis could be conducted on the corridors with the highest potential.

8 Conclusions

This study has led to the elaboration of a methodology used to select and rank the most attractive corridors for the implementation of a first commercial Hyperloop line. This methodology has been based on a Multi-Criteria Analysis, which differs from the most usual assessing methodology for large transportation projects: the Cost-Benefit Analysis.

Starting from a list of the most populated cities all over the world, it has been possible to select and rank the most suitable corridors for an investment on the development of a first vacuum-tube train line. The data used to obtain this ranking have been thoroughly chosen, analysed and weighted in order to integrate multiple dimensions (economic, geographical, environmental, political, safety-related).

At the end, a list of the 250 most attractive corridors for the implementation of a first commercial Hyperloop line has been elaborated. This list is a good starting point for further study. But it can be revised and ameliorated by cross-checking the data with help of complementary databases. Besides, routes located in the United States are overrepresented, whereas some promising connections in the Middle East do not appear on top 20 of the ranking. A reevaluation of the data and the methodology could help correct these inconsistencies.

Now that the most attractive corridors for the implementation of a first Hyperloop line have been identified, it would be interesting to develop a methodology to forecast ridership and revenues on a connection and to apply it to the 10 best corridors in the ranking. To do that, transport models like the Logit Model could be used. This will help refining this study by quantifying precisely the costs and benefits associated with the vacuum-train system on each line. If the profitability of the exploitation is demonstrated, a hyperloop service could then be implemented on the most favorable corridor.

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