TUM Hyperloop Program
TUM Department of Aerospace and Geodesy
Technical University of Munich

Book of Abstracts

1st INTERNATIONAL CONFERENCE ON

ULTRA-HIGH-SPEED TRANSPORTATION

RESEARCH MEETS INDUSTRY

March 1 - 2, 2021

CONFERENCE PROGRAM

The interest in revolutionary ultra-high-speed modes of transportation has been growing considerably in recent years due to, in no small part, the publication of the Hyperloop Alpha white paper in 2013 by Elon Musk and the resulting large number of initiatives started all over the world. Newly founded commercial enterprises and student organizations as well as established academic institutions and industry-leading corporations have been drawn to the topic and have begun to explore future sustainable ultra-high-speed transportation options and develop appropriate technical solutions.

The **1st International Conference on Ultra-High-Speed Transportation** aims at bringing together scientists and student initiatives with subject-matter experts from the mobility industry to foster the exchange of ideas and to discuss opportunities, potential impact and challenges of ultra-high-speed transportation. The event will take place in an online format (using the video conference tool Zoom) on the **March 1-2, 2021**.

The conference includes four Sessions (*Propulsion & Suspension Systems* and *Demand & Routes* on Day 1, *System Concepts* and *Infrastructure & Operations* on Day 2), covering the key aspects and challenges of the hyperloop technology, as well as a Keynote Lecture and a Panel Discussion. Each slot of the Sessions will comprise a 13-minute-long presentation and a two-minute questions and answer session. The speaker of each slot is marked in bold. Additional contributions will be provided to registered participants as downloadable materials only.

The Organizing and Scientific Committees are looking forward to welcoming you!

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Prof. Johannes Klühspies (TH Deggendorf)

Conference Secretary

Stephanie Henne
hyperloop@lrg.tum.de
Tel. 0049 (0) 89 289 55520

Day 1 – March 1, 2020

Time	Title	Authors / Speakers
14:00 – 14:35	Opening Remarks	Prof. Dr. Thomas F. Hofmann *President, Technical University of Munich* Dipl.-Pol. Dorothee Bär, MdB *State Minister for Digitization, German Federal Government* Prof. Dr. Mirko Hornung *Dean, TUM Department of Aerospace and Geodesy* Prof. Dr. Thomas Wunderlich *Head of TUM Hyperloop Program & Chairman of the Conference*
	Keynote Lecture	
14:35 – 14:55	Innovation Ecosystems – Bridging the Gap Between Innovative Research and Economic Success	Prof. Dr. Isabell Welpe *School of Management, Technical University of Munich*
	Session 1: Propulsion & Suspension Systems	
14:55 – 15:00	Introduction to the Session	Prof. Dr. Agnes Jocher *Department of Aerospace and Geodesy, Technical University of Munich*
15:00 – 15:15	Ride Comfort Transfer Function @1000 km/h	**Florian Dignath**[1], Philipp Schmitz[1], Qinghua Zheng[1], Patrick Schmid[2] & Peter Eberhard[2] [1]*thyssenkrupp Transrapid GmbH* [2]*Institute of Engineering and Computational Mechanics, University of Stuttgart*
15:15 – 15:30	Superconductivity and Smart Control – Key Enablers to meet Hyperloop Vision	**Markus Bauer**[1] & **Friedrich Loeser**[2] [1]*THEVA Dünnschichttechnik GmbH* [2]*thyssenkrupp Transrapid GmbH*
15:30 – 15:40	Break	

Session 2: Demand & Routes		
15:40 – 15:45	Introduction to the Session	Prof. Dr. Johannes Klühspies *Faculty of Applied Economics, Deggendorf Institute of Technology* *President, The International Maglev Board e.V.*
15:45 – 16:00	Hyperloop in Germany: Feasibility Study on the Implementation of a Hyperloop System in Germany	**Ana Eloisa Garcia de Gortari B.Sc.**[1,2], Maximilian Mayerföls B.Sc.[1,2], Daniel Loureiro Pacheco da Rocha B.Sc.[1,2], Maximilian Stark B.Sc.[1,2] & Prof. Dr. Isabell Welpe[1] [1]*Technical University of Munich* [2]*NEXT Prototypes e.V.*
16:00 – 16:15	Land management requirements and impacts when constructing Ultra-High-Speed and large-scale Transportation infrastructure projects such as hyperloops	**Prof. Dr. Walter Timo de Vries**[1] [1]*Department of Aerospace and Geodesy, Technical University of Munich*
16:15 – 16:30	Introducing Hyperloop to the UK	**Katelin Donaldson**[1], **Munya Mzenda**[1], Nourdin Mismar[1], Moritz Mörker[1], Brandon Henwood[1], Mercè Sánchez Oller[1], Gregory Dayao[1], Elliot Govier[1] & Stella Antonogiannaki[1] [1]*HYPED*
16:30 – 16:45	Understanding the factors influencing the acceptance of Hyperloop systems	**Md. Ashraful Islam**[1], Christelle Al Haddad[1], Mohamed Abouelela[1] & Prof. Dr. Constantinos Antoniou[1] [1]*Department of Civil, Geo and Environmental Engineering, Technical University of Munich*
16:45 – 16:50	Closing Remarks	Prof. Dr. Thomas Wunderlich *Department of Aerospace and Geodesy, Technical University of Munich*

Day 2 – March 2, 2020

Time	Title	Authors / Speakers
14:00 – 14:15	Introduction to Day 2	Prof. Dr. Thomas Hamacher *Department of Electrical and Computer Engineering, Technical University of Munich* Thomas Jarzombek, MdB *Commissioner for the Digital Industry and Start-ups & Federal Government Coordinator of German Aerospace Policy*
Session 3: System Concepts		
14:15 – 14:20	Introduction to the Session	Prof. Dr. Thomas Hamacher *Department of Electrical and Computer Engineering, Technical University of Munich*
14:20 – 14:35	Comparison of Technical Design Options for a Hyperloop System	**Domenik Radeck**[1, 2, 3], Prof. Dr. Agnes Jocher[1] & Prof. Dr. Thomas Hamacher[2] [1]*Department of Aerospace and Geodesy, Technical University of Munich* [2]*Department of Electrical and Computer Engineering, Technical University of Munich* [3]*NEXT Prototypes e.V.*
14:35 – 14:50	Unsteady Flow Investigation of a UHSGT Vehicle driving through an Enclosed Environment	**Francisco Guerrero**[1, 2], Rafael Andrade[1], Christopher Reinbold[2], Nils Wagner[1, 2] & Levente Csilik[1, 2] [1]*NEXT Prototypes e.V.* [2]*Technical University of Munich*
14:50 – 15:05	Lessons learned from MagLev train development ready to foster Hyperloop systems	**Dr. Ralf Effenberger**[1], Prof. Dr. Walter Neu[2,3], Prof. Dr. Thomas Schüning[2, 3] & Lukas Eschment B.Eng.[2, 3] [1]*Integrated Infrastructure Solutions GmbH & Transrapid Versuchsanlage Emsland (Emsland Transrapid Test Facility - TVE)* [2]*Institute of Hyperloop Technologies, University of Applied Sciences Emden/Leer* [3]*School of Mathematics and Science, Carl von Ossietzky University of Oldenburg*
15:05 – 15:15	Break	

Session 4: Infrastructure & Operations		
15:15 – 15:20	Introduction to the Session	Prof. Dr. Thomas Wunderlich *Department of Aerospace and Geodesy, Technical University of Munich*
15:20 – 15:35	A vacuum technology supplier's view on Hyperloop	**Tom Kammermeier**[1], Derek Corcoran[2] & Sebastian Rosenstraeter[1] [1]*Leybold GmbH* [2]*Leybold USA Inc.*
15:35 – 15:50	Hyperloop's integration into the existing transportation landscape	**Bruce Kemp**[1] [1]*Virgin Hyperloop*
15:50 – 16:05	Design of a European Hyperloop Large Scale Technology and Research Infrastructure	Prof. Dr. Walter Neu[1,2], Dr. Ralf Effenberger[3], Lukas Eschment B.Eng.[1,2] & Prof. Dr. Thomas Schüning[1,2] [1]*Institute of Hyperloop Technologies, University of Applied Sciences Emden/Leer* [2]*School of Mathematics and Science, Carl von Ossietzky University of Oldenburg* [3]*Integrated Infrastructure Solutions GmbH & Transrapid Versuchsanlage Emsland (Emsland Transrapid Test Facility - TVE)*
Panel Discussion		
16:05 – 16:50	Hyperloop: where and how can the vision become reality?	Prof. Dr. Thomas Hamacher (moderator) *Department of Electrical and Computer Engineering, Technical University of Munich* Prof. Dr. Johannes Klühspies *Faculty of Applied Economics, Deggendorf Institute of Technology* *President, The International Maglev Board e.V.* Dr. Friedrich Loeser *Chief Executive Officer, thyssenkrupp Transrapid GmbH* Dr. Stephan Liedl *TÜV SÜD Rail GmbH* Johannes Spatz *President, Panasonic Industry Europe GmbH* Ana Eloisa Garcia de Gortari *NEXT Prototypes e.V. & Technical University of Munich*
16:50 – 17:00	Closing Remarks	Prof. Dr. Agnes Jocher *Department of Aerospace and Geodesy, Technical University of Munich*

OPENING STATEMENTS

Opening Statement by

Prof. Dr. Thomas F. Hofmann
President of the Technical University of Munich

Dear colleagues, students, guests and friends,

Welcome to this first International Conference on Ultra-High-Speed Transportation – a great opportunity to exchange ideas as well as discuss the challenges and impacts of innovations in climate-neutral, ultra-fast transit between mobility hubs.

My special welcome goes to Thomas Jarzombek, Federal Government Coordinator of the German Aerospace Policy, and Commissioner of the Economic Affairs Ministry for the Digital Industry and Start-ups. Furthermore, Prof. Mirko Hornung, Dean of the Department for Aerospace and Geodesy and Johannes Spatz, President of Panasonic Europe.

In these turbulent times, sustaining success and increasing societal impact means to act and to position our university with the agility, dynamic and transformational power required to cope with the fast-shifting challenges of our modern world. Future mobility concepts ask for an open culture of innovation as well as collaborative structures in which universities are not merely the first link in the knowledge creation chain. Instead, universities need to become central players in an innovation ecosystem made up of research institutes, enterprises, technology companies, incubators, start-ups and NGOs.

That is why we need to integrate our curious, open-minded students to join us as key players and a valuable source of new ideas. Like the international team of almost 40 TUM students from eight departments, who for the fourth consecutive time became the undefeated world champions in the SpaceX Hyperloop pod competition. Motivated by the future importance of novel air and ground mobility concepts and, definitely re-enforced by the passion of the Hyperloop student team, Minister-President Markus Söder announced the new TUM Department of Aerospace and Geodesy in 2018.

Just one year later, the new department took off with its interdisciplinary “Mission Earth”. It combines our expertise in high-performance propulsion and materials, additive manufacturing, miniaturization as well as artificial intelligence – embedded in our leading system competencies in geodesy. With a broad focus ranging from new transportation systems on and above earth, such as air taxis. To satellite swarms, enabling seamless internet connectivity. Right up to capturing urbanization developments, surveying the planet and observing climate change with unprecedented precision.

To fulfill our technological ambitions, the new department links its headquarters on the Ludwig Bölkow Campus in Taufkirchen/Ottobrunn with the TUM Science & Engineering Campus in Garching, the competences in remote sensing and satellite navigation on the TUM main campus in Munich, and the German Aerospace Center in Oberpfaffenhofen. We strengthen this core of a Greater Munich Space Valley by joining forces with the University of the Bundeswehr and companies such as Airbus, IABG, Hensoldt and MTU Aero Engines. As well as new high-tech companies such as the TUM start-up Isar Aerospace, which recently opened its production halls in Taufkirchen/Ottobrunn to manufacture low-cost rockets for small-scale satellites.

The department also benefits from its interactions with the TUM Munich School of Robotics and Machine Intelligence – the MSRM. This integrative research center bundles competence across disciplines on "embodied artificial intelligence" and autonomously acting machines for the future of health, the future of work and the future of mobility. As members of the MSRM, Prof. Holzapfel and Prof. Walter represent important bridgeheads of the Department of Aerospace and Geodesy. Through Prof. Xiaoxiang Zhu, the department is also connected to the new Munich Data Science Institute (MDSI) and the BMBF-funded Lab for "AI for Earth Observation." This lab focuses on the use of satellite data and intelligent big data analysis to study global urbanization challenges.

In the future, we want to inject this collaborative thinking and teamwork culture further into our students' study programs. We will substitute traditional disciplinary boundaries in our degree programs by problem-oriented team project weeks. We want to develop our students' ability to synthesize knowledge and method competences from different disciplines on demand.

Enabled by the new "TUM Entrepreneurial Master Class," we have started to support student teams in linking their studies with cutting-edge research and entrepreneurship, encouraging them to explore avantgardistic technologies, such as the Hyperloop, and in this way accelerate the transition into new businesses. So far, we reached an excellent output of more than 70 growth-oriented high-tech start-ups per year, and in 2019 alone, our start-ups raised more than €1 billion in capital investment.

However, to push these successes to the next level, we collaborate with UnternehmerTUM on building a network of connected innovation centers: The TUM Venture Labs. These Labs aim at developing start-up families in high potential Deep Tech areas. They provide the necessary development environment – from the technical and social infrastructure via entrepreneurship coaching and venturing, all the way up to the support from investors and global enterprises. In this realm, we are planning the "TUM Venture Lab Aerospace" as a powerful innovation launchpad in Taufkirchen/Ottobrunn.

This will also benefit our "TUM Hyperloop program." It is supported by the Hightech Agenda Bayern and develops as well as evaluates core technologies for ultra-high-speed transportation. Including a focus on their future technical and economic feasibility. The TUM Hyperloop program combines expert knowledge from various fields such as drive and high-power technologies, lightweight design, traffic route construction and geodetic engineering to develop a functional and save super-high-speed train technology. To achieve systems integration and analysis, to identify potential security risks at an early stage, and to develop feasible solutions, we will construct a full-scale technology demonstrator; it will consist of a 24-meter vacuum tube and a matching human-sized pod.

My cordial thanks go to Prof. Thomas Wunderlich, Head of the "TUM Hyperloop Program", and his passionate team of faculty, scientific staff and highly motivated students. I am grateful to all our people who pursue this dream together and thus accomplish seemingly impossible goals. I want to thank our student-led, non-profit organization "NEXT Prototypes" under the Hyperloop project leadership of Gabriele Semino. Your team is a source of inspiration for our entire TUM community. And that's why you can always build on our ongoing support through contributions such as the newly created professorship in "Ground-Based High-Speed Transportation Systems," which will be filled soon.

Dear colleagues, students, guests and friends, you are well aware that Bavaria is the place where "tradition has a future." We are known for our Bavarian "Gemütlichkeit" and the Oktoberfest. However, Bavaria is also the place, where "the future has tradition": Through close collaboration with business and industry, TUM has provided important contributions to Bavaria's development from an agricultural land to a center of high-level and precision technology.

Today, this international conference will lay the groundwork on which we can build the future of climate-neutral ultrahigh-speed ground transportation. I want to thank the speakers who give this conference a vital impetus, and wish all of you lots of inspiration and time to meet and to exchange thoughts.

Opening Statement by

Prof. Dr. Thomas Wunderlich
Chairman of the Conference

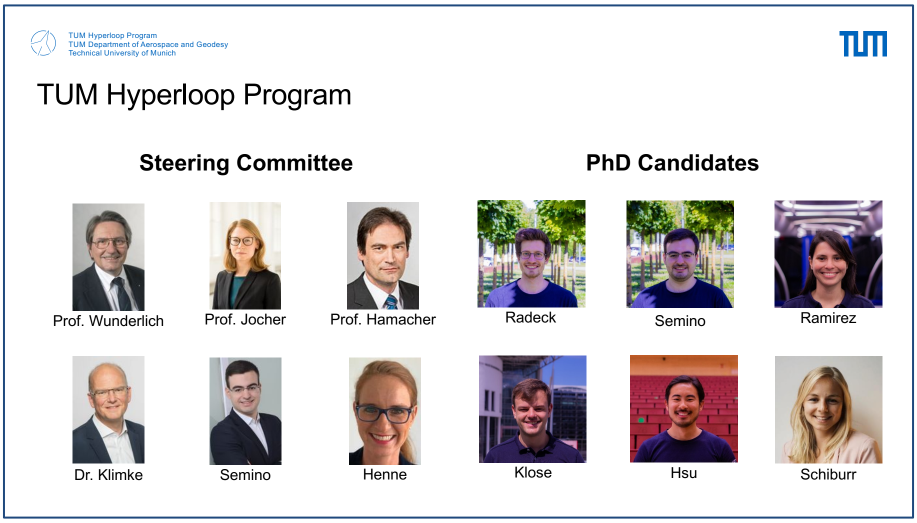
Dear Representatives of the Federal and State Ministries, dear colleagues of the Scientific Committee, dear Ladies and Gentlemen,

a very warm welcome from the Technical University of Munich, Bavaria, Germany, to all our guests scattered across the globe. My name is Thomas Wunderlich, Chair of Geodesy; together with Prof. Agnes Jocher and further members of the committee, I'm going to lead you through the two afternoons of this 1st International Conference on Ultra-High-Speed Transportation – Research meets Industry.

Please allow me to give you a brief introduction to this online conference. We will have two Sessions each day with a 10-minute break in between. Today before the first Session we will start with a Keynote Lecture by Prof. Isabell Welpe and tomorrow after the last session we will have a Panel Discussion, conducted by Prof. Hamacher, followed by the concluding words to be given by Prof. Agnes Jocher. The sessions will be chaired by Prof. Agnes Jocher, Prof. Johannes Klühspies, Prof. Thomas Hamacher and my humble self. During the sessions, please submit your questions to each presentation using the Zoom Q&A function. The Chairperson of each Session will use the last couple of minutes of each slot to discuss some of them with the respective speaker. I also want to add that the materials and recordings will be available for all registered participants after the Conference.

Maybe this is the best occasion to introduce you to our Organizing and our Scientific Committees. As it mostly consists of members of TUM, I will only emphasize here the external members, Prof. Andreas Wieser from ETH Zurich and Prof. Johannes Klühspies from TH Deggendorf, President of the International MagLev Board.

I'm deeply indebted to all members and to the Conference Secretary, Stephanie Henne, for the great efforts and the magnificent collaboration during the preparation and the present realization. The volatile pandemic situation was at no time helpful to produce an international Conference. This brings me with proper respect to very warmly thanking all the speakers and online presenters for their contributions, be it extended abstracts, slides or video recordings and moreover the people of the studio here at TUM ProLehre Media and Didactics, who will support us from the technical side during this Conference and guide us through it, hopefully without any technical difficulties.



Perhaps you will also be interested in the people of the TUM Hyperloop Program: there is a Steering Committee and staff to be seen at the left side and the first six PhD candidates on the right side, which will become nine in the near future. In addition, a large number of students is also highly involved in the program. From some of them you will hear contributions in the course of this Conference.

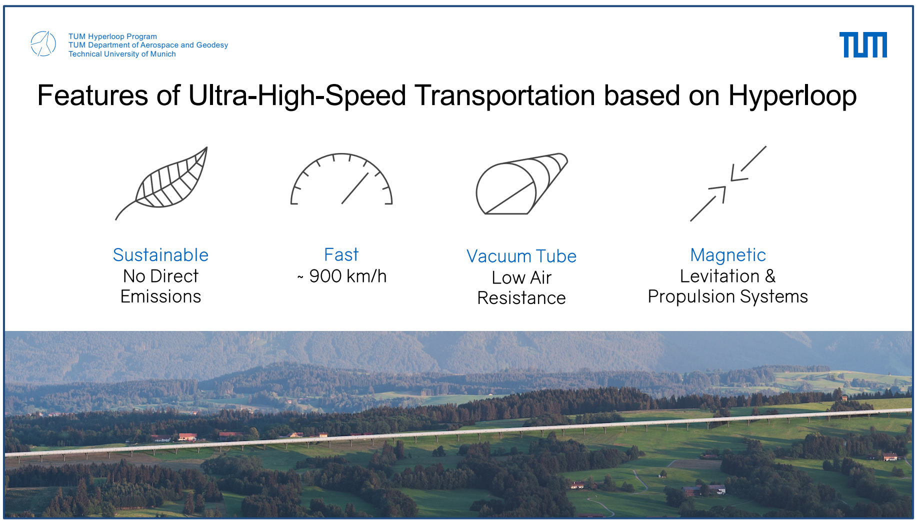
The TUM Hyperloop Program was founded when TUM and the Bavarian Government, inspired by the highly successful student initiative, decided to start an extensive research program on Hyperloop technology, as part of the innovation effort Hightech Agenda Bayern. In the current phase of the program the team is developing a full-scale technology demonstrator, in order to test crucial subsystems and their integration, as well as performing detailed concept analyses with the goal of optimizing the system and defining its application scope. We would also like to thank once again the Bavarian Government and in particular minister president Dr. Markus Söder for the funding and for their enduring and prosperous support!

As you might know, the hype started with Elon Musk's SpaceX Hyperloop Pod Competition in 2017, when dozens of student teams all over the world tried to reach record speeds through a tube of 1,2 km length. As the team of TUM's student initiative NEXT Prototypes won the contest four times, the hype spread to TUM and to the Bavarian Government here in Munich.

And that happened in a comparable way at other locations and universities. Exemplarily, with Swissloop at the ETH Zurich in Switzerland. And the eagerness of project-based learning and developing did not stop at this competition; meanwhile there's a European Hyperloop competition and also a tunnel-boring contest, organized by Elon Musk's Boring Company.

At some of these places the interest grew and programs, foundations and institutes were founded, like e.g. the Bavarian TUM Hyperloop Program, the Swiss EuroTube Foundation or the Lower-Saxony Institute of Hyperloop Technologies. On the other hand, industry interests arose from start-ups to big enterprises, not forgetting important specialized suppliers. The slide here only presents a selection.

There are sporadic links in between the three types of Hyperloop pioneers, but too loose. It is the defined goal of this conference series to initialize and improve the networking and collaboration.



It is a worthwhile destination to combine the efforts to arrive earlier and conclusive at an ultra-fast, smoothly levitating and energy-efficient, near-vacuum transportation system. Nevertheless, there are also remarkable MagLev systems, in part not using a vacuum tube, so we must have a close look at all ideas and analyze their relevance, but we should never lose our vision of making ultra-high-speed transportation become reality!

Today, we are used to forward messages, pictures and parcels at the push of a button, within extremely short time – so why not let us propel ourselves?

Having said that, I want to thank you all again for attending today!

Additional opening remarks by Dipl.-Pol. Dorothee Bär, MdB, Prof. Dr. Mirko Hornung, Thomas Jarzombek, MdB and Prof. Dr. Thomas Hamacher have not been provided in written form. The recording of their contribution as part of the conference will be provided separately to the attendees.

SESSION 1

Propulsion & Suspension Systems

Ride Comfort Transfer Function @1000 km/h

F. Dignath[*,1], P.Schmitz[1], Q. Zheng[1], P. Schmid[2], P. Eberhard[2]

[1]thyssenkrupp Transrapid, Munich, Germany

[2]Institute of Engineering and Computational Mechanics, University of Stuttgart, Germany

Keywords: Transrapid, Fast Fourier Transformation (FFT), Vehicle Dynamics, Ride Comfort Transfer Function (RCTF), Measurements & Simulation

Introduction

Reaching acceptable ride comfort at the Hyperloop speed of 1000 km/h is a challenge because the ride comfort generally deteriorates with the vehicle velocity. When designing the first Hyperloop vehicles, matters are complicating because no measurements of previous, or indeed, any track-mounted vehicles are available at this velocity from which design details may be deducted. Simulation models may give first hints on the vehicle dynamics in the low frequency range, that can mainly be influenced by the levitation and guidance system. However, above the second vertical and roll Eigenfrequencies many details of the vehicle and guideway structure influence the vehicle dynamics which cannot easily be determined beforehand and calculated.

While this problem is inherent in the first stage of the design process, the question arises, how more reliable predictions of the ride comfort can be given when measurements of first prototypes on short tracks at low speeds become available, which seems to be the logical next stage in the design process of an Hyperloop vehicle. In this paper, the application of a Ride Comfort Transfer Function (RCTF) in the frequency domain according to the definition in [11] is suggested, which can be setup based on preliminary simulation models of the vehicle dynamics in combination with measurement results recorded at smaller vehicle velocities than aimed at. In this way, vibrations in the full frequency range relevant for ride comfort are predicted. This frequency range comprises about 0.3-80 Hz for vertical vibrations according to standard ISO 2631 [5].

The validity of the method is shown by comparing the such predicted ride comfort with measurements for the MAGLEV system Transrapid - that has proven good ride comfort up to its record speed of 501 km/h. Then, the method is exemplarily applied to the prediction of the ride comfort at the Hyperloop speed of 1000 km/h on a suitably smooth guideway, whose property is extrapolated from the analysis of existing guideway designs for the Transrapid.

Ride Comfort Transfer Function (RCTF)

During a typical ride of a high-speed MAGLEV vehicle, or any high-speed train, vibrations with small amplitudes occur much more often than vibrations with large amplitudes. Therefore, it is assumed that linear methods can be applied for the statistical ride comfort analysis, and the measured or simulated data are transformed to the frequency domain by use of the Fast Fourier Transformation (FFT). In the frequency domain, a Ride Comfort Transfer Function (RCTF) is defined, that describes the relation between guideway irregularities as the input and the accelerations close to the passenger seats as output.

For this, the whole vehicle, including mechanical structure, the magnets and their controllers as well as the magnet-track interaction, is considered approximately by a linear and autonomous input-output model. Based on this ideal conception, it is possible to calculate the RCTF in the frequency domain via numerical simulation as well as by using measurement data, see Figure. Such, the assumptions of linearity and autonomy can be checked by comparison of the RCTF obtained by different methods and for many measurement rides at different vehicle speeds. In addition, the influence of the geometric irregularities and speed of travel can be analyzed in detail.

* Corresponding author: Florian.Dignath@thyssenkrupp.com

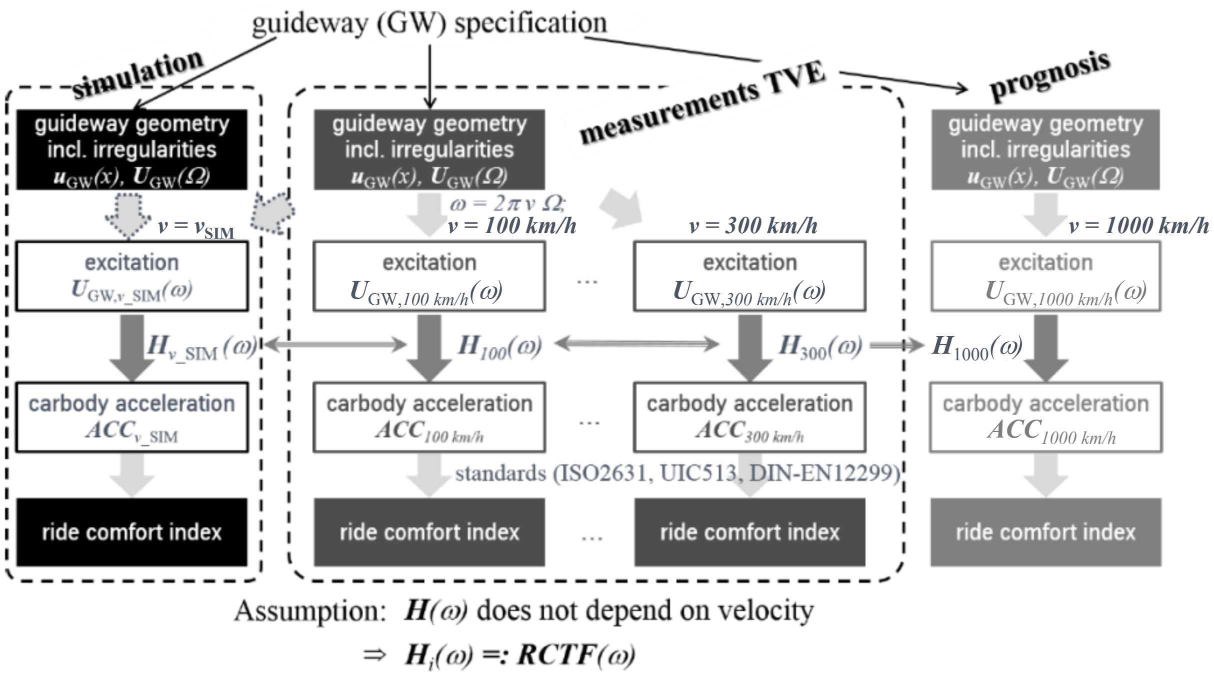


Figure 1: Principle of ride comfort prognosis using the RCTF

For calculating the transfer functions $\boldsymbol{H}_i(\omega)$ mentioned in Figure from either simulation results or measurements, two steps are necessary for each considered vehicle ride *i*:

i) The time histories of the guideway excitations $\boldsymbol{u}_{GW}(t)$ and the carbody accelerations $\boldsymbol{acc}(t)$, where $\boldsymbol{u}_{GW}$ and $\boldsymbol{acc}$ are vectors containing the respective inputs and outputs of the considered directions of the idealized input-output model, are both transformed into the frequency domain using an FFT. In order to reduce the dependency of the FFT from the discretization and length of the considered time intervals, the time history is divided into shorter, overlapping strips, each having the same length and discretization, thereby following the method for power spectral density analysis as described in [10]. The FFT is applied to each of these time strips and the average of the results is calculated along the common frequency axis yielding the amplitude spectrum for these time histories $\boldsymbol{U}_{GW}(\omega)$ and $\boldsymbol{ACC}(\omega)$.
ii) Such calculated amplitude spectra for the carbody accelerations are divided by the amplitude spectra for the excitations yielding the transfer functions

$$H_{kj}(\omega) = \frac{ACC_j(\omega)}{U_{GW,k}(\omega)}; \tag{1}$$

where each component *j* of the vector $\boldsymbol{ACC}$ is divided by each component *k* of the vector $\boldsymbol{U}_{GW}$. The resulting transfer functions are assembled in the matrix $\boldsymbol{H}_i$ for each vehicle velocity *i*. To reduce the influence of random occurrences and single events during the rides, several rides for each vehicle velocity on the same piece of track are evaluated and the average is calculated along the common frequency axis.

It could be shown that the calculated transfer functions $\boldsymbol{H}_i(\omega)$ are very similar for all rides of the vehicle, even at different velocities, see [11]. Thus, the transfer function represents a vehicle property, independent from the guideway or the vehicle velocity, and the general Ride Comfort Transfer Function can be defined as $\boldsymbol{RCTF}(\omega)$ for the vehicle as an approximation of all found transfer functions $\boldsymbol{H}_i(\omega)$.

Once the RCTF is calculated for a given vehicle, the prognosis of ride comfort is a straightforward task, that is, multiplying the excitations arising from the guideway irregularity by the RCTF, according to the right column in Figure. Results for the Hyperloop speed and a suitably smooth guideway are shown towards the end of this paper.

Calculating the RCTF by using a Mechatronic Multibody Simulation Model

According to the previous section, the RCTF can be computed from measurement recordings or from simulation results. In order to verify the method, both ways are exemplarily applied to rides of the Transrapid TR09, and their results are compared.

A MAGLEV vehicle is a coupled mechatronic system including mechanical, electromagnetic, and electronic subsystems. Moreover, its 3D motion can be split into the travelling, the heave-pitch, and the lateral-yaw motions and can be investigated by considering two-dimensional models as substitutes, as e.g., proposed in [7]. For driving straight ahead with constant velocity, the heave-roll-lateral motion remains as the essential motion for ride comfort analysis. Moreover, the simplification is reasonable, since the individually controlled magnets along the vehicle can be treated as autonomous systems according to the vehicle's structure, see [4].

The considered mechatronic simulation model comprises a 2D multibody system describing the mechanical part, four network models of the electro-magnets – two levitation magnets and two guidance magnets – and a signal model of each magnet controller, coupled by the overall structure shown in Figure. The model can be considered an enhanced version of the model presented in [1] using the detailed modelling of magnets described in [8] and the multibody software [6]. The simulation model can be used to compute the carbody accelerations for a given data set of guideway positions. Then a model based RCTF, see Figure, can be calculated by the method described in the previous section.

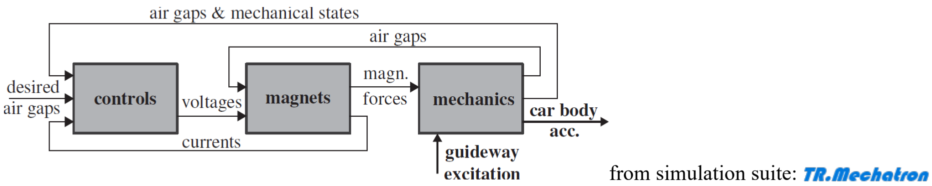


Figure 2: Schematic signal flow diagram describing the overall structure of the mechatronic simulation model

Calculating the RCTF from Measurement Recordings

The calculation is based on measurement results of test runs of the Transrapid TR09 on its former test track (TVE) in Northern Germany, recorded in 2009. From these measurement results two characteristic quantities are generated for several different vehicle velocities. Firstly, the position of the guideway is reconstructed by using an integration scheme of the measured absolute accelerations of the magnets and the signals of the magnet's sensors for the air gap, similar to the method described in [9]. The resulting guideway is given as a function $\boldsymbol{u}_{GW}(x)$ that can be converted to a time dependent function $\boldsymbol{u}_{GW}(t)$ assuming constant velocity.

Secondly, the accelerations within the carbody are measured on top of the passenger floor, directly beneath the seat fixations, suitable for evaluation of the ride comfort for standing passengers. From these recordings the relation between the accelerations at the carbody and the guideway position is calculated in the frequency domain applying a FFT as described in Figure.

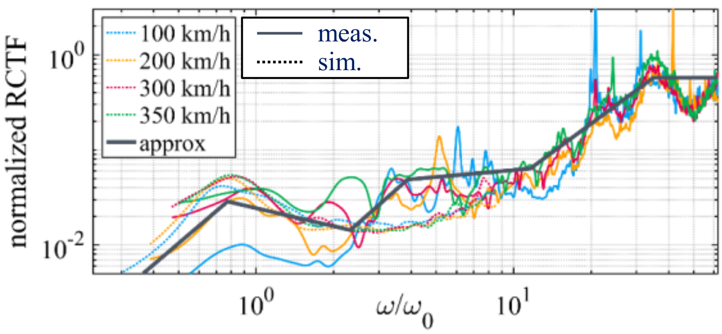


Figure 3: RCTF for the Transrapid TR09 calculated from simulation results and measurement recordings

The resulting transfer functions contain random parts, and thus provide individual results for each ride. There are, however, great similarities between the transfer functions of different rides with the same vehicle speed. For the prognosis of future ride comfort evaluations, only the deterministic part of the transfer function is of interest. Therefore, a smoothed version of the transfer functions can be calculated by taking the mean value of the transfer functions for several rides with the same speed and subsequent filtering. These resulting RCTFs for several vehicle speeds are shown in Figure in comparison with the RCTF calculated from simulation results.

Definition of Guideway Irregularities

For validation of the suggested method, the measured guideway irregularities identified as described in the previous section can be employed as input for the method proposed in Figure. However, as this guideway design of the 1980's is not suitable for the Hyperloop speed, a guideway is constructed in simulation according to published guideway design principles with longer wavelengths and smaller tolerances to keep the necessary magnet accelerations within acceptable limits.

For constructing this reference guideway *hyperloop REF-TRail*, the tolerances given in the Design Principles High–speed MAGLEV System (MSB)" [3] are used. It is assumed that the built irregularities follow a random pattern but are always smaller than the specified tolerances. Therefore, a normal distribution is applied, whose 3σ–limits are set to the specified tolerances. For a straight, even piece of track, a comparison for the TVE guideway showed that some tolerances can be reduced by a factor of about ½ with respect to the documents, especially in the lateral direction. Contrary to the existing guideways for the Transrapid, it is assumed that the *hyperloop REF-TRail* will be supported nearly continuously within its tunnel, thus omitting the bending amplitude of the TVE's 25 m long girders. Instead, shorter 9 m modules are assumed with small bending amplitudes that are, nevertheless, modelled as Euler–Bernoulli beam bending curves. The resulting table of deviations from the nominal center line are given as triplets of the three degrees of freedom y_{GW}, z_{GW}, ϕ_{GW} vs. the distance x along the track. A data file of a 10 km example piece can be enquired from the authors.

While this artificial definition is not suitable to simulate a certain situation in time or place, i.e., a very specific guideway situation, it yields the same statistical excitations, containing the same power content as the measured guideways, as was shown by comparing the power spectral densities (PSD), see [11]. The PSD of the *hyperloop REF-TRail* is shown in *Figure* for the vertical direction in comparison to the reference guideway REF used for simulating Transrapid vehicles and some references from literature.

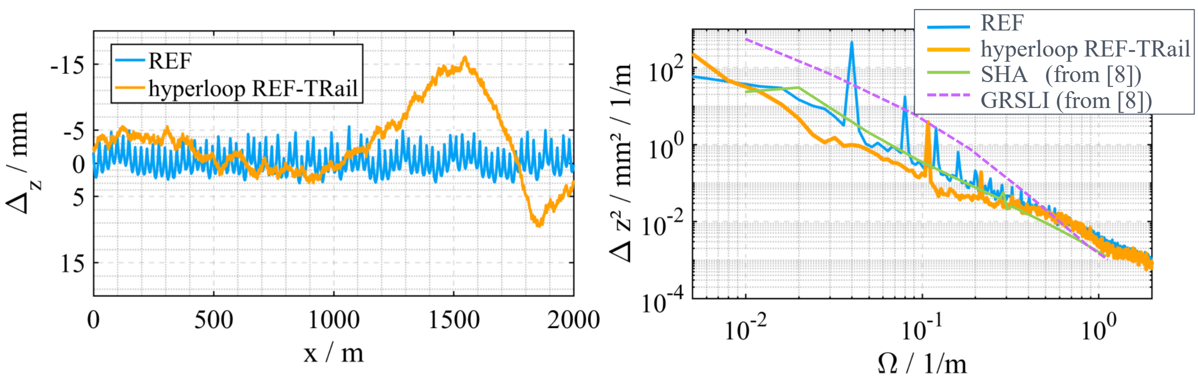


Figure 4: Constructed Hyperloop guideway in the space domain (left) and its PSD in the spatial frequency domain (right) in comparison to the reference guideway (REF) according to the Design Principles High–speed MAGLEV System (MSB)" [3] and the Shanghai Maglev guideway (SHA) according to the parameter fitting from [9] including German railway spectra of low irregularity (GRSLI)

Prognosis of Ride Comfort

With this *hyperloop REF-TRail* guideway as input to the RCTF, the ride comfort is predicted for vehicle velocities up to 1000 km/h according to the sequence in Figure. The multiplication of the irregularity spectrum with the approximated version of the RCTF shown in Figure yields a prognosis of the resulting accelerations in the frequency domain. While this is well suited for a comparison of different designs, a better insight into the resulting effect for the passengers is given by scalar ride comfort index values that can be calculated according to one of the accepted standards.

For high-speed railways in Germany, e.g., the standard DIN-EN 12299 [2] in combination with ISO 2631 [5] describes the calculation of a scalar index value from the time history of measured accelerations. For the prognosis in Figure, the necessary time history is generated from the predicted accelerations in the frequency domain by using an inverse Fourier transformation assuming random phase. The comparison of the prognosis for the Transrapid with the measurements described on the previous pages shows the validity of the presented approach. This was validated for many samples of random phase to prove the independence of the calculated ride comfort index from the phase.

Exemplarily, the RCTF of the Transrapid TR09 is applied in combination with the *hyperloop REF-TRail* guideway, yielding the ride comfort index shown in Figure. For simplicity, the presented results in this work are restricted to the scalar transfer function between the vertical guideway position and the vertical carbody acceleration. For practical application, however, the proposed method can be used to investigate the RCTFs for other inputs and outputs without loss of generality. In fact, the authors have successfully applied the method to all three degrees of freedom of the guideway definition given above.

The scalar ride comfort index in Figure is quite a good value for a high-speed vehicle and, in fact, well within the best category “not uncomfortable” (<0.315 m/s²) according to ISO 2631. It must be noted that the ride comfort is shown for the position in the center of the middle section of the vehicle. The ride comfort will be worse near the windows, where additionally, the roll motion is relevant, and it will be worse near the end of the sections where the yaw and pitch motions of the vehicle section have more effect. If these motions are of interest, the model and the presented prognosis method can be augmented to all six degrees of freedom of the carbody using corresponding sensor points outside the shown cross-section.

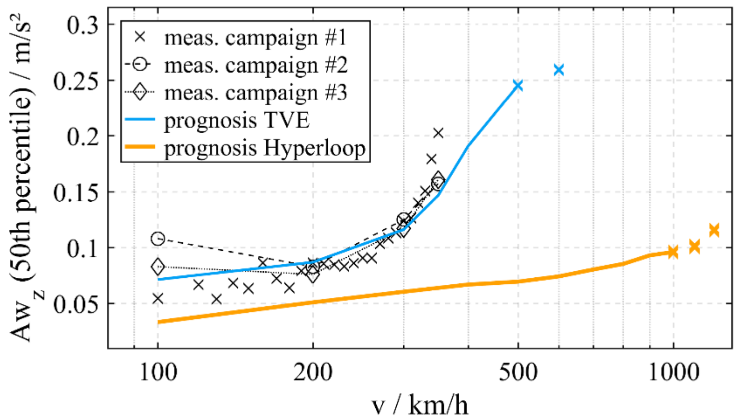


Figure 5: Prognosis of the Hyperloop ride comfort index according to DIN-EN 12299 up to 1000 km/h in comparison to the prognosis for the Transrapid TR09 on the former test track TVE

Conclusions

During a typical ride of a high-speed MAGLEV vehicle, or indeed any high-speed train, vibrations with small amplitudes occur much more often than vibrations with large amplitudes. Therefore, linear methods can be applied for the statistical ride comfort analysis, which is verified by the results of this paper. By the described methods, a transfer function in the frequency domain is calculated which allows the prognosis of the ride comfort for an Hyperloop vehicle based on simulation models and/or first measurements at slow vehicle speeds.

This Ride Comfort Transfer Function (RCTF) gives the relation between guideway irregularities, i.e., given positions of the guideway’s stator packs and guidance rails, and resulting accelerations close to the passenger seats.

It is verified at the example of the MAGLEV system Transrapid by comparing its calculation based on mechatronic simulation models, considering the coupling between control, electrical, magnetical, and mechanical subsystems, with the calculation based on signal processing of measurement data. Furthermore, its results are validated by comparing the predicted ride comfort index with measured ride comfort index values for the Transrapid TR09.

For application of the suggested method to Hyperloop vehicles, suitable guideway irregularities are constructed in the time and frequency domain, based on technical specifications, and compared with known irregularities for MAGLEV and high-speed railways. Exemplarily, applying the validated RCTF of the Transrapid to these reference guideway irregularities *hyperloop REF-TRail,* the ride comfort index according to standards is predicted up to 1000 km/h. The resulting ride comfort index predicts a very good ride comfort even at the highest speeds for an Hyperloop vehicle with similar transfer function as the Transrapid. Although Hyperloop vehicles may be built much lighter, this is a positive indication, that Hyperloop vehicles based on the usage of controlled magnetic attraction forces may provide good ride comfort on an Hyperloop guideway built according to state-of-the-art construction tolerances.

Since it is shown that the RCTF is independent from the driving situation, itself can be regarded as a measure for the vehicle quality concerning the ride comfort. Such, it is possible to compare different Hyperloop vehicle designs with respect to ride comfort beforehand, without detailed knowledge about the guideway.

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Superconductivity and Smart Control - Key Enablers to Meet Hyperloop Vision

Markus Bauer[1], Friedrich Loeser[*, 2]

[1]THEVA, Ismaning, Germany

[2]thyssenkrupp Transrapid GmbH, Munich, Germany

Keywords: Magnetic Levitation, Superconductors, Model Predictive Control, Riding Comfort

Introduction

The Hyperloop vision of ultra-high speed transportation in evacuated tubes demands the groundbreaking combination of new materials and smart control to meet technical and economic feasibility. In addition, Hyperloop's passengers expect excellent ride comfort rather than a roller coaster ride.

Existing high-speed ground transportation systems achieve reasonable ride comfort by massive concrete structure and demand continues maintenance to keep the tracks aligned; Hyperloop has to overcome such principle, otherwise it will fail economically.

This paper proposes a smart combination of model predictive levitation control and superconducting coil technology to extend existing limitations of design.

Core Requirements on System Configuration

Pods running in low-pressure tubes must not introduce abrasion and cannot transfer heat to the environment.

Non-contact support, guidance and propulsion of pods is a mandatory precondition for normal operation except taxiing and passenger handling at stations. Low weight and volume of pods is required to limit mass forces and cross section. Any equipment generating heat or demanding installation weight and volume on board shall be restricted to necessary hotel, communication and life functions.

In consequence, magnetic levitation and electrical propulsion by a linear motor is the promising configuration to meet the requirements. For magnetic levitation - support and guidance of the pods - two different principles exist, Electromagnetic Levitation System (EMS) and Electrodynamic Levitation System (EDS).

EMS is based on electronic stabilizing gap control of attractive forces between ferromagnetic cores and poles. EDS is based on self-stabilizing repulsive forces between magnetic poles of opposite polarity. Both, EMS and EDS are well experienced in the speed range 500 to 600 km/h. Numerous variants of magnetic levitation systems ("Maglev") exist after decades of testing and commercial application (Masada, 2011). The question is which one is the best for Hyperloop.

Issue of Ride Comfort

Passengers expect a smooth and safe trip. If they feel shaken up, they also feel unsafe without any visual contact to the environment. The physical quantity for evaluation of ride comfort is the acceleration mainly in vertical and lateral direction. Most sensitive frequencies of uncomfortable motion range at 1 to 10 Hz, as is considered in the standards for evaluation of ride comfort for passengers. Additionally, dampers are not or less effective in such range. Existing high-speed ground transportation systems use big amounts of concrete and ground works to get a smooth track alignment. Active damping fails under the restrictions on volume, weight and power.

A quick look might suggest that existing Maglev systems would be insensitive to deformations and deviation of the track, because a smooth carpet of magnetic fields could equalize any unsteadiness by itself. Actually, this is not the case, because both kinds of Maglev systems just follow their track. If the track is perfectly straight, run is

* Corresponding author: friedrich.loeser@thyssenkrupp.com
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beautiful; if the track is humpy, Maglev follows the humps. EMS is following with superposed dynamic deviations from magnet control. EDS is following with weakly damped, uncontrollable self-oscillations.

With current technologies, the only way to mitigate this issue is a perfect alignment of stiff and precisely manufactured guideway beams, placed on massive foundations with adjustable bearings to compensate later settlements of the ground. However, even if an investor would pay for all that concrete and ground works, it would not yet fully solve the issue for Hyperloop speed.

Assuming a typical speed of 900 km/h or 250 m/s, at comfort relevant vibration ranging 1 to 10 Hz, the exciting wavelength of track deviation from the ideal alignment curve is in the range of 25 to 250 m. Thus, extended ground settlements may have a massive impact to ride feeling and give an expensive challenge to surveying and adjustment work under operation.

Approach to a Smart Solution

Pods cruising in science fiction movies glide along a smooth trajectory with an invisible guideline. Advanced control technology is required to make it real, based on control algorithms dealing with multi-state non-constant parameters and magnetic actors featuring controllable forces on a larger distance.

Current EDS Maglev systems are unsuitable, because magnetic forces cannot be controlled. Current EMS Maglev systems are in principle suitable, because levitation forces can be controlled. However, they have to be improved by two core items to meet the vision of a very smooth motion in a tube.

First item is to extend the control in such a way that the position of the pod within the tube will be controlled as a whole - lateral and vertical position, pitch, roll, and yaw. Current EMS Maglev apply multiple controllers, each just controlling a local gap versus the planes along the tube as a single scalar quantity. Based on the measured gap, electromagnets are fed keeping a fail-safe distance of about 10 ± 5 mm. Future controllers have to perform a coordinated control of the pod's position in space, rather than performing a multiple gap control. The geometrical tube planes depend on the location along the tube and may vary with changing environmental conditions and long-term settlements of the ground. Therefore, the acting magnets shall not exactly follow the geometrical reference line, but an adjusted calculated reference line created by an advanced control scheme. Related techniques of model-predictive control, dynamic state observer and self-adaptation of parameters by Artificial Intelligence are subject to strong R&D activities worldwide, and Hyperloop may take benefit from it. Luckily, latest controllers provide nearly unlimited processor performance, thus allowing model-based multi-parameter control and self-adaptation to track changing parameters. The great challenge ahead lies in the approval of safety core features embedded in a complex piece of control software and a failure tolerant architecture providing perfect availability of function.

Second item is to overcome the limiting conditions of the electromagnets. With conventional materials - iron core and aluminum coils - a highly reliable gap control at about 10 mm can be achieved with reasonable use of materials at far beyond 500 km/h, if the guideway fulfils strict requirements, which are feasible but costly. Significant increase of the useful gap by 2 to 3, from 10 mm up to about 20 to 30 mm, would open great options to run advanced control strategies as outlined above. With conventional materials, either heat and power demand or weight and volume of magnets would increase exorbitantly. However, latest superconducting wires promise a feasible solution.

Superconductor Technology

Since the discovery of the oxide superconductors in 1987 the development of wires for practical applications made out of this new class of material has been a triumph of scientific insight, sophisticated processing and determined scale-up efforts. Today so-called coated conductors (CC) are readily available and have reached a high degree of quality. They offer unique possibilities to design magnets beyond the current state of the art because of their high current density, good mechanical properties and comparably low cooling requirements. CC consist of a flexible metal foil that is coated with a thin layer of the superconducting material. Several architectures were developed worldwide to achieve a high quality of the superconductor as well as to meet necessary mechanical and electrical requirements (Bauer, 2020).

An industrial approach to manufacture CCs is based on developments which started at the Technical University of Munich soon after the discovery of oxide superconductors. The architecture used is shown in Figure .

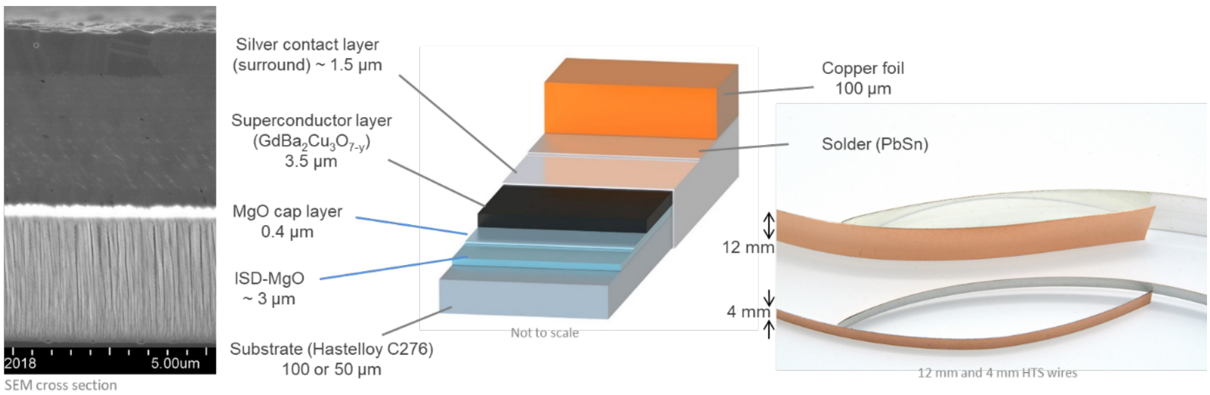

Figure 1: Architecture of the CCs developed by THEVA Dünnschichttechnik in Germany.

It consists of a flexible 50 or 100 µm thick metal foil, two buffer layers of MgO needed as diffusion barrier and to supply a nearly single crystalline orientation layer on which a 3.5 µm thick layer of the oxide superconductor Gadolinium-Barium-Copper-Oxide is deposited. Furthermore, a thin Silver coating is needed to protect and contact the superconductor. For robust industrial coil applications an additional copper foil is laminated which protects the superconductor against overcurrent or mechanical damage. This superconducting wire is now readily available in long length and large enough amounts.

Due to their unique performance coils using the CC tapes are currently developed for a wide range of applications ranging from motors and generators of many sizes (Haran, 2017) to high field magnets used for fusion. Also, for Maglev systems based on EDS CC coils were developed and already tested successfully mechanically as well as electrically (Mizuno, 2020 and Mizuno, 2018).

Already some more applications were realized in real size today. One successful example is the EcoSwing 3 MW wind power generator. Here CC coils were used in the rotor field windings of the direct drive generator to achieve a significant increase of the magnetic field strength in the airgap compared to conventional designs (Song, 2019). One of the 40 coils used in the rotor is shown in Figure. It has two layers of the CC tape with about 100 turns each. To stabilize and protect the tape a special potting process was developed. The resin used is compatible with cryogenic environment. A very similar design can also be used for Maglev applications.

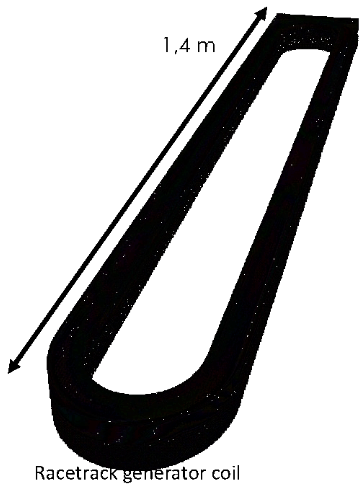

Figure 2: CC coil for a wind power generator

In order to design an application using superconducting coils, it has to be taken into account that the performance of CC wires increases with decreasing temperature and decreases with increasing magnetic field at the actual position of the wire. Furthermore, alternating currents and magnetic field components will lead to losses in the superconductor itself. A detailed electromagnetic design is therefore necessary for the superconducting coils.

Equally important is the implementation of a cooling system that can fulfill the requirements regarding operation temperature, weight, mechanical robustness as well as reliability. Choosing the operation temperature is always a compromise of as low as possible temperature for an optimal use of the superconductor and as high as possible temperature to avoid high power consumption for the cooling. Several well-developed options for cryocooling exist:

- Using the latent heat of vaporization of cryogenic fluids like liquid nitrogen is the most common for CC. It is easy to use in laboratory but the temperature rage is limited and for Hyperloop application, the gas load of the nitrogen vapor will lead to additional pumping requirements in the tube.
- An alternative is to use cryocoolers based on the sterling process or similar which are available off-the-shelf. Here the power consumption of the cooler as well as the back cooling of the warm end have to be considered.

- The connection between the cryocoolers and the coils has to be considered too. For distances up to one or two meters this can be done using copper because of its high thermal conductivity. For longer distances the cross section and weight of the copper for low enough thermal resistance will most likely rise above an acceptable limit especially for Maglev. The alternative is a liquid or gas cooling circuit. With liquid nitrogen temperatures between 65 K and 77K are easily possible and used in all superconducting high power cables. For lower temperatures Neon or He are an option, too.

Proposal for Hyperloop Application

In the following we propose a setup with superconducting magnets based on the design used for EMS levitation. In order to demonstrate the huge performance increase possible with superconducting coils we made a direct comparison using the same geometry of a levitation magnet with parameters close to the real ones.

The conventional design with 10 mm airgap is based on an aluminum coil. The current density for normal operation is limited to about 2.5 A/mm² to prevent overheating. The magnets are arranged as successive south and north poles along the track because they are also the excitation coils for the long stator linear motor. The principle cross section of this arrangement is shown in Figure together with an FEM calculation of the magnetic field. A magnetic flux density in normal (vertical) direction of about 0.7 T is calculated.

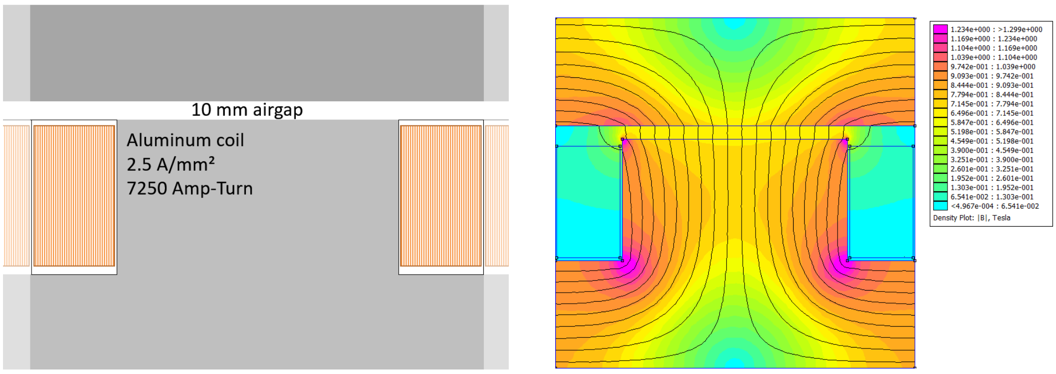

Figure 3: Conventional EMS levitation magnet arrangement with 10 mm air gap (left) and corresponding FEM calculation of the magnetic field (right).

For an identical magnet arrangement using a superconductor the current density is limited by the critical current of the superconductor at the chosen temperature and magnetic field. For the comparison we use 70 K as maximum operating temperature because subcooled liquid nitrogen could be used as cooling agent then. The distribution of the cooling power can be realized easily by pumping the liquid through copper tubes together with centralized highly efficient recooling units.

The operating current is then set to only 25% of the critical current of the CC at this temperature and magnetic field in order to have sufficient reserve for the feedback control as well as to limit the losses from alternating currents in the CC. Using today available wires will then lead to a realistic current density of 40 A/mm². As motivated above a three times larger airgap of 30 mm is assumed leading to three times higher ampere-turns for the same levitation force. In order to achieve a good thermal insulation of the coil a clear space of 20 mm is assumed around the coil to include a cryostat with good thermal insulation as well as the space for the liquid nitrogen distribution.

The resulting design is shown in Figure. It confirms that an air gap of 30 mm can be realized with a superconducting coil. Furthermore, the height of the poles can be reduced compared to conventional design reducing the weight of the magnet.

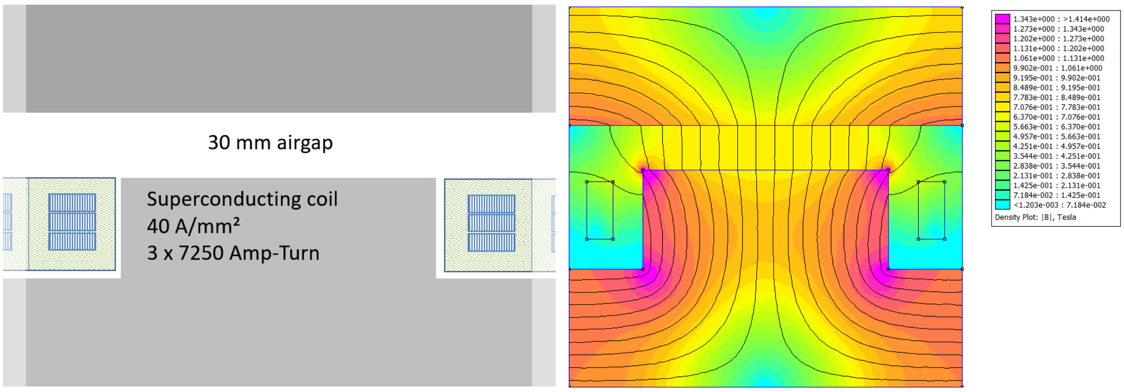

Figure 4: Superconducting levitation magnet arrangement for 30 mm air gap (right) and FEM calculations of the magnetic field (right).

For a realistic design the power for cooling has to be taken into account. In a superconducting coil arrangement, the main power consumption will be for the cryocooling as the electrical losses in the coil are negligible. We used ballpark numbers of 2 W/m² of heat input through the cryostat wall and 5% efficiency of the cryocoolers at 65K. With these numbers only about one third of the electrical power would be needed compared to the I^2R losses of the conventional coils even for a three times larger airgap.

In order to develop a superconducting magnet a detailed investigation of the optimum magnet arrangement is necessary first, which was not done for the purpose of this paper. For example, the combination of levitation magnet and long stator propulsion system may not be the optimum solution. If separate systems are used, the levitation magnet will be arranged differently, but the basic arguments given above will still hold.

For the detailed design many aspects have to be considered. For example, the combination of a sufficiently stable magnet fixation with still good thermal insulation properties will be key. Here modern 3D printing may offer preferrable solutions. AC losses in the superconductor have to be taken into account, too. In order to calculate these losses, the anisotropic properties as well as the high aspect ratio of CC have to be taken into account. This can be done using already developed codes. Of course, also efficient and reliable cryocooling has to be developed using state of the art cryocooling equipment and last but not least safety against failures of components has to be considered.

Conclusions

Hyperloop systems should ensure high ride comfort for the passenger to be attractive. On the other hand, low requirements on track alignment are necessary for cost reasons. To achieve both goals a new kind of levitation system and control taking advantage of very large air gaps enabled by superconducting magnets is proposed.

Due to the huge progress in control algorithms including artificial intelligence and todays processor performance a new kind of pod control can be developed aiming for a smooth trajectory instead of ensuring only a safe distance from the track to avoid contact as it is the case today. To ensure sufficient freedom in space for such a control strategy a significant increase of the air gap is necessary. This cannot be achieved by conventional magnet technology due to the prohibitive high electrical losses. To investigate the possibility to use superconducting magnets, a conceptual design of superconducting levitation magnets was developed taking into account efficient cooling as well as sufficient reserve in performance. It was shown that such magnets can be realized using state of the art oxide superconductor wires.

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SESSION 2

Demand & Routes

Hyperloop in Germany: Feasibility Study on the Implementation of a Hyperloop System in Germany

B.Sc. Garcia de Gortari, A.E.[1,2], B.Sc. Mayerfoels, M.M. [*,1,2], B.Sc. Loureiro, D [1,2],

B.Sc. Stark, M [1,2], Prof. Dr. Welpe, I.M. [1]

[1]Technical University of Munich

[2]NEXT Prototypes e.V.

Keywords: Demand, Routes, Costs

Introduction

Analyzing the multiple-time winner of the SpaceX Hyperloop Pod Competition, the TUM Hyperloop team, in order to understand opportunities and barriers of developing and implementing a Hyperloop system in Germany we argue that a Hyperloop system in Germany has great potential.

Based on a trend analysis of the long-distance transportation industry we found that a major driver of innovative ultra-speed transportation system is the willingness of the German Federal Government to invest in transportation infrastructure (Federal Ministry of Transport and Digital Infrastructure, 2016). In addition, this kind of investment would enable Germany to better reach its emission reduction targets, switching to more sustainable means of transport. In addition, we observed an increased preference for ground transport among the population, especially on recently opened high-speed lines, where a high level of acceptance and willingness to change to new means of transportation can be observed (Nordenholz, Winkler, & Knörr, 2017). In addition, we argue that the current status of COVID-19 crisis can have a significant effect on the development of the transportation industry in the long run and will affect the analyzed trends in the following ways: We expect demand to fall by 20 percent in 2020, but we also expect the increase in mobility to continue with a focus on high-speed in the European Union (Diemer, 2019; Frick, 2014).

The current knowledge about the operation and feasibility has so far mainly routes in the United States, Netherlands, Thailand, India, Canada among others (Gueze, 2020; Sohoni, Thomas, & Rao, 2017; Stubbing, 2020; Taylor, Hyde, & Barr, 2016). Routes as well as the market in Germany have not yet been studied except for very preliminary analyses. Costs for different routes have also been investigated and validated, but with large differences (Decker et al., 2017). This research addresses the feasibility of implementation of a hyperloop system in Germany. By doing a introspective analysis of the air and rail market revealed that the markets are dominated by Lufthansa and Deutsche Bahn respectively. This lack of competition affects the potential market entrants and also the passengers and must be closely analyzed by the TUM Hyperloop team when developing the entry strategy to establish cooperative relationships with the mentioned companies instead of creating enmities. It is widely known that the realization of infrastructure projects in Germany is quite difficult and it usually involves bureaucracy and long processes. Likewise, as it was shown in the trend analysis, the quasi-monopolistic air and rail market make it difficult for new entrants to become active competitors with a fair environment. Thus, these difficulties have to be solved through a strategy and selection of entry mode.

Our results show that, instead of focusing on cargo transportation, the Hyperloop has greater potential in passenger transport, because of its strengths in high speed, good urban integration, low noise levels, independence of weather and sustainable energy use. Hyperloop cannot prove its strengths in cargo transport as the logistic environment is high-cost and not time-driven. A first application as a cargo case could be a good starting point due to its reduced complexity and regulatory measures, and could be used as a proof of concept but for the long run passenger transport suggests a bigger potential.

A market analysis identified a transportation demand from other high-speed transport modes that Hyperloop could meet, up to 50 percent in the cases considered. Furthermore, we identified the barriers and deal breakers for a potential Hyperloop project to be similar to other large infrastructure projects such as strong citizen participation

[*] Mayerfoels, M.M.: maximilian.mayerfoels@next-prototypes.de

and bureaucratic obstacles. Finally, we identified several routes with the most promising ones being those between Munich, Berlin, Frankfurt, Dusseldorf and Hamburg.

An iterative software application developed for this study leads to fast and accurate route planning results that can be used on a worldwide scale. The routes chosen to be analyzed in this study take all cost factors under account by using algorithms to arrive at an optimal length, in terms of overall costs. This tool allows fast and accurate route planning taking into account constraints for Hyperloop such as terrain and material costs. It is a powerful and fast application software for finding the shortest route between two points on the given dataset with a cost-simulation model trying to minimize construction costs. This means that the routes obtained are already the best possible alternative to connect the cities here listed, avoiding dense forests, too many cities, challenging terrain, et cetera.

With this approach, it was possible to normalize the costs of all routes and focus entirely on economic efficiency. When comparing the system cost breakdown, for example, it became evident that longer tracks would imply a higher impact of the tube costs rather than infrastructure costs. This is probably due to the low economies of scale for the tube components when compared to the construction and civil engineering costs involved in the system's infrastructure portion. The anticipated infrastructure costs of Hyperloop are expected to be similar to other lane-based transport modes for long distance travel.

Conclusions

Since route length carries so much weight on the final cost structure of the system, the more attractive routes, in terms of use of investment, would be the ones involving high passenger demand and short distances, such as Munich - Frankfurt. The difficulties to set up a Hyperloop system might be reduced in less populated regions, as infrastructure costs could be reduced and optimal path determination, without considering a lot of shareholders, applied. As potential markets, countries which do not have an established high-speed train system are more likely to be willing to invest in a new type of transport due to the fact that upgrading an existing infrastructure does not come with compatibility problems. Hyperloop can fill the gap of high-speed and at the same time sustainable transport, which will be needed to face climate change. The team expects it as the transport mode of the 21 century that can connect intercontinental and seamlessly cities.

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Land Management Requirements and Impacts when Constructing Ultra-High-Speed and Large-Scale Transportation Infrastructure Projects such as Hyperloops

Walter T. de Vries[1*]

[1]Chair of Land Management, Department of Aerospace and Geodesy, Technical University of Munich

Keywords: Land management, Land mobilization, 8R framework of responsible land management, RRR model, Tragedy of commons, Transportation infrastructure

Introduction

The construction of large-scale transportation infrastructure projects usually requires various forms of land acquisition, land mobilisation, land consolidation and possibly relocation of citizens. Specific for large-scale and ultra-speed transportation projects, such as the hyperloop trajectories, are a variety of socio, spatial and legal requirements that accompany these transportation infrastructures, such as transit-oriented constructions and real estate, noise and pollution zones, security and access regulations, environmental impact assessments, demographic mobility profiles and socio-economic spatial development objectives. Such a complex land intervention relies on multiple land management instruments and legal-institutional frameworks of land use planning and zoning alongside the transfer, reallocation and re-registration of land rights. de Vries (2017) describes how and when such land mobilisation projects take shape and what the effects of such land mobilisation efforts are. Land mobilisation refers to processes of conversion of land rights, land interests, land values, land sizes, land claims prior, during and after a large infrastructural projects or projects of public use, public value, public means. It occurs in the form of evaluation, planning, valuing, acquiring and compensation of land. Land mobilisation is more than just a spatial legal conversion of land. In all phases of land interventions – preparation, execution and finalisation – changes in governance, legal, social, economic relations, perceptions and behaviour occur.

Land management frameworks

There are different frameworks in land management to conceptualise and assess the requirements and impacts of land interventions. All of these frameworks rely on specific tenets and assumptions and aim at both providing design and process requirements as well as normative values of institutional structures, which shape the land interventions and reach certain outcomes. One can describe the intervention of land mobilisation for large-scale transportation infrastructure projects as an instance of a land management intervention ΔLM, resulting in and relating to a combination of 6 types of changes and adaptations: Governance (ΔG); Land, property, real estate, land use Law (ΔL); Social-spatial relations (ΔS); Economic opportunities and dependencies (ΔE); Perceptions, beliefs and values (ΔP); Behavior (ΔB). In short form, any instance of land mobilisation can be described as a function of a number of changes which either occur or need to occur:

$$\Delta LM \text{ (Land Mobilisation)} = f(\Delta G, \Delta L, \Delta S, \Delta E, \Delta P, \Delta B).$$

This generic relation can be used to describe and review a number of examples of land mobilisation relevant for large-scale transportation infrastructures. Although in some cases this can be organised through existing regulatory procedures, such as the land consolidation according to §87 ('Unternehmensverfahren'), whereby acquired land can be compensated or readjusted in cash or in kind, in most cases the acquisition of rights comes together with social resistance, conflicts and unequal benefits. Hence, regardless of the type of infrastructure such reactions are common.   In this context, it is crucial to verify to verify if, when and under which conditions certain land management and property right theories and concepts make any sense. Some of these frameworks include:

The RRR model of land administration (Bennett, 2007). This model refers to the intrinsic inter-relation between property rights, restrictions and responsibilities, which exist both for the private and the public domain. One of the key tenets and backgrounds of this model is that each private land right comes with a social or public

* Corresponding author: wt.de-vries@tum.de

responsibility to take care of the property itself and to limit any damage or harmful effects to the right holders for any adjacent parcels or properties. The private right also comes along with a restriction right to exclude others (i.e. other citizens, firms, stakeholders, parties from the public) from using or accessing the property. Reversely, a public restriction secure a public good or public benefit and restricts a particular use or access of a private right. Registering private properties should therefore be extended by registering restrictions and responsibilities, which come along with the rights. The land administration domain model (LADM) foresees in this possibility (van Oosterom & Lemmen, 2015). The classes 'rights', 'restrictions' and 'responsibilities' are included in LADM as a set of classes which are connected to parties (subjects, stakeholders, right holders, communities, firms) on the one hand and geographic and legal objects on the other hand. In the case of large-scale infrastructure projects, the interplay of private rights and public restriction plays a crucial role. (Kitsakis & Dimopoulou, 2020) describe for example how to register environmental restrictions, such as environment and nature protection, water protection, spatial and land use planning zones, cultural heritage, public infrastructure corridors and zones, public easements/servitudes and mining rights. A question for large-scale infrastructure is which kinds of social and public restrictions come along with the (lack of) formal rights on objects in space. How can one enforce rights and public restrictions and how do we deal with compliance or accountability.

Specifically for countries where land rights are not fully registered the concept of the continuum of land rights is applicable. This continuum concept posits that land tenure by land occupants is not just legal or illegal, but that there is a whole spectrum in between. This spectrum makes that not just documented/registered claims on land are valid but one can also have informal/undocumented land rights/claims, which are rooted in either long-term or socially accepted occupation. Such informal rights can lead to de facto land rights or 'adverse possession'. These concepts could be relevant for discussing questions of permanent settlements on the moon or mars. Although ownership of parcels on the moon is not possible (despite the fact that some firms are actually selling these), long-term occupation may in fact lead to adverse possession – and hence ownership (with full exclusion of others /third parties). For large-scale infrastructure projects in primarily developing countries the continuum of land rights is important because land needs to be acquired from land tenants whose land is not registered. Evictions can lead to resistance of tenants with legitimate land interests and compensation claims.

The tragedy of the commons is a theory developed by (Hardin, 1968) and further expanded by (Ostrom, 1990). One of the main tenets is that if all land and natural resources belong to everybody (hence no specific ownership right or responsibility is attached), either no one will take responsibility for the public good or public benefit of the environment, or there will be free riders who benefit at the expense of others. The tragedy in both cases is then that all will suffer because the resources from the land will deplete for everybody. Such a theory would be relevant to evaluate the effects of interventions. The solution offered by Ostrom is a set of core principles, which strike a balance between open access and regulatory responsibility: 1) Clearly defined boundaries, whereby members know they were part of a group and what the group was about; 2) Proportional equivalence between benefits and costs, whereby members have to earn their benefits and couldn't just appropriate them; 3) Collective choice arrangements; 4) Monitoring;; 5) Graduated sanctions, whereby; disruptive self-serving behaviors can be detected and punished; 6) Fast and fair conflict resolution; 7) Local autonomy; 8) Appropriate relations with other tiers of rule-making authority.

The 8R framework of responsible land management provides a normative tool to design and evaluate land interventions (Walter T. de Vries & Chigbu, 2017) . This framework essentially discusses the normative question of when, how and how much land interventions can be 'responsible'. It relies on 8 aspects - responsiveness, robustness, respect, recognizibility, resilience, reliability, reflexivity, and retraceability. Such a framework would be relevant to evaluate where and why one can expect a public resistance or public support for spatial interventions.

Methodology

The analysis relies on the one hand on an interpretation and synthesis of selected relevant peer-reviewed publications which address specific impacts of particular large infrastructure (mega-)projects. Such projects include large-scale water management projects (such as dams) and the constructions of high-speed railway lines. On the other hand the analysis draws on several selected (published and unpublished) case study research works executed at TUM in the context of project study, bachelor, master or doctoral research projects. As no hyperloops already exist, one needs to rely on similar examples and comparable experiences in order to assess the most likely or potential land management requirements and impacts. Such analogies can draw on spatial, legal, economic and institutional characteristics. Spatial and legal characteristics similar to hyperloop linear designs are transnational and high-speed train trajectories, which are also structures, which requires on the one hand the mobilisation of a large volume of smaller portions of parcels along linear trajectories together with the acquisition or conversion of smaller volumes or larger portions for the stops and transits. Legally high-speed and transnational train trajectories also come with linear safety restrictions, usually buffer zones, at certain distances from the linear structures. Another type of similarity is in the project size and associated economics and financial aspects. Mega-projects such as dams, airports and bridges do not only require land, but also are likely to require similar amounts of financial and other resources as hyperloops. Alongside these financial requirements are also the effects on land and real estate properties. Often, constructions of new infrastructures, can even its design, planning phase, lead to rapid value increases and even speculation in properties adjacent, and close the newly designed structures. A last, yet important aspect from the perspective of land tenure security, concerns the social aspect. New infrastructures often lead to social resistance, evictions and relocations of people living close (or actually too close) to the new infrastructures. Security, noise and visual landscape concerns are rooted in legal spatial planning requirements. To understand and predict such impacts a comparative integrative analysis based on multiple aspects is necessary. The comparative analysis relies on a synthesis of impacts documented in similar other types of such large-scale land interventions.

Cases

Hensher, Li, and Mulley (2012) describe the impacts of new transportation infrastructures on land values. Following the theory of land rent, later described in more details in connection to transportation systems (Pászto & Pánek, 2020; Rodrigue, 2020), they posit that accessibility and accessibility potentials increase land values. Moreover, if land values increase they implicitly guide land use and land users, and ultimately who can be land right holder where. Transportation infrastructure therefore do not only require land, they also affect the spatial dynamics of land transaction and land rights, mostly without a direct control of government interference. In theory, such relations would exist for all types of transportation infrastructure. Specifically for high-speed railway an increase of property values is likely to be more significant if stations are built in an area with a greater potential to grow and where the railway project is well embedded in the growth or redevelopment strategy, such as transit oriented development initiatives. (Rungskunroch, Yang, & Kaewunruen, 2020) add, based on recent studies in China, that land prices have not increased much more as a result of the construction of additional high-speed railway lines in major cities, such as Shanghai. The reasons could be that in such cases multiple factor play a role on the land values, and not only the accessibility of locations. Chang and Murakami (2019) address the effects on land use rights by construction of high-speed railway lines. They argue that the variations in prices of land-use rights for compensational housing cannot be attributed to spatial development effects originating from the new construction of high-speed rail stations. Additionally, these variations might trigger an unfair redistribution of property rights, accessibility, and economic opportunities among relocated farmers around city-fringe areas.

Boelens, Shah, and Bruins (2019) posit that planning and constructing large dams and other mega-hydraulic infrastructure projects are manifestations of contested knowledge regimes. One could understand this in the sense that any plan or design contains a bias in line with a particular problem framing and problem solution in relation to water management and protection from water. Groups with different epistemological values and goals may not share these frames and solutions. The differences lead to a knowledge contestations and critical debates beyond the usual adversaries, such as politicians, constructors and dam-affected communities who may need to be expropriated and relocated. An additional group however include a much broader group who start to participate in the knowledge and spatial contest, namely multinational donor agencies, global policy institutes, international human rights courts, local and international civil society movements, indigenous groups, environmental Non-Governmental Organizations, media, government and bureaucratic agencies, experts and engineering schools, and independent scholars and activists. This makes the process far more complex. This is however not the only effects. There are also serious delays in decision-making, uncertainties about what is valid and trustworthy background information, and powering and politicking. In large-scale high-speed transportation infrastructures, one could expect similar contested knowledge regimes and a rapidly increasing number of stakeholders engaging in the problem framing, knowledge contest and powering games.

Ogunmuyiwa (2019) evaluated the land impacts of airports, drawing on documented evidence and interpretations using the 8R framework. Specifically this included an evaluation of the new airports Berlin Brandenburg, Milan Malpensa, Tivat Airport (Montenegro), the New Jakarta Airport, the New Istanbul Airport, New Mexico International Airport, Navi Mumbai International Airport, and Lekki International Airport. Common problems connected to the land expropriation practices for the construction of these new airports constitute illegal acquisition of land, non- monetary compensation, forceful eviction, urban sprawl, and protest. Often the affected communities and land tenants constitute farmers whose livelihood depend on the land, which is cleared. In some cases the clearing of the lands was forceful. In some cases, the authorities cut off the supply of water and electricity of land tenants who failed to comply with the eviction notice. The pressure to continue with the construction despite the possible resistance is usually political. The new airport in Jakarta, if built close to the existing airport, will need clearing of about 600 hectares of land, and if built in a further location would reclaim 2000 hectares of land. Another plan would be to reclaim 2000 hectares of land in Karawang, West Java, in a location, which is currently a nature reserves in Java. The area is a sand dune that has special functions for reducing the danger of tsunami threat, intrusion prevention or seawater infiltration to groundwater layer, and inhibit erosion of coastal land by waves. The new airport cuts across six agricultural villages and requires 645 hectares of productive land where 11501 people live and work. In short, the airport, even before its construction creates a lot of tenure insecurity for local tenants.

Additionally, (Nwankwo, 2020) used a similar approach combined with an environmental impact assessment to investigate land tenure impacts from the construction of new bridges. Changing land rights and land expropriation are common in such projects, but are not always transparent from the start of the projects. Land acquisition, improper compensation and unwanted resettlement are therefore bottlenecks and land tenure insecurity can be a direct effect. This can in turn lead to improper resettlement, illegal acquisition of land, non-monetary compensation and forceful eviction.

Discussion

The discussion relates to implications from the 3R, 8R and tragedy of commons perspective. From these perspectives one can infer and predict land management requirements and implications.

Implications from the RRR model perspective

All examples reveal that mobilisation of land to constitute the infrastructure usually requires forced expropriation by the eminent domain. Only if such forced acquisitions coincide with appropriate consultative and participatory actions and fair compensations the execution of such infrastructure plans may lead to social acceptance and legitimacy. Regarding the restrictions, most prominent are the restrictions arising from risks close to infrastructure itself and from environmental concerns. Such restrictions are, however, often not consistently part of current land administration systems. Consequently these heterogeneities in information or may lead to ineffective or inaccurate spatial monitoring and impact assessments.

Implications from the 8R framework perspective

Most critical for (ultra)high-speed transportation infrastructures in the context of the 8R framework are the aspects of responsiveness, respect and reflexivity. The urgency of the need, including long-term views of stakeholders may be questioned in a public discourse. On the other hand, the symbolic meaning of a new technology-driven solution may lead to a situation where decisions and actions are valued positively, and decision makers are seen as appropriate leaders or managers of spatial problems which the transportation infrastructures are aiming to solve. . These manifestations of respect may therefore drive the knowledge contests where are behind these decisions. A core question will therefore be at which moment in time the aspect of reflexiveness will start to play a role, and whether at regular points in time there are moments at which the rightfulness or appropriateness is re-evaluated or re-assessed.

Implications from the tragedy of commons perspective

Most apparent in the tragedy of commons perspective are the regulatory aspects, which pertain to the affected communities by any infrastructure development. Specifically for the (ultra) high-speed developments is the concern of the involvement off the collective. Pressures from politics might outweigh the proportional equivalence between benefits, costs, and choices, which are based on collective choice and local autonomy.

Conclusions

The overall impacts and implications of large-scale high-speed transportation infrastructure projects, such as hyperloops on land management are complex and diverse. The evaluation of the projects derive that hyperloop projects will have to address major concerns in how to design and control spatial land restrictions in particular.

Secondly, there needs to be a strong expectation management and control of land value increase along the trajectory of the new transportation infrastructure. Finally, from a responsible land management perspective, one can raise serious questions for both the structural and operational aspects of responsiveness, resilience and recognisability.

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Introducing Hyperloop to the UK

Katelin Donaldson[1], **Munya Mzenda**[1], Nourdin Mismar[1], Moritz Mörker[1], Brandon Henwood[1], Mercè Sánchez Oller[1], Gregory Dayao[1], Elliot Govier[1] & Stella Antonogiannaki[1]

[1]HYPED*

Keywords: Challenges to hyperloop in UK, UK regulation, Public opinion on infrastructure in the UK

Introduction

The HYPED team from The University of Edinburgh are conducting a multi-layered study into the adoptability of Hyperloop technology by the United Kingdom. One of the many aspects which has fallen into the preview of this study is to assess the extent to which the general public of the United Kingdom is ready to adopt and support the proposal of a new and revolutionary transport system. While conducting our study, we have found several key factors and concerns that the public takes into consideration when reviewing such a proposition. These concerns are founded upon the potentially adverse environmental and community life impacts of implementing a hyperloop network. Noise pollution, road traffic congestion at key hubs and the big financial burden placed upon the taxpayer are just some of these impacts. A recent major infrastructure project which has drawn a significant amount of criticism has been the government's HS2 project (the high-speed railway connecting London, the Midlands, the North). This project encapsulates not only the potential issues that may arise from the implementation of hyperloop technology, but also the motivations behind the reluctant mindset of the British public to accept this technology.

Conclusions

HS2 has shown us that having to build significant infrastructure, such as railways and hyperloop tubes, can lead to a considerable amount of backlash from the public. This is due to the fact that infrastructure links may need to criss-cross communities, carbon capturing forests and areas considered to be of natural beauty. This has, as a result, nullified the public's consideration of the long-term potential benefits to the climate that using hyperloop technology can have. Thus, giving rise to the first issue a proposal must address: How do we strategically position stations and hyperloop tubes to best mitigate disruptions? The proposal should, ideally, utilise some of the pre-existing infrastructure so as to minimise its immediate footprint and cut costs. This has the added benefit of minimising impact on communities that will not benefit from the positioning of the links and stations. We have also learnt from the development of HS2 that the public are wary of the ability of the government to adhere to timelines and complete projects on time[1]. Ill management and lack of transparency has also led to an increase in cost estimates. Additionally, the UK will need to develop regulation and appoint a government oversight body to help it navigate the implementation of new technology. This a lengthy and bureaucratic process that will also be costly.

The hyperloop system conceptualised by Elon Musk is designed to carry 120 trains of 28-seater pods each hour, thus providing a maximum capacity of 3360 passengers per hour[2]. On the other hand, HS2 will have an approximate capacity of 21000 passengers per hour[2]. This clear deficit must be addressed within the proposal, including exploring ways to increase capacity to such a level that it can cope with the high level of demand for travel in the United Kingdom. Furthermore, the future HS2 trains seem to be compatible with the existing train

* HYPED is also the corresponding author: team@hyp-ed.com
1st International Conference on Ultra-High-Speed Transportation – Research meets Industry
[1] Plimmer, G. (2019, September 03). HS2 to be delayed by up to 7 years, government admits. Retrieved from https://www.ft.com/content/02f4a330-ce3f-11e9-99a4-b5ded7a7fe3f

[2] Taylor, C. L., Hyde, D. J., & Barr, L. C. (2016). Hyperloop Commercial Feasibility Analysis: High Level Overview. 20-23. doi: https://rosap.ntl.bts.gov/view/dot/12308

network, a sizable contrast to the hyperloop pods[3]. For an effective and sufficient hyperloop system to be implemented in the UK, there would be a need for intermediate stops or branching. This, however, bears the risk of leakages, leading to potential depressurisation within the system. These issues are not to be viewed as detrimental to the livelihood of adopting such a technology, they are instead an opportunity for global stakeholders to collaborate and derive the best preventative solutions that are mutually beneficial to the development of hyperloop as a concept. This means that hurdles to hyperloop technology can be mitigated and its potential, realised. A significant factor which can tilt the scales towards a hyperloop network, is its relative ease to integrate renewable energy as an electricity source directly into its infrastructure by placing solar panels on the outer cladding of the tube. Leading to a reduction to its carbon footprint and land use. Most importantly to the public, this will have the added benefit of reducing the operating costs of such a project.

HYPED's conceptual plan is to use a hyperloop network to replace existing domestic flight routes, drawing both tourists as well as business travellers as its main users. The transformation of domestic flight networks into a hyperloop network would be extremely beneficial for the UK's target of achieving net-zero carbon emissions by the year 2050. By strategically positioning stations at different airports, we also believe that the capacity of these travel hubs will be increased. Initially, the reduction in domestic flights will lead to an increase in flight slots available for international travel. Making the UK more interconnected by facilitating a higher volume of tourism and business travel. Hubs such as London's Heathrow and Gatwick are prime examples where the integration of hyperloop can have an immediate and direct effect[4].

In conclusion, a proposal for a hyperloop system in the UK will need to balance the competing issues of a more environmentally sustainable solution with that of the interests of the general public of the UK. Taking into account the potential adverse impacts the public may suffer as a result. One of the sticking points will be that of cost. In light of the current pandemic, the government has found itself criticised for reckless spending and not investing enough into the National Health Service of the country. It is unlikely that there will be sufficient support from Members of Parliament, by power of the people, to green-light hyperloop integration. That said, the UK's dated infrastructure can benefit greatly from hyperloop technology.

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Understanding the Factors Influencing the Acceptance of Hyperloop Systems

Md. Ashraful Islam*, Christelle Al Haddad, Mohamed Abouelela, Constantinos Antoniou

Chair of Transportation Systems Engineering, Technical University of Munich, Arcisstrasse 21, 80333 Munich, Germany

Keywords: Hyperloop, Acceptance, Stated preference, Discrete choice modeling, Factor analysis

Introduction

Hyperloop is a proposed transportation mode for passengers and freight transportation. The name "Hyperloop" and the concept was first publicly mentioned by Elon Musk in 2012 (Covell, 2017; Gkoumas & Christou, 2020; Janic, 2018; Matteo, 2018; Pérez, 2018). Hyperloop is described as a sealed vacuum tube where a pod or capsule may travel substantially free of air resistance or friction due to low air pressure (Hansen, 2020; Janić, 2020; Musk, 2013). Few studies (Goddard, 2016; Janić, 2020; Musk, 2013; Van Goeverden et al., 2018) stated that Hyperloop systems can potentially convey passengers at hypersonic speeds while being more convenient and energy-efficient than existing transportation modes. According to some researchers, Hyperloop is considered as the fifth mode of transportation after planes, trains, cars, and boats, which would be faster, immune to weather, environmentally friendly, and resistant to earthquakes (González-González & Nogués, 2017; Musk, 2013).

According to Hyperloop Transportation Technologies (HTT), Hyperloop operates on the same fundamental principle as airplanes, but it is much faster and energy-efficient, environmentally friendly, and aligned with sustainable development goals (SDGs) 7-10, 11 (HyperloopTT, 2020; Planing et al., 2020; Rajendran & Harper, 2020; Taylor et al., 2016); it makes more economic sense than traditional transportation (Chandran & Fujita, 2017; HyperloopTT, 2020). Hyperloop will be considered the most advanced technology in the transportation field and will create a massive shift in human inventiveness (Bradley, 2016; HyperloopTT, 2020). Whether now or 30 years in the future, Hyperloop may bring powerful and auspicious opportunities for society and the environment (Antoniou, 2018). Moreover, some researchers believe that Hyperloop systems will accelerate economic growth (Marshall, 2019; MORPC, 2020; Pączek, 2017) and enhance the connectivity between cities and become a game-changer tool for intercity mobility (Decker, 2017; Schenker, 2019). The recent rapid studies on Hyperloop research funded by the private and public sectors and feasibility studies of commercial routes in different countries have generated enormous expectations in the performance of this transport technology (Bordone, 2018).

Many consider Hyperloop to be one of the most promising technologies in transportation to date (Alves, 2020; Antoniou, 2018). According to Hyperloop Alpha white paper, Virgin Hyperloop, and Hyperloop Transportation Technologies (HTT), Hyperloop can travel with a maximum speed ranging between 1000 km/hr and 1200 km/hr, with fewer emissions and noise, compared to other high-speed modes, namely high-speed train, and jets (Goddard, 2016; HyperloopTT, 2020). Since Hyperloop deployments do not exist yet, and as to the best of the authors' knowledge research around its acceptance is limited, it would be crucial to understand user perceptions towards it.

This research intends to gain insights into the differentiation of users' preferences between Hyperloop and other high-speed transportation modes in Germany. Service attributes and users' sociodemographic characteristics that may affect the system's acceptance will also be identified.

In this study, we designed and collected stated preference (SP) data to address the users' acceptance by answering two main questions that would help in the future systems development and implementation process:

- What are the factors affecting the choice between Hyperloop and competing modes, namely high-speed train and air?
- What are the factors affecting the acceptance and adoption of the Hyperloop system?

* Corresponding author: ashraful.islam@tum.de

Methodology

A stated preference survey including a stated choice experiment was designed and used for the elicitation of the acceptance parameters for this study. The survey also covers a wide range of acceptance-related questions, including reasons, concerns, willingness to use the technology, expectations, users' usual commute and travel patterns, and their socio-demographics. The online SP survey is being completed from respondents in Munich and other cities in Germany during the period of mid-January to February 2021.

One of the routes that are expected to be popular and busy (Munich - Berlin) (Welle, 2018) was chosen for the design of the stated choice experiment. Since the number of transportation modes between Munich and Berlin contains many alternatives, it is crucial to select the most viable alternatives. Thus, high-speed train and flight were included as relatively comparable alternatives in the stated choice experiment.

The attributes included in the stated choice experiment were travel time (including access time, egress time, and waiting time), travel cost, safety level, and daily frequency of the different modes. These attributes were defined based on relevant literature for experimental design (travel time, travel cost, frequency - ± 30% of the current state; safety – 2x and 4x of the current state of driving) to specify each of the three alternatives transport modes. The attribute levels are described as follows:

Total travel time (min) - defined as the door-to-door travel time, including the access, egress, and waiting time at the station/airport: Hyperloop (100, 140, 180); high-speed train (230, 310, 390); flight (180, 250, 320).

Total travel cost (€) - indicates the monetary cost (ticket cost) for the trip: Hyperloop (46, 69, 92); high-speed train (46, 69, 92); flight (90, 140, 190).

Safety level (in terms of driving safety level) - denotes the likelihood of having an incident: Hyperloop (driving safety level, 2x more safety, 4x more safety); high-speed train (driving safety level, 2x more safety, 4x more safety); flight (driving safety level, 2x more safety, 4x more safety).

Frequency of the service per day (every hr/min) - indicates the number of trips per day between the origin and destination: Hyperloop (5 min, 10 min, 15 min); high-speed train (3 hr, 4hr, 5hr); flight (3 hr, 4hr, 5hr).

The survey was structured into four parts: basic questions about transport mode and long-distance trip; Hyperloop and technological concerns; stated choices scenario; personality and demographical questions. Ten choice sets were created for each hypothetical scenario (ten scenarios) using a randomized experimental design with a minimal overlap principle.

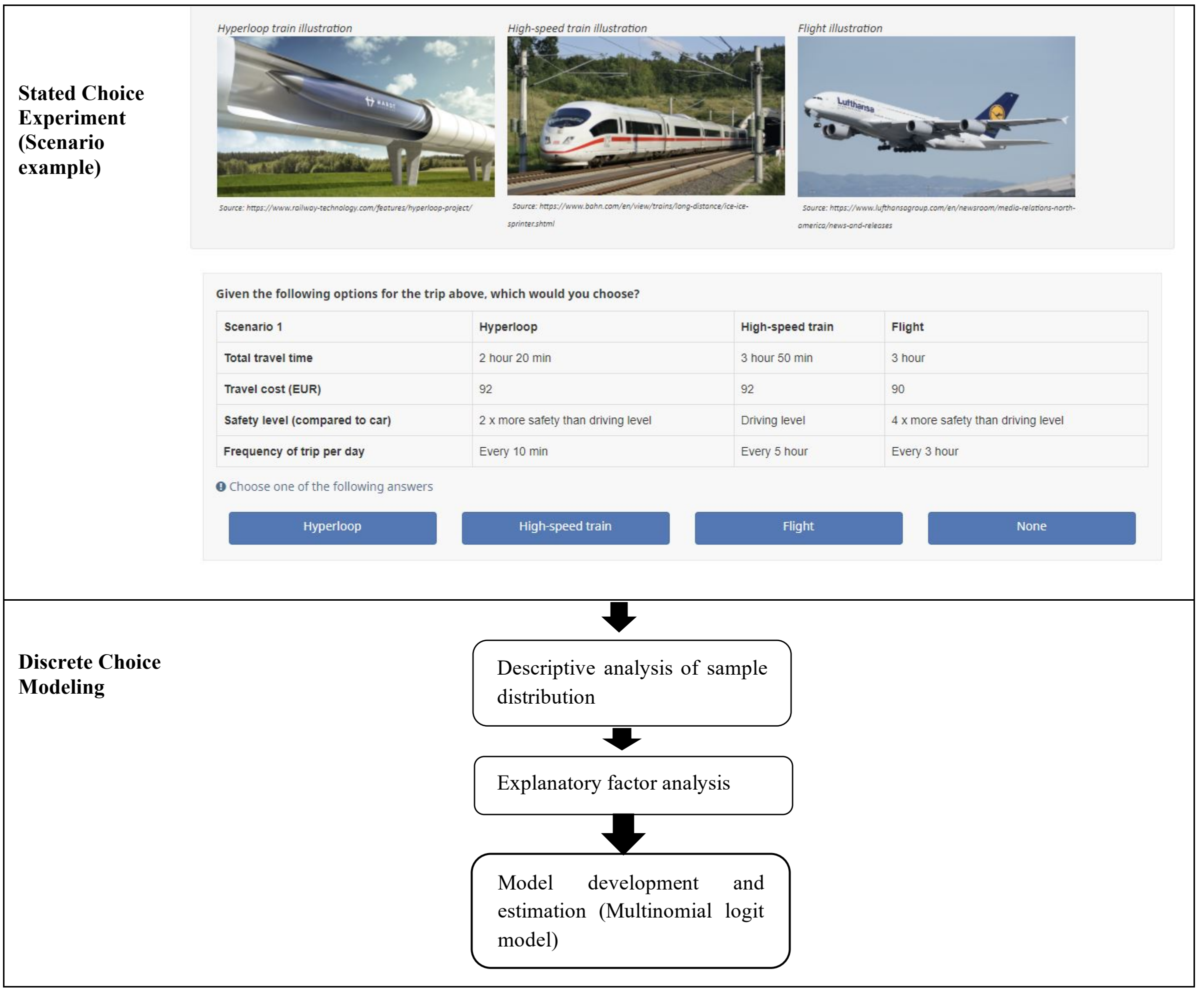

Figure 1. Methodological framework

Preliminary results

At the time of submission of the extended abstract, the survey had generated N=194 responses, with most respondents residing in Germany (70%) and in mostly Munich (54%). The sample overrepresents younger and higher educated respondents, possibly due to the online survey dissemination. Most respondents stated car (32%)(∈ N) and high-speed train (31%) (∈ N)) as the main mode of transport for long-distance travel (>400 km). Each of the 194 respondents completed ten choice tasks. Therefore, 1940 choices were observed based on the combined dataset. Hyperloop was chosen in 62%, high-speed train in 25%, flight in 9%, and None in 4% of all observed choices.

The majority of respondents (70%) (∈ N) stated that they had heard about Hyperloop technology prior to the study, out of which 9% claimed to have a deeper understanding of Hyperloop systems, whereas 30% people had no prior knowledge about Hyperloop system. Respondents were asked whether they believed that Hyperloop would be successful in Germany. Interestingly, the majority of respondents (61%) believed that Hyperloop would be successful in Germany.

Among the 194 respondents, 34% of respondents stated that they would adopt Hyperloop in the 1st year of its implementation, followed by 31%, 6% adopting Hyperloop during every subsequent two years of implementation. Only 3 % claimed that they would never use Hyperloop due to safety concerns. A preliminary analysis of different demographics' attitudes with different adoption intentions is illustrated in figure 2.

A summary of the sample characteristics and a comparison between the research sample and census data, and some statistics about average household income, age, education, and modal split are illustrated in Table 1.

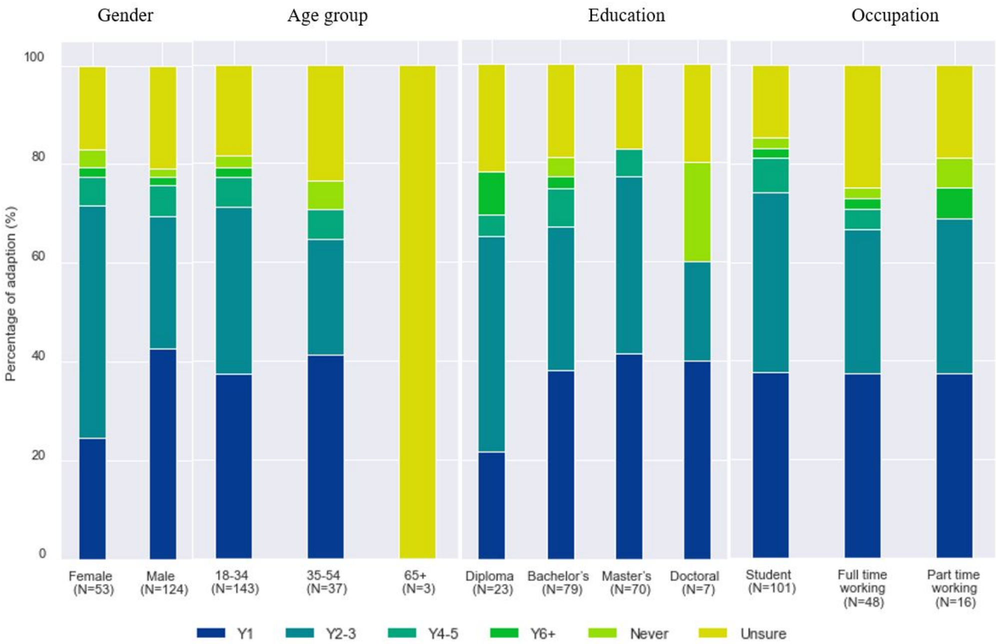

Figure 2. Hyperloop adoption by different demographics

Ongoing work and Conclusion

A descriptive analysis was performed to understand the sample distribution and the stated adoption of different demographics. The obtained data will be evaluated using factor analysis to explore users' perceptions and attitudes. Discrete choice models (multinomial logit models) will also be specified and estimated using exploratory factor analysis to investigate the mode choice behavior and willingness to pay for the different modes in question and the critical factors that influence the Hyperloop acceptance.

Since this is a stated preference (SP) survey, some statements might be biased. The online dissemination of the survey is a limitation of the sampling approach, might influence the results, and lower the population's representativeness. This study's key challenge is that most people are not fully aware of the Hyperloop technology and its development, advantages, and disadvantages. The summarized results will help to understand the overall perceptions concerning the Hyperloop. The findings will provide meaningful insights for researchers and policymakers for future research and roadmaps for early implementation.

Table 1: Summary of sample characteristics.

		Total sample (N=194) %	Munich subsample (N = 106) %	Munich Census (2011) %
Gender	Female	27.2	28.9	48.6
	Male	68.6	67.7	51.4
	Prefer not to answer	4.2	3.3	-
Age	0–17	0	0	
	18–24	38.5	24.6	9.2
	25–34	45.2	59.5	21.7
	35- 44	5.7	9.0	22.4
	45–54	2.6	3.3	22.2
	55–64	0.6	1.1	16.8
	65+	1.1	1.7	7.7
	Prefer not to answer	1.6	0.8	
Main occupation	Full time employed	28.6	26.4	87.1
	Part-time employed	8.2	12.3	
	Student	51.7	52.0	2.9
	Unemployed	1.6	1.6	2.2
	Self-employed	3.6	2.4	7.8
	Retired	1.1	1.7	-
	Prefer not to answer	2.1	0.8	-
Education	High School	11.8	14.8	34.1
	Apprenticeship	0.6	0.8	40.7
	Bachelor	40.6	33.0	22.7
	Master	35.8	45.45	
	Doctorate	2.6	3.3	2.5
	Prefer not to answer	3.6	0.8	
Household income	<500 €	7.6	9.0	
	500–1000 €	24.6	31.4	
	1000–2000 €	12.8	14.8	
	2000–3000 €	8.7	11.5	
	3000–4000 €	4.6	6.6	
	4000–5000 €	2.1	2.5	
	5000–6000 €	2.2	2.4	
	6000–7000 €	1.1	1.0	
	>7000 €	3.1	3.3	
	Prefer not to answer	28.2	17.2	
Main transport mode for long-distance	Bus	17.5	14.8	
	Car	31.8	20.6	
	Flight	17.4	20.7	
	High-speed train	30.5	41.3	
	Ridesharing	0.6	0.9	
	Other	2.1	1.7	

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SESSION 3

System Concepts

Comparison of Technical Design Options for a Hyperloop System

Domenik Radeck[*, 1, 2, 3], Agnes Jocher[1], Thomas Hamacher[2]

[1]Department of Aerospace and Geodesy, Technical University of Munich, 82024 Taufkirchen/Ottobrunn, Germany

[2]Department of Electrical and Computer Engineering, Technical University of Munich, 85748 Garching, Germany

[3]NEXT Prototypes e.V., 85748 Garching, Germany

Keywords: Hyperloop, Concept Evaluation, Propulsion, Suspension, Energy Transmission

Introduction

Around the world, efforts are increasing in the development of ground based Ultra-High-Speed Transportation Systems as a future proof solution. The vision of connecting metropolitan areas with the speed of planes, the throughput of subways and the ecological footprint of trains is inspiring engineers and researchers in many countries. Especially, the term Hyperloop is widely spread in this context. However, in contrast to the use case, the technical solution for a Pod moving in an evacuated Tube is not yet clearly defined.

This work investigates different technical implementation options for a Hyperloop system with a special focus on power supply, propulsion and suspension. An extensive literature review was conducted, including the technical concepts of the major Hyperloop players as well as past and present concepts in the area of magnetically levitating trains. Additionally, the experience made by the TUM Hyperloop student initiative during years of work with the Hyperloop topic were exploited. By means of a structured approach the different design options are comprehensively explained. Advantages that arise from the combination and arrangement of the partial solutions are discussed. A top-level overview is given in the following paragraphs.

Power Supply

One of the major challenges for the Hyperloop system is the supply of power to the moving Pod. In particular, in order to propel the Pod megawatts of power are required (Schach, Jehle, & Naumann, 2006).

As shown in Figure, the power can be stored inside the moving Pod as fuel or electrically in a battery or a supercapacitor. But only fuel is expected to have an energy density sufficient to supply propulsion power to an Ultra-High-Speed Transportation System, which is not considered sustainable. On the other hand it is possible not to store but to transfer the power to the moving Pod. This can be realized wireless via inductive power transfer, a linear generator or a long stator propulsion system. Inductive power supply features magnetic field coupling to transfer power wireless (Zheng, 2005). A linear generator creates a braking force and therefore converts part of the propulsion power into electrical power available onboard the moving Pod (Farrok, Guo, Zhu, & Xu, 2018). A long stator propulsion system means that the pod is wirelessly dragged by a traveling magnetic field created from the active part of a linear motor. Here, the only way of supplying power for the propulsion system is considered to be a long stator propulsion system with the active part in the Tube. Also, a contact connection, like a pantograph stops working at about 400 km/h (STEMMANN-TECHNIK, 2012).

* Corresponding author: domenik.radeck@tum.de

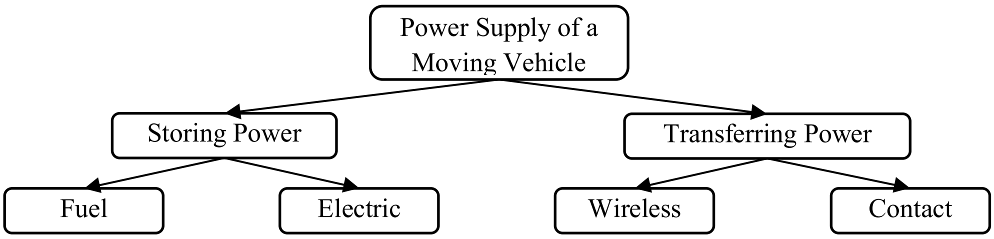

Figure 1: Overview of potential options for supplying power to a Hyperloop Pod

Propulsion

Efficient and sustainable propulsion together with regenerative braking are core elements of the Hyperloop system. A proven concept for propulsion is the rotational motor in combination with a wheeled suspension like in trains. In Figure is shown that electromagnetic propulsion systems are also applicable. They promise a wear free operation. A distinction must be made between a linear synchronous motor and a linear induction motor. The linear synchronous motor features a strong static magnetic field created by permanent magnets or (superconductive) coils and a traveling magnetic field on Tube side. On the other hand, the linear induction motor features a similar traveling magnetic field in the track but an electrically conductive material in the Pod. Theoretically also an aerodynamic propulsion system like in airplanes is possible. But like for a mechanic propulsion system the power supply is problematic if fuels are to be prevented.

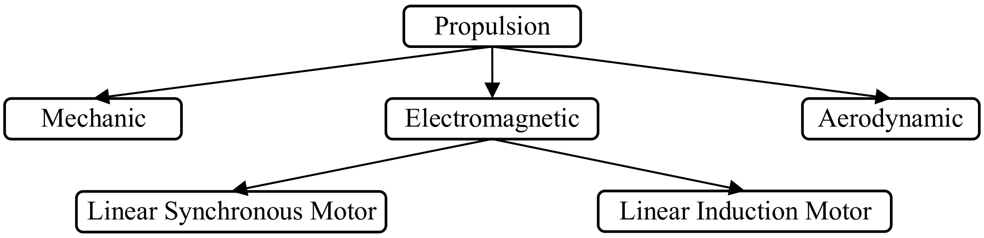

Figure 2: Overview of potential options for a Hyperloop propulsion system

Suspension

For the suspension of the fast moving Pods several options are available. Figure shows that the Pods can be suspended mechanically by wheels. This is simple and therefore cheap during investment but can be, because of the wear, more expensive during operation (Xue, 2014). A magnetic levitation system can be realized in various ways. Most important are the electromagnetic and the electrodynamic suspension system. For the electromagnetic systems the gap between a coil and a ferromagnetic material is measured and actively controlled. In the electrodynamic system the relative movement between a static magnetic field and an electrically conductive surface creates a lift force. In contrast to the electromagnetic system the electrodynamic system is passively stable but the dampening of vibrations is more complicated. An aerodynamic suspension can be realized by air bearings or wings. The first comes with very small air gaps and the latter with large, necessary wing areas. Therefore, aerodynamic suspensions are theoretically possible but not sensible for the Hyperloop application (Chaidez, 2019).

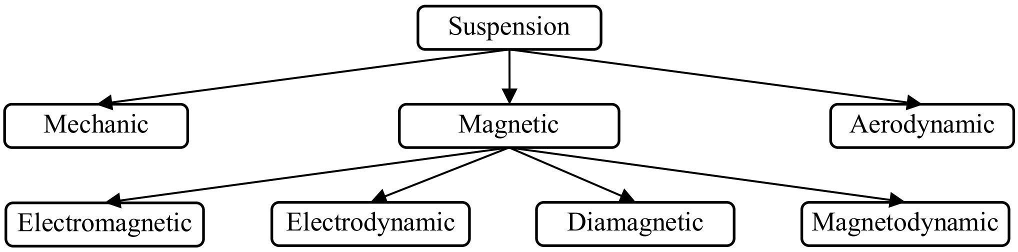

Figure 3: Overview of potential options for a Hyperloop suspension system

Conclusions

The presented set of technical design options for an Ultra-High-Speed Transportation System is meant to comprehensively explain various technical concepts the Hyperloop idea is based on. The set can be used to compose an optimal concept for predefined requirements. The work shows that those requirements strongly influence the concept design (BMJV, 2005). A focus on either safety, costs, passenger comfort, lane switching, or speed can lead to considerably different systems.

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Unsteady Flow Investigation of a UHSGT Vehicle Driving through an Enclosed Environment

F. Guerrero[*,1,2], R. Andrade[2], C. Reinbold [1], N. Wagner [1,2], L. Csilik [1,2]

[1] Technical University of Munich

[2] NEXT Prototypes e.V.

Keywords: Ultra-high-speed ground transportation, Hyperloop, UHSGT fluid dynamics, shockwave development, choked flow, unsteady aerodynamic drag

Introduction

An ultra-high-speed ground transportation concept shall be understood as a series of magnetic levitation vehicles (pods) that travel at transonic speed through an enclosed environment. The enclosed environment consists of an air-tight closed network of tubes in which the fluid density is sensibly lower than the atmospheric air.

The required technical complexity of the system to reach transonic speeds and the necessary initial investment to build a network of air-tight tubes are some of the main factors that define the feasibility of the system. The increase in infrastructure costs, in comparison with air or high-speed rail travel, means that the operational costs must be reduced significantly, by accordingly decreasing the aerodynamic resistance of the vehicles, for the concept to be a competitive mode of transportation.

It is necessary to find a trade-off between infrastructure costs, mainly driven by the cross-section of the tube, and operational costs, driven by the tube pressure and the pod velocity. To this end, a detailed investigation of the fluid phenomena is necessary. Literature and research in the area of UHSGT aerodynamics are still scarce. An analog topic, which has been investigated since the second half of the 20th century, is the behavior of high-speed trains crossing tunnels. However, these phenomena are not only difficult to analyze analytically but also computationally expensive to simulate with numerical methods or experimental techniques due to their intrinsic unsteady nature and the long domains in which they operate (Sajben, 1971). Moreover, the higher velocities and blockage ratios aimed for a UHSGT system, in comparison with railways, emphasize friction and compressibility effects and significantly increase the complexity of the flow.

This work describes the most relevant UHSGT flow phenomena by extensive literature review, analytical deductions, and qualitative numerical analysis. The unsteady aerodynamic drag of a simplified pod, as well as the fluid behavior in the near and far-flow fields, are discussed. Moreover, the flow regions and limits are presented.

Numerical Model

Kenner et al (2017) found the optimal range of tube pressures between 1 $mbar$ and 10 $mbar$ for dry air. For this operational range, the Knudsen number is low enough for the flow to be treated as a continuum. Therefore, the results presented in this work are supported by numerical analysis of the Navier-Stokes equations. The flow generated by a UHSGT vehicle is simulated in a 2D axisymmetric low-pressure environment. A pod moves rightward through the tube with the sigmoid velocity profile $v_b(t)$ presented in Equation 1.

$$v_b(t) = v_{b_{max}} \cdot \frac{1}{1 + e^{(-7t+5)}} \tag{1}$$

A dynamic mesh approach with overset interfaces is taken to simulate the actual movement of the body and investigate the unsteady behavior of the flow. The domain is presented in Figure 1. It consists of a simplified blunt body, formed by a cylindrical middle section of radius R_b and length L_b, and two semi-ellipsoids for the nose and tail. L_{nose} and L_{tail} define the semi-major axes of the ellipsoids. The vehicle is placed along the tube center-line. The tube is also cylindrical with a radius R_T. The computational effort constrains the length of the tube. A specific

[*] Francisco Guerrero: franciscojavier.guerrero-gonzalez@tum.de
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length $L_u = 200\ m$ is defined upstream the vehicle and $L_d = 1500\ m$ downstream. From Figure 1, the blockage ratio can be defined as $\varphi = {R_b}^2/{R_T}^2$.

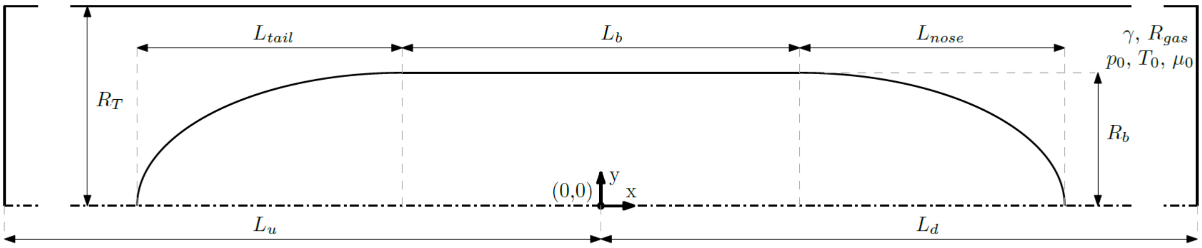

Figure 1: Schematic Domain

The fluid in the tube is considered as a thermally and calorically diatomic perfect gas with a dynamic viscosity $\mu_0 = 1.79 \cdot 10^{-5}\ \frac{kg}{m \cdot s}$, specific heat ratio $\gamma = 1.4$ and specific gas constant $R_{gas} = 286.9\ \frac{J}{kg \cdot K}$. Initially, the fluid is at rest with a pressure $p_0 = 1000\ Pa$ and temperature $T_0 = 300\ K$. A fully turbulent flow is assumed for the whole simulation. At the vehicle and tube walls, no-slip boundary conditions are imposed. The downstream inlet is also treated as a no-slip wall. The upstream boundary is defined as a pressure outlet. The vehicle and tube walls are assumed as adiabatic, neglecting heat transfer effects along the domain.

A baseline geometry based on a possible UHSGT system design is used in this work to investigate the UHSGT flow phenomena. For the pod, $R_b = 1.25\ m$ and $L_b = 25\ m$. The nose and tail lengths are chosen in agreement with the findings of Mossi (1999). He reports that for the Swissmetro vehicle configuration the drag has a minimum for an 8 m long tail for various blockage ratios and a driving velocity of 100 m/s. In this work $L_{nose} = L_{tail} = 7.5\ m$. The blockage ratio is $\varphi = 0.6$.

Unsteady Flow Behavior

Figure 2 shows how the unsteady flow phenomena around a UHSGT pod evolve with increasing vehicle velocities. At t_0, the vehicle stands still in the middle of the tube. It starts moving rightward with a certain velocity profile at t_1. In front of the body, wavelets propagate along the tube with the local speed of sound relative to the fluid they are crossing. These wavelets are generated by the accelerating vehicle compression work that is introduced in the stream. Furthermore, the flow accelerates in the vicinity of the body nose due to the convergent cross-section variation. It moves along the annular part of the vehicle length until it reaches the tail, where it decelerates due to the still subsonic behavior of the flow and the divergent cross-section variation. The same principles that propagate compression wavelets forward propagate expansion wavelets from the body tail in the opposite direction. However, these rarefaction wavelets become less steep over time and end dissipating in the far flow-field.

At t_2, when the vehicle velocity has increased enough, two phenomena are observable. The compression waves closer to the body have higher pressure and temperature values than those further away from the body. The waves closer to the vehicle have, therefore, a higher traveling speed of sound and tend to overtake those further away. When the vehicle acceleration is low, the needed distance for all wavelets to collapse onto a shockwave might be large. This is the case for a UHSGT passenger system due to comfort constraints. It might happen that the wavelets merge close enough to each other to cause steep gradients in the fluid properties but not close enough to form a single discontinuity and that these stream conditions exist for a significantly long time. A large amount of the fluid would have an entropy between the one of the earlier isentropically compressed gas and the later shock compressed gas. The analysis of this flow becomes harder as unsteadiness, viscosity, and heat conduction come into play. Neither the isentropic unsteady simple wave equations nor the steady shockwave equations apply (Mann, 1970).

The second observable phenomenon at t_2 is the flow choking in the annular section when the Mach number of the fluid relative to the fixed vehicle frame of reference reaches unity. The reduced mass flow through the annular section becomes fixed. After this point, a normal steady shockwave appears at the beginning of the tail. Although both phenomena represented at t_2 are independent of one another, which one happens first is highly dependent on the acceleration profile. It might be possible that steep gradients in the fluid properties in front of the vehicle appear before the flow chokes. However, for usual UHSGT accelerations, the flow is already choked when a highly non-isentropic fluid state appears in the far flow-field.

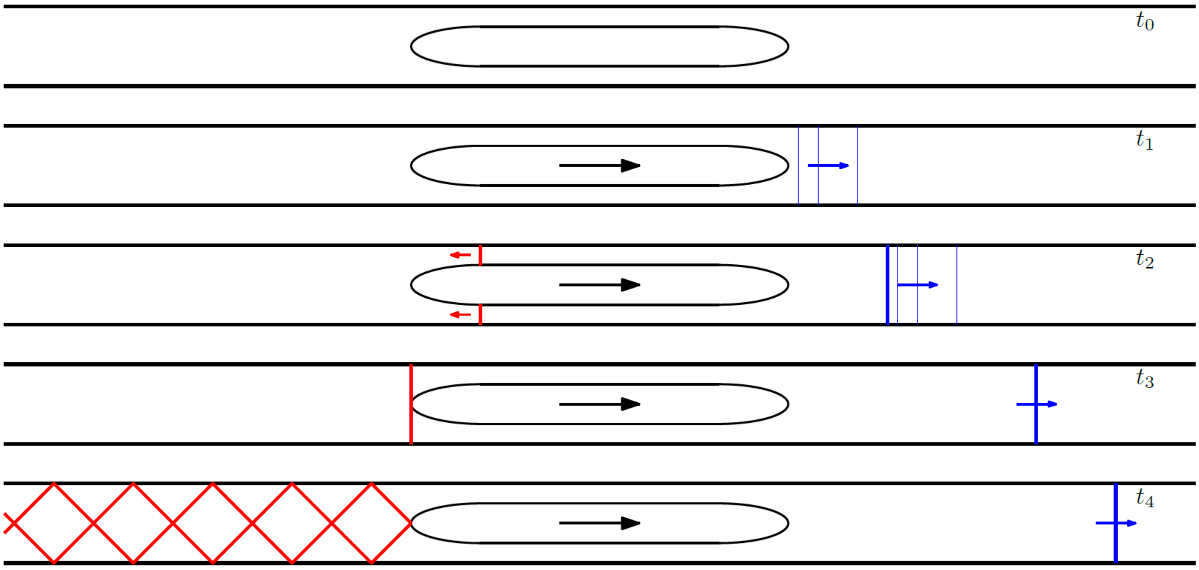

Figure 2: Schematic unsteady flow development around a UHSGT pod

At t_3, as velocity increases further, so does the pressure difference between the vehicle nose and tail, forcing the normal shockwave to move toward the tail-end. The static pressure in front of the vehicle keeps rising as more compression work is introduced into the flow and the complex entropy state of the fluid develops further.

At t_4, the shockwave has reached the end of the body tail caused by the excessive pressure difference between both sides. The shockwave detaches from the tail and reflects against the tube walls and against itself, creating the so-called diamond pattern. As the reflections propagate further away from the vehicle, they lose strength and dissipate with distance due to turbulent shear at the discontinuities.

The regions described in Figure 2 influence the behavior of the pod aerodynamic drag. A simulation is run for the baseline geometry up to a maximum pod velocity $v_{b_{max}} = 550\ m/s$ to visualize this behavior (Figure 3). When the vehicle velocity is low, the flow around the body remains subsonic. Under the choked flow limit, the drag rises quasi-quadratically with the vehicle velocity. At $v_b = 130\ m/s$ the flow chokes. This value has been determined numerically when the Mach number at the end of the annular section reaches sonic conditions in the vehicle fixed frame of reference. It is observable, both for the pressure and skin-friction drag, that behavior changes its tendency to a quasi-linear increase after the flow choking. Already at $v_b = 130\ m/s$, the skin-friction drag represents only 10% of the total drag due to the dominance of compressibility effects over the choked flow limit. The pressure difference between the nose and the tail is more important than the viscous effects on the walls. If the velocity increases further, the normal shockwave at the vehicle tail detaches. For the studied case, it happens at $v_b = 300\ m/s$. At this point, the drag increases faster again, as it did under the choked flow limit.

Traveling over the Choked Flow Limit

Some of the most relevant UHSGT aerodynamics research has been done under the umbrella of the Swissmetro Project (Jufer and Cassat, 2010). The focus of this work was set under the choked flow limit, studying concepts with blockage ratios and maximum pod velocities of 0.4 and 400km/h, respectively.

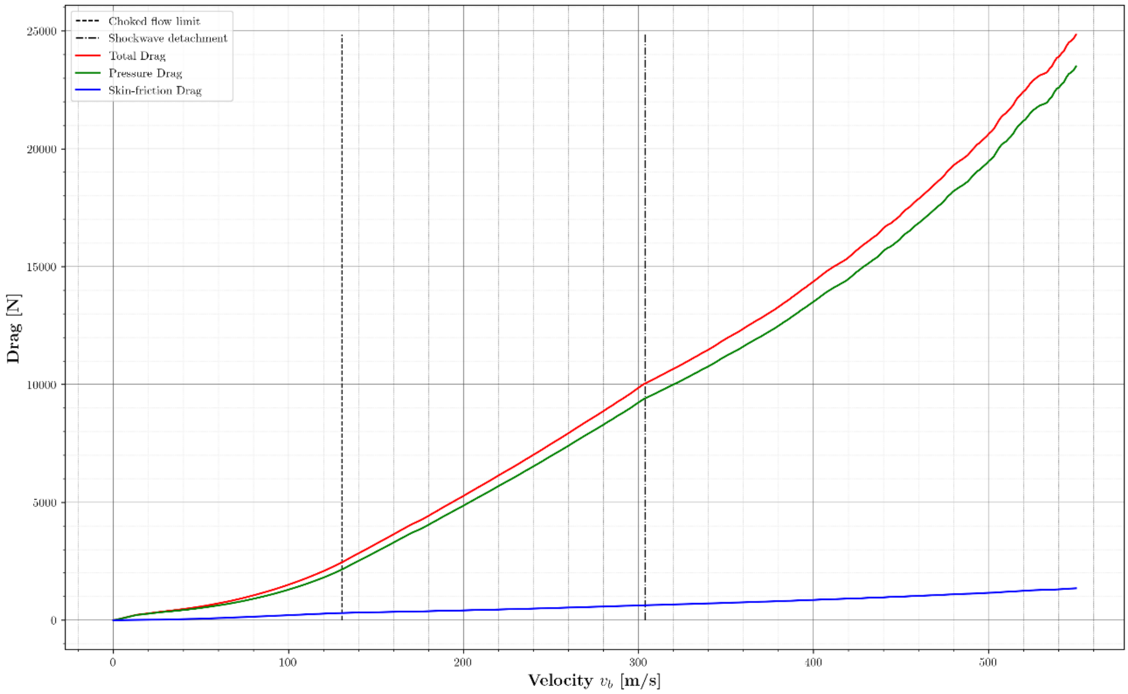

Figure 3: Effect of pod velocity on the aerodynamic drag

However, the higher infrastructure costs and traveling speeds of UHSGT systems in comparison with traditional modes of ground transportation tend to favor concept designs with significantly higher blockage ratios. This means that the flow chokes earlier and that, if no active flow bypass systems, such as a compressor, are included in the front of the vehicle, traveling over the choked flow limit might be required to make the system feasible. As no main focus has been put on driving over the choked flow limit, the literature on its complex unsteady, turbulent, and compressible behavior is still scarce.

Two critical behaviors are found when driving over the choked flow limit. The temperature distribution along the tube is presented in Figure 4. Three simulations of the baseline geometry, in this case with a blockage ratio $\varphi = 0.8$ and a $v_{b_{max}}$ of 80, 125, and 200 m/s, have been performed.

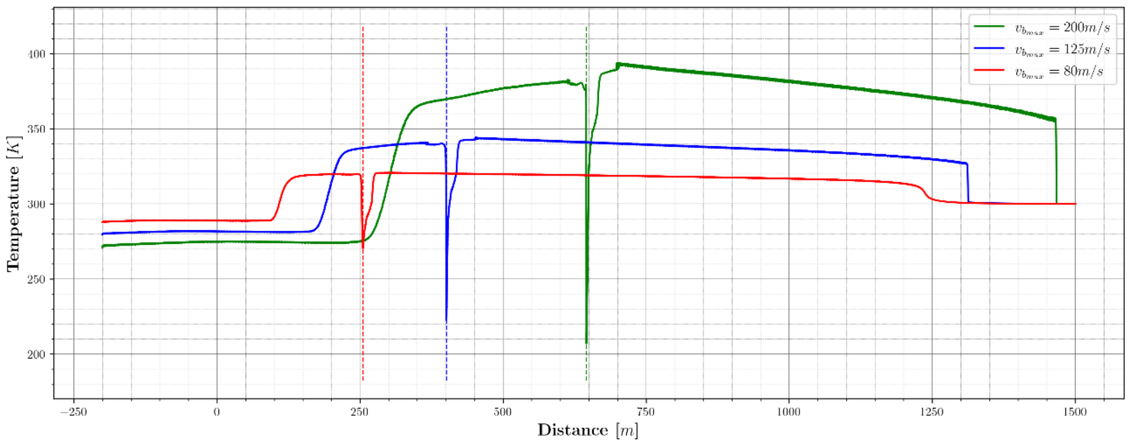

Figure 4: Temperature field distribution along the domain over the choked flow limit. Vehicle position for each studied case (-----).

The temperature in the unperturbed far flow-field remains at 300 K. However, for the $v_{b_{max}} = 200\ m/s$ and $v_{b_{max}} = 125\ m/s$ cases, a discontinuity in the temperature field is already present at x = $1470\ m$ and x = $1315\ m$, respectively. For $v_{b_{max}} = 80\ m/s$ the shockwave is not fully developed. Friction effects along the tube walls produce a further temperature increase along the tube. In the near flow-field, due to the supersonic expansion across the normal steady shockwave at the pod tail, the temperature around the vehicle drops. This drop is more significant the higher the velocity, as the strength of the shockwave increases. For $v_{b_{max}} = 200\,m/s$, the temperature drop reaches almost 200 *K*. This phenomenon, and the accelerated fluid speed of the annular section can help the vehicle cooling by transferring the generated heat through convection into the tube walls. However, it has to be mentioned that the convective heat transfer coefficient of the gas is reduced significantly when the environment pressure decreases. Moreover, the transient thermal loads generated might affect the infrastructure and vehicle integrity.

The second critical behavior found over the choked flow limit is the unsteadiness of the drag for constant driving velocities. Driving at a constant speed reduces the inertia resistance and the energy consumption of the system. Therefore, it is relevant to investigate how the drag behaves when the vehicle stops accelerating and drives constantly at a certain velocity $v_{b_{max}}$. To this end, six simulations are performed using the baseline geometry. The velocity profile follows Equation 1 with $v_{b_{max}}$ equal to 50, 100, 175, 250, 350 and 550 *m/s*. Figure 5 shows how the maximum pod velocity affects the temporal evolution of the total aerodynamic drag. From t = 1.5 *s* the vehicle velocity remains constant. For these cases, the flow chokes at $v_b = 130\,m/s$.

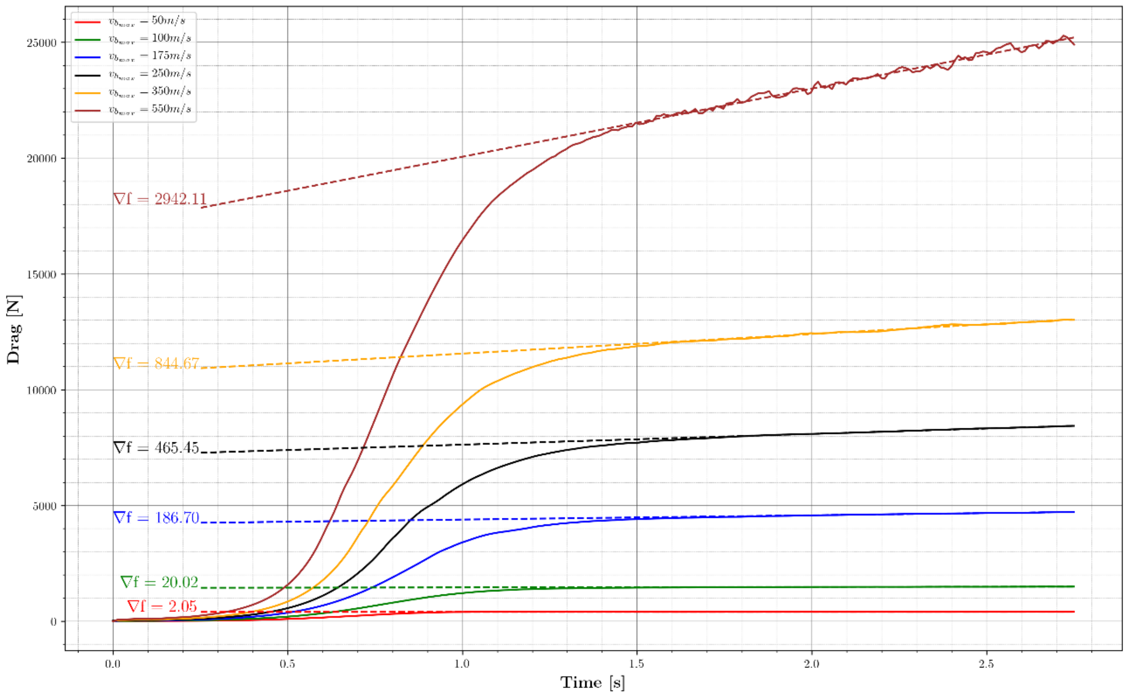

Figure 5: Effect of the maximum pod velocity on the temporal evolution of the total aerodynamic drag

It is observable that even if the vehicle stops accelerating (t > 1.5 *s*), the aerodynamic drag increases linearly with time. The slope of the linear increase is plotted for each $v_{b_{max}}$. Over the choked flow limit ($v_b > 130\,m/s$), the fluid properties in front of the pod do not remain constant when the body stops accelerating due to friction effects on the tube walls. On the contrary, at the body tail, the expansion wave strength is maintained. Therefore, the pressure difference between the nose and the tail rises. This pressure difference is the driving factor that determines the intensity of the aerodynamic drag. It is visible that the further over the choked flow limit the pod drives, the steeper the drag gradient becomes.

Under the choked flow limit, for $v_{b_{max}} = 50\,m/s$ or $v_{b_{max}} = 100\,m/s$ the drag increase is positive. However, a second geometry where $\varphi = 0.8$ and $v_{b_{max}} = 25\,m/s$ has been investigated. For this case, the slope was negative ($\nabla f = -0.25$). Therefore, it is still unclear how exactly friction on the tube walls affects the drag when driving at a constant velocity under the choked flow limit, but the effect shall be negligible.

Conclusions

The development of an ultra-high-speed ground transportation system necessitates comprehensive research and well-founded understanding on a multidisciplinary level. Particularly, the aerodynamic resistance is one of the main barriers that the development of this technology encounters due to the increasing energy consumption at high-speeds. To reduce the aerodynamic resistance, the vehicles travel within air-tight tubes that are able to generate an environment with a lower density than atmospheric air. However, the behavior of this flow is significantly different from that observed in the open air. The fluid is confined to a finite domain that constrains the air displacement created by the moving vehicle, generating more pronounced aerodynamic effects.

Those effects are mainly defined by sensitive design variables of the system, such as the blockage ratio, the tube pressure, the pod speed, or the body length and geometry. Due to operational and economical reasons, the blockage ratio and maximum pod speed of the system are usually desired as high as possible, which would mean that the pods might need to travel over the choked flow limit. In this region, the Mach number around the body relative to the vehicle fixed frame of reference is unity and a normal steady shockwave appears at the pod tail.

New challenges arise when driving over the choked flow limit. Along the domain, the temperature rises significantly due to the compression work introduced by the moving vehicles. The gradients of the fluid properties in the near flow-field are strong and produce severe temperature drops across the vehicle which may generate additional requirements in the pod and tube structure. The low-pressure environment reduces the heat convection coefficient of the fluid, reducing the overall heat extraction from inside the tube.

Moreover, the aerodynamic drag over the choked flow limit increases linearly with time for a constant vehicle velocity. The further over the choked flow limit the vehicle drives, the stepper the drag slope becomes. This fact encourages the investigation of pressure-field attenuation measures such as an active increase of the effective bypass area or low-pressure-relief ducts. Under the choked flow limit, the aerodynamic drag is maintained quasi-constant.

Acknowledgments

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Lessons Learned from MagLev Train Development Ready to Foster Hyperloop Systems

Dr. Ralf Effenberger[*1], Prof. Dr. rer. nat. Walter Neu[2,3]

Prof. Dr.-Ing. Thomas Schüning[2,3], B. Eng. Lukas Eschment[2,3]

[1] Integrated Infrastructure Solutions GmbH & Transrapid Versuchsanlage Emsland (Emsland Transrapid Test Facility - TVE), Hermann-Kemper-Str. 23, 49762 Lathen, Germany

[2] University of Applied Sciences Emden/Leer, Institute of Hyperloop Technologies, Constantiaplatz 4, 26723 Emden, Germany

[3] Carl von Ossietzky University of Oldenburg, School of Mathematics and Science, Carl-von-Ossietzky-Str. 9 – 11, 26129 Oldenburg, Germany

Keywords: MagLev, Transrapid, test track operation, inductive charging, linear propulsion, operation and control, safety

Introduction

One of promising concepts that has received extensive attention since 2013 as a sustainable alternative for high-speed transportation is maglev based Hyperloop. With the potential speed of an aircraft and possibly even lower energy consumption compared to current High-Speed Rail (HSR), Hyperloop may become a very good solution for sustainably improve and disrupt our European-wide mobility.

Magnetic levitation (maglev) based developments have a long history in Germany. Its industrialization however, was boosted after the decision of the German Federal Government (end of the 1970th), to set-up a large scale maglev testing facility (Transrapid Versuchsanlage Emsland, TVE). The facility installation was done in two steps, with a final guideway length of 31.8km. The first part of the facility was put into service in the middle of 1983 and the second part was handed over for testing purposes at the end of 1987. The first model tested at TVE was the Transrapid model 06. Successful testing and qualification of the later model TR08 marked a precondition for the first commercial maglev application in Shanghai. The last vehicle tested at TVE was the model TR09, slightly modified (in comparison to model TR08) for an application between Munich central railway station and Munich airport. This project was successfully finalized at TVE with EBA (Eisenbahnbundesamt) approval at the end of 2011. For other reasons the Munich airport link has not been realized and based on a decision of the German Federal Government, maglev testing activities at TVE had to be shut-down at the end of 2011.

This decision in Germany did not hinder further developments of maglev technology. Unperturbed, countries like Japan, South Korea and especially China continue to further develop maglev technology. China started commercial operation of the Shanghai maglev system in 2004. Daily operation starts at 6am and ends at 11pm. System availability and technical reliability are higher than 95%. Up to now about 90 million passengers have been transported on this 30km long maglev link between Shanghai Pudong International Airport and Longyang Road Station.

China plans to build up to eleven maglev lines within the next years[1], and the development of modern vehicles on the basis of Transrapid 08 is ongoing. According to the Corresponding Author's information Hyperloop- and maglev developments in China will preferably base on the same technology, especially for vehicle propulsion, levitation and guidance. China's criterion to distinguish between maglev and Hyperloop is understood to be the system/ vehicle speed. Systems with a design speed up to 600km/h are defined as maglev while systems with design speed above 600km/h are defined as Hyperloop. Such definition surely will help for a smooth transition from maglev to Hyperloop, once higher speeds become relevant in China.

[*] Corresponding author: ralf.effenberger@intis.de

When Hyperloop was born

Patents for maglev systems had already been published in Germany in the first half of the 20th century. In particular the two patents 6433162[2] and 7070323[3], both granted to Dipl.-Ing. Hermann Kemper in the years 1934 and 1941, outline implementation proposals for the key-components of maglev systems. Transrapid implementations do base on his inventions in many details. Moreover, and this is very remarkable, he describes in his patents technical solutions which now, about 80 years later, are readopted by engineers in the frame of Hyperloop developments. Three of his proposals with relevance to Hyperloop are mentioned as follows:

(1) Reduction of energy losses with the help of evacuated tubes

(Remark: The below text will be translated during the Author's presentation at the conference)

> "… Bei höchsten Geschwindigkeiten, für die die Schwebebahn in erster Linie gedacht ist würde es für die Verringerung der Gesamtfahrwiderstände keinen großen Gewinn bedeuten, wenn nur eine Vermeidung des Widerstandes der rollenden Reibung erreicht würde, da dann der Luftwiderstand der wichtigste wird. Darum ist ein weiteres Mittel dies, dass die mit luftdichten Wagen ausgestattete Schwebebahn in dichte Röhren verlegt wird in denen die Luft eine Verdünnung erfährt, wodurch der Luftwiderstand weitgehend herabgesetzt werden kann. Durch Vereinigung beider Mittel der Schwebung und der Luftverdünnung, lässt sich bei der Schwebebahn der Fahrwiderstand selbst für höchste Geschwindigkeiten ganz gering halten…"

Figure 1: Patent 643316 - excerpt introducing evacuated tubes

(2) Vehicle levitation and guidance on the top-side of the vehicle and (3) guideway switches without moving legs

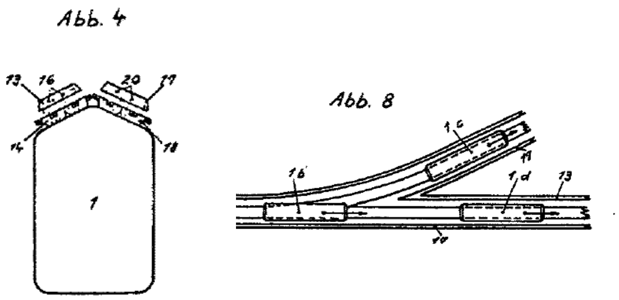

Figure 1: Patent 707032- Abb.4 "top side guidance and levitation", Abb.8 "switch without moving leg"

Lessons learned from maglev train development ready to foster Hyperloop Systems

During nearly 30 years of TVE-operations a lot of technical effects and operational aspects have been discovered and observed, which – even today – cannot be forecasted with required exactness through engineering, numerical simulation or synthesis of operational and maintenance programs. After all it was crucial to have a large scale testing facility available for technology validation, technical developments, the validation of procedures (operations, passenger evacuation, handling of emergency situations, etc.), for system maintenance, spare part management, warehousing, training of operators, for the evaluation of environmental aspects and the impacts to the people living in close neighborhood to maglev high speed transportation systems. Furthermore the activities at TVE helped to define many criteria in regard to system approvals and acceptance at component, sub-system and system level. Last but not least TVE formed a nucleus for thousands of engineers and hundreds of companies which met at TVE in order to get validated their ideas and products.

A small number of areas with TVE lessons learned will be presented at the conference as follows:

- Wireless infrastructure for maglev onboard battery charging; a method that has been developed by the Technische Universität Braunschweig and implemented into the TR09 vehicle by ThyssenKrupp in order to maintain battery charging while the vehicle speed is lower than about 80km/h; presenting an example on how to improve and furthermore to give some examples, how the technology has been successfully converted for micromobility- and passenger vehicle applications (spin-offs)

- Maglev guideway girder thermal deformation effects due to thermal gradients induced by day/ night temperature changes and unfavorable dynamic properties (mechanical), leading to problems with the vehicle's guidance and levitation control
- A proposal for shortening the concrete girder manufacturing time with the help of "molding by centrifugal forces"

Conclusion

Recognizing the fact, that maglev originates future Hyperloop technology to a large extend, many of the lessons learned from the nearly 30 years of TVE-operations suit to accelerate upcoming Hyperloop developments and will contribute to the establishment of European Hyperloop Standards. The TVE-Management supports the establishment of a large-scale European Hyperloop Research Infrastructure (LSRI), as such research infrastructure is crucial to validate all kinds of materials and components up to system level and gets highest relevance in regard to the avoidance of technology investments, which finally may fail to suit Hyperloop technical and operational requirements. An assessment of required facility adaptations is currently ongoing in order to get TVE converted to that large scale testing facility as part of LSRI.

Acknowledgements

University of Applied Sciences Emden/Leer, Carl von Ossietzky University of Oldenburg, Professor Emeritus Hermann Flessner, University of Hamburg

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SESSION 4

Infrastructure & Operations

A Vacuum Technology Supplier's View on Hyperloop

T. Kammermeier[1], D. Corcoran[2], S. Rosenstraeter[1]

[1]Leybold GmbH, Bonner Str. 498, D-50968, tom.kammermeier@leybold.com,

[2]Leybold USA Inc., 6005 Enterprise Drive, Export, PA 15632, USA

Keywords: Vacuum technology, pump down, operation pressure, roots pump, fore pump,

Vacuum technology and creation of low-pressure environments is inherently required for the Hyperloop vision of high-speed-travelling in tubes without air friction. As a major vacuum equipment supplier, Leybold has carefully followed the rise of this new transportation technology over the last few years. A significant amount of engineering and research support effort has been invested. Cooperation was established with most global players of all sizes.,. These investments have already paid off, as Leybold has equipped all Hyperloop test tracks with vacuum systems up to now. Today, the demand for vacuum pumps in Hyperloop activities is rather limited but the long term potential is enormous. There are no major suppliers of vacuum technology that can ignore future impact on the vacuum equipment market.

Since the interviews given by Elon Musk back in 2012, media hype about Hyperloop is abound. In the very beginning the only payback for Leybold was participation in such media coverage. Our activities have opened some doors with new customers who might not know Leybold so well. What we see is that hyperloop is an inspiring topic for our sales teams – it is very relatable in terms of a real-world application of the future.

Apart from publicity, technological discussions with leading Hyperloop companies, such as Hyperloop Transportation Technology and Virgin Hyperloop One started in 2015. Leybold, as a supplier of vacuum technology with long history (dating back to 1850), is familiar with customers providing well defined specifications for their vacuum systems. Unlike every other customer, Hyperloop companies tend to provide very rough ideas with a huge range of technical parameters, the most important being the operating pressure. Many hundreds of requests have been filed with Leybold in this regard. Undoubtedly, there is not one pumping technology which can (within economic reason) cover every scenario. The wide variation in issues at that time was not only influenced by limitations in low-pressure fluid-dynamics simulations, but also by the commercial considerations, i.e. the cost of ownership calculations, of different technical solutions. Another great uncertainty is in leak rates. In fact, the ultimate operating pressure of a vacuum system is reached if the leak rate equals the pumping speed at such a pressure. Leybold, as a vacuum technology supplier, can only provide answers to a small fraction of the questions which naturally arise with regard to engineering a viable Hyperloop. The greater picture has many more aspects and efforts from a plethora of different specialties in science and engineering.

The aspect ratio (diameter/length) of a hyperloop system is enormous – 1/1000,000 is easily possible – and imposes inescapable design constraints in terms of vacuum pumping capability. A single-site pumping station, whilst minimizing capital outlay, would result in some undesirable pressure variations and gradients along the hyperloop track within the tube. The solution is an intelligent distribution of pumping capacity along the track – crucial for the compensation of any leaks and pump failures. Reducing the capital and operational expenditure (as every additional pumping site means more outlay in terms of enclosures, power supply, water supply and associated infrastructure) on the other hand, favors limiting the numbers of pumping stations. The higher the permissible operating pressure, the lower the pumping speed, and the greater the aggregate energy savings over time. A large-scale Hyperloop system will therefore require a smart pumping network to optimize the spread of pumping speed dynamically versus local inleak flow conditions – a capability that, in turn, will yield significant (and recurring) operational savings. It is also worth noting that an understanding of the pumping-speed distribution (essentially a granular map of pressure along the tube) will enable efficient leak detection without recourse to a conventional and time-consuming leak search.

Nowadays, we expect the operation pressure to be below 1 mbar, which is already below the ultimate pressure of some rough vacuum pump technologies. In view of the high leak flows that can be anticipated from the big surface/volume ratio of the tube, pumps with a high volumetric flow at low pressures with low energy consumption are desirable. Roots pumps backed by a fore pump (e.g. screw pump or rotary vane pump) are the pump technology of choice for this. A low energy consumption is achieved by pre-compressing the gas by the Roots pump before further compression up to atmospheric pressure takes place inside the fore pump. Typically, Roots pumps are not able to operate (efficiently) at high inlet pressures. Sophisticated programming of variable frequency drives can be used to overcome constraints caused by intrinsically fixed volumetric compression ratios between Roots pump and fore pump.

Peak energy consumption for any hyperloop vacuum system will occur during end-to-end pump-down along the track. With this in mind, Leybold is working to optimize multi-stage Roots combinations for very long pump-downs (of the order of 12–24 hours) that will be required in large-scale hyperloop tubes. Issues can include overheating due to gas compression; overload of the motor; or exceeding temperature limits due to low heat dissipation at low gas pressures. Total pumping speed requirement can easily add up to millions of m^3/h for a 1000 km track. In view of this, calculation capabilities of power requirements or energy consumption, respectively, have become as important as vacuum performance. Leybold has put significant effort in the past into developing reliable simulations of energy consumption, which can become a non-trivial task in case of variable frequency drives.

Apart from vacuum and energy performance, Leybold is often requested to suggest service concepts. The importance of serviceability becomes apparent, if one considers items like: regular oil changes, pump overhaul, cooling water supply, reliability during power blackouts etc. Maintenance must be possible without impairing the vacuum performance – or at least without exceeding given limits for continuous operation of the Hyperloop.

Figure 1: Container-based vacuum pump system as delivered by Leybold.

If Hyperloop transportation becomes a reality, it will represent a massive growth market for the vacuum industry. Even a mid-size hyperloop project will require significant focus and scale-up from suppliers like Leybold. The biggest challenge will be developing, then bringing to market, a new generation of application-specific pumping systems – at the required scale and the right price-points.

How Innovative Technologies like Hyperloop can Create a Zero-Emissions Transportation Future

Bruce Kemp[1]

[1]Virgin Hyperloop

Keywords: hyperloop, transportation, innovation, zero-emissions, carbon-neutral, sustainable development, high-speed rail, electrification, mobility.

Introduction

The European Union's goal of climate neutrality by 2050 (Directorate-General for Climate Action (European Commission), 2019) requires introducing necessary and ambitious measures to reduce transport's reliance on fossil fuel. The bar has been set for at least 30 million zero-emission vehicles by 2030, for high-speed rail traffic to double by 2030 and triple by 2050, and for zero-emissions aircraft and ships to be market-ready by 2035 (Directorate-General for Climate Action (European Commission), 2019).

The opportunities for all of us to make sure environmental sustainability is a platform for the success of future generations exist right now. We must change the way we think – innovation is pivotal. Rather than working in silos, the transportation industry can work together, smarter, and discover its true potential for an integrated European transport network that works together to achieve carbon neutrality.

The current EU goals are critical, but to view them each in a vacuum would be a mistake. Integration between modes is key. To grow high-speed ground transportation, we must see more interconnected networks and we must see electric vehicles and public transport for the last mile.

The Role of Hyperloop

More than just vision, hyperloop is tested technology. Just last month Virgin Hyperloop proved that hyperloop is safe for real people to ride and experience.

Figure 1: Josh Giegel, CEO and Co-Founder of Virgin Hyperloop, and Sara Luchian, Director of Passenger Experience, the world's first passengers to ride hyperloop.

The technology may seem sci-fi, but it's really technology that keeps pace with today as a fully autonomous system that can run on renewable energy. Machine learning is utilized to create relationships and insights into how the system is performing, discover new ways to optimize efficiency, and fix issues before they become problems using these predictive analytics. Beyond ensuring safety and high-quality service, this data can be used to foster interoperability with other transportation modes. A hyperloop can connect cities hundreds of kilometers away in minutes, connect ports with inland terminals, connect regional airports with each other or the city center, and connect fractured rail lines. The system can support increased passenger and cargo flows with zero direct emissions and up to ten times greater energy efficiency than short-haul flights.

Figure 2: A rendering of a hyperloop system with solar panels covering the top of the tube.

By integrating existing modes and offering an exceptionally high-quality service – on-demand, ultra-fast, reliable – hyperloop can pave the way for a shared, multimodal, emissions-free transport ecosystem for Europe and the world.

The Need for Big Solutions

To make the EU the world's first climate neutral continent by 2050 will not be easy. We need all options on the table – both innovative and traditional, and we need to work together. For example, while it is clear electrification is the way forward, electrification alone is not sufficient. You can have 100% electric vehicles on the road, but if you have a million more cars on the road you will have the same challenges. The California Corporate Average Fuel Economy (CAFE) standards show that while fuel efficiency has improved by 35% from 1990 to 2016, emissions have risen 21%, and vehicle miles traveled have increased by 50% (Small, 2019).

Having worked across the rail and aviation sectors for over 20 years, I have always believed in the power of moving together. With mass transportation, the more people use it, the less congestion we face (Litman, 2020). The key is converging the benefits of mass transportation with the technological gains we've made since the digital revolution, making it the first-choice option for passengers across the European Union. The benefits would be enormous. There are realistic and achievable opportunities to shrink distances between cities from hours to minutes, which will redefine mobility, decrease emissions, and develop innovative solutions to combat the climate crisis.

Conclusion

This is a time that requires us to be bold. That is not the same as sacrifice. People around the world and future generations deserve their opportunity to make their dreams come true. Coming from the rail and aviation sector and working on this new mode from the ground up, I am convinced we can build a future for both finite resources and infinite possibilities.

About the Author

Bruce Kemps is the Global Director of Safety Certification and Regulatory Compliance for Virgin Hyperloop, where he works with governments and regulators around the world to ensure hyperloop technology can be deployed rapidly and safely.

He has over 22 years of global exposure in the development and governance of integrated management systems, predominantly in the rail and aviation sectors. A fully qualified lead auditor and Transport Safety Investigator, Bruce is passionate about innovation in safety and always maintains high levels of focus on customer practices, stakeholder, and community engagement.

Bruce is passionate about increasing knowledge transfer and skills of workers and is a fully qualified NVQ Level 3 trainer. He is highly experienced in the field of business ethics, anti-bribery and corruption legislation, and leadership and management development.

He is a Graduate Member of the Australian Institute of Company Directors (GAICD) a Graduate Member of the Institution of Occupational Safety and Health, UK (Grad IOSH) and former non-executive Director of the Australian Rail Industry Safety Standards Board (RISSB).

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Design of a European Hyperloop Large Scale Technology and Research Infrastructure

Prof. Dr. rer. nat. Walter Neu[*1,2], Dr. Ralf Effenberger[3],
B.Eng. Lukas Eschment[1,2], Prof. Dr.-Ing. Thomas Schüning[1,2]

[1] University of Applied Sciences Emden/Leer, Institute of Hyperloop Technologies,
Constantiaplatz 4, 26723 Emden, Germany

[2] Carl von Ossietzky University of Oldenburg, School of Mathematics and Science,
Carl-von-Ossietzky-Str. 9 – 11, 26129 Oldenburg, Germany

[3] Integrated Infrastructure Solutions GmbH & Transrapid Versuchsanlage Emsland
(MagLev test facility Emsland), Hermann-Kemper-Str. 23, 49762 Lathen, Germany

Keywords: Large-Scale Research Infrastructure, Hyperloop, research hub network, system design, safety, magnetic levitation, magnetic suspension

Introduction

A European multidisciplinary Large-Scale Research Infrastructure (LSRI) for Hyperloop enables both academia and industry to assess relevant technical performances of such a novel transport system, as well as to design and develop innovative concepts and technologies that will support a fast, high-capacity, carbon-free long-distance mobility in line with the European strategic goals on sustainable transport. The proposed work will design a multidisciplinary infrastructure where researchers of various backgrounds will work towards advancing scientific efforts to extract relevant and practical information aiming to boost innovative processes in future mobility industry.

A substantial share of the high standard of living in the modern world is attributable to the availability of excellent transport infrastructure. It grants access to goods, services, employment, recreation and interconnection. While the transport sector fulfils a pivotal socio-economic role, the sector is simultaneously one of the largest energy consumers, responsible for about 25% of the global CO_2 emissions. Unless immediate measures are taken, the global transport emissions will grow by another 60% by 2050, causing the international community to fall dramatically short of the Paris Agreement from 2015 as well as the recent goal of Europe to become a CO_2 neutral continent by 2050. Therefore, the transport sector has a large responsibility in implementing clean transportation alternatives to combat climate change.

One of the most promising concepts that has received extensive attention since 2013 as a sustainable alternative for high-speed transportation is the Hyperloop. With the potential speed of an aircraft and possibly even lower energy consumption compared to current High-Speed Rail (HSR), it may very well be one of the best solutions we have to sustainably improve and disrupt our European-wide mobility. But it is not only the distances where aviation dominates the market and Hyperloop will thrive. Its expected high transport capacity, tiny infrastructure footprint and the unique possibility to connect cities along a line without disrupting long-distance travelers, make the Hyperloop an exceptional solution. Furthermore, Hyperloop will be independent of outside factors like weather for example. This makes Hyperloop an alternative to rail and aviation that people will be more likely to use, as reliability and speed increase while the carbon footprint decreases.

As transport infrastructure plays a substantial role in the high standard of living of modern societies, technological progress in vehicles, in infrastructures and in Information and Communication Technology (ICT) solutions have facilitated the globalization of the world economy, reduced trip times and provided more comfort at a cheaper price. However, it has become apparent that the contemporary transportation system also has severe drawbacks related to increased air pollution, noise nuisance and traffic congestion that can deteriorate the quality of life they are meant to support instead[1,2]. One possible way to address these concerns in the long term is to develop new and advanced modes of transportation that satisfy environmental compatibility through minimal carbon footprints on

* Corresponding author: walter.neu@hs-emden-leer.de

the one hand, while on the other hand accommodate future high-capacity and high-speed throughput to support societal future needs.

In order to accelerate the development of Hyperloop many research organizations, startups and non-profits have started to plan and construct test tracks to test and develop different subsystems which are necessary for the realization of Hyperloop as a new mode of transport. Up until now, none of these existing or planned Hyperloop facilities fulfills the purpose of a full-scale research infrastructure to identify the most efficient Hyperloop technology from many different concepts. An independent assessment of all applicable technologies that constitute the Hyperloop needs to occur in order to converge towards a system that allows for interoperability among different actors while still achieving the same levels of safety as well as performance. This will set the foundation for the European Hyperloop technology, which at the same time will contribute to the establishment of a clear set of standards as well as regulation.

Large-Scale European Hyperloop Research Infrastructure

Research infrastructures are key investments in all areas of research, and they meet both the demand of the scientific community for state-of-the-art resources for supporting excellent science, but also the demand of knowledge transfer for innovation at social and economic level. Furthermore, research infrastructures are a key component of the European Research Area (ERA) as they have the ability to bring together a wide variety of stakeholders to search for solutions to the scientific problems being faced by society today.

Research infrastructures can enable research and provide the proper environments for leading researchers and scientists to conduct innovative science at European and international levels, thus increasing the productivity of the EU industry in the long term. As a result, research infrastructures can provide unique opportunities for all scientists, while facilitating knowledge transfer and innovation and thus, creating the basis for technological developments which will lead to the creation of highly skilled jobs – and the birth of several start-ups in very diverse fields that can lead the way to new technologies and markets. In line with this, it has been proven that "extreme" scientific and technological research projects and infrastructures are significant in terms of economic and social returns. Moreover, research infrastructures stimulate research environments and attract researchers from different countries, regions and disciplines. Thousands of researchers and students from universities, research institutions and industry from Europe and from outside Europe use research infrastructures each year.

Magnetic Levitation (MagLev) and the Hyperloop concept are future technologies that could support the conceptual and technical design for new research infrastructures in the transport domain. Discussing the engineering demands of a Hyperloop infrastructure also relates to cost considerations, building needs, interoperability of different technologies and long-term testing as well as the application of real life conditions at full-scale. Leveraging an existing LSRI as a possible location under assessment is the former Magnetic Levitation Transrapid test facility (Transrapid Versuchsanlage Emsland -TVE) in Lathen, Germany (Figure 1).

Figure 1: 32km MagLev Transrapid test facility Emsland, Lathen, Germany (TVE)

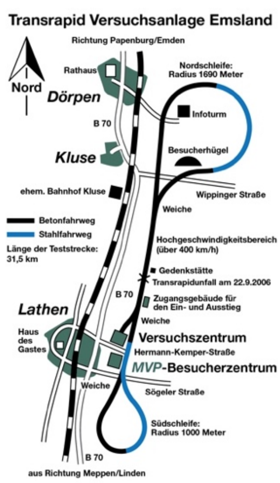

Figure 2: Overview of the existing 32km TVE[3]

The setup of a Large-Scale European Hyperloop Research Infrastructure is based on operational and planned test tracks in Europe and around the world to foster a full-scale system integration. Thus, long term operational test cases are possible under real life conditions. This includes different levitation systems, guiding, suspension and navigation as well as fluid dynamics and structural components. Some variants for these technologies might not be suitable for high speeds or prove other challenges like the integration into an operational Hyperloop system. On the other hand, these satellites in Europe allow for strategic testing of different technologies, so that proven and operational technologies can be implemented in a full-scale European test track. There the focus should be on improving and comparing those technologies based on their performance in continuous testing and interaction with other systems.

A Large-Scale European Hyperloop Research Infrastructure has the potential of proving different subsystems in one system as a whole. Testing might involve heat dissipation, pressure levels, power and energy requirements and communication. This includes the investigation of energy losses in the system, such as remaining air friction due to pressure buildup in front of the pod and electromagnetic losses in the levitation and propulsion systems. Only these tests on a large-scale test track can answer those questions well and specify further design choices. Key parameters for tests are continuous operation, scalability and interoperability regarding a full-scale system and realistic application.

Figure 3:
TVE in Lathen with existing support structure and uninterrupted 32km test track

Upgraded and additional technologies in a Large-Scale Research Infrastructure

The MagLev test track in Lathen will provide a time saving and cost-efficient implementation of a Large-Scale European Hyperloop Research Infrastructure. The availability of a continuous test track and foundations on which tube elements can be placed without interrupting existing trainlines, roads and other linear infrastructure offers an additional advantage. Furthermore, existing knowledge of the Transrapid's Electromagnetic Suspension (EMS) technology will help an accelerated development of magnetic levitation and wireless power transfer for the Hyperloop system. Additionally, previous approvals for test operations of the TVE and contracts with surrounding parties allow for an accelerated land use planning procedure and planning permission hearings.

An extensive list[4] of technologies required for the evolution of the TVE to a LSRI for Hyperloop includes:

- Vacuum equipment
- Levitation and guidance systems
- Propulsion and braking systems
- Bogies and suspension
- Pod motion physics
- Power generation and distribution
- Network communication and control
- Environmental control and life support systems (ECLSS)
- Emergency braking system
- Emergency management
- Power supply system
- Control systems
- Air docks

Additionally, there can be further expertise involved, such as logistics and distribution partners to demonstrate freight transport and intermodal connectivity for the Hyperloop system as well as specialized technologies such as cryo technology for Superconductor Magnetic Levitation (SML).

Technologies that need to be developed for a LSRI include e.g. large-scale vacuum technology with high volumes of throughput and tube technology. There are already prototypes in development for most of these questions, that have been posed, which will face additional challenges when being insplemented in a large-scale Hyperloop track. Figure 4&5 show tube segments from concrete and steel. Different challenges such as vacuum-tightness with very small leakage rates, balancing of different expansion coefficients from superstructure, tube and levitation system as well as overall structural integrity have to be investigated before constructing a LSRI.

Figure 4:
Concrete Hyperloop-Tube[5]

Figure 5:
Hyperloop Tube from Steel[6]

Technological aspects: magnetic levitation

The Hyperloop system constitutes in part technologies that are established and emerging technologies e.g. levitation technologies including High Temperature Superconductors (HTS) systems, and composite materials. Matured technologies with proof of operational compatibility can be integrated in the main LSRI to be tested under real life continuous operation. Not only could there be different technologies for the same subsystems, like a pod suspended with an EMS system from the top of the tube, an Electrodynamic Suspension (EDS) system with suspension from the bottom or a Superconductor Magnetic Levitation (SML) system (Vehicles with different types of levitation in Figure 6-8), but also multiple different geometric designs to test one system, e.g. different versions of the inductrack technology. The research infrastructure therefore has to be designed with a modular approach to accommodate for different designs.

Figure 6:
Shanghai EMS MagLev Transrapid train[7]

Figure 7:
Superconducting EDS Shinkansen L0 Series[8]

Figure 8:
Superconductor SML prototype[9]

Hyperloop Research Network and Hubs in Europe[4]

HYPERION[4] (HYPerloop European Research Infrastructure & Open Network) envisions a European Hyperloop Research Network with a central European LSRI and several hubs functioning as satellites for the LSRI. The network includes universities, industries, SMEs, public stakeholders and EU platforms and projects. Figure 9 shows a potential concept for a framework to shape the collaboration of the partners.

HYPERION envisages to specify and design a research infrastructure and network, that will cause important change in cross- domain and collaborative research related to high-speed transportation sciences. The HYPERION project shall contribute to the simplification of experiments for data collection through the design of a novel data sharing infrastructure and also on the basis of the virtual experimentation environment. These two components are envisaged as key elements for boosting cross domain research, and to utilize data derived through specialized experiments of other researchers. Moreover, these will also be key elements for strengthening junior research groups, young scientists and startups who can apply for "flight time" thus providing an open infrastructure for the initial tests of novel ideas on existing data that can sufficiently cover their needs.

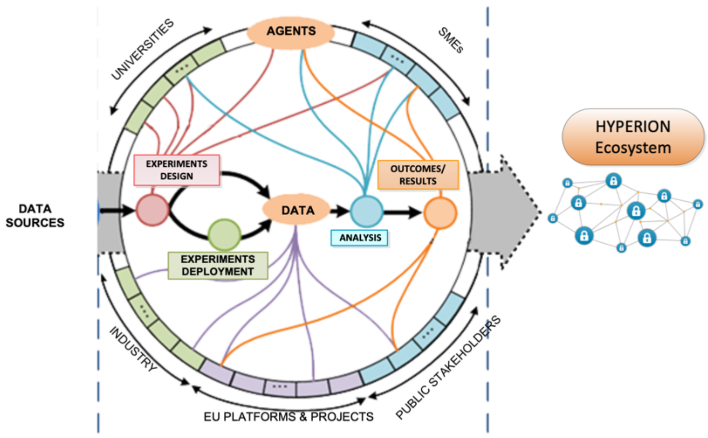

Figure 9: HYPERION system interfaces, embedded data models, automation, intelligence and field applications[4]

As such, the project will allow for the integration of analysis methodologies under its framework and the straightforward sharing of approaches within the scientific community.

Standardization is an additional outcome of the process of testing technologies in many different hubs in Europe, as well as from results of a LSRI. Especially for Hyperloop which has the potential of being a continent spanning transportation system, standardization is a major benefit that can be gained from a LSRI.

Conclusions

A short-term implementation of existing, as well as new technologies into a LSRI is essential in order to setup a common European standard and quick realization of an ultra-high-speed transportation system to extend the high living standards and ensure the challenging requirements to obey the Paris Agreement. Nevertheless, research needs to be conducted regarding all possible technologies existing today to maximize economic operability and compatibility with the environment in the future.

Time to market shouldn't be the only concern for a Hyperloop system, which will require a completely new infrastructure to be built. That is why the European research community is urgently needed to pursue Hyperloop (subsystems) with all its possible solutions. At the end Hyperloop is a new mode of transportation with drastically new approaches to the way we travel which is why the development should not stop at a point of possible realization, but rather when all available technologies have been tested.

Taking best practice knowledge of CERN's ideas to the HYPERION facility is a challenging approach but fits very well into the scope of today's demands and needs on innovative transportation and future mobility. Environmental and societies expectations cannot be tackled on a national scale but require a pan European or even a global approach. Science, engineering, ecological, economic, and social aspects are interwoven and have to be disentangled only on a common base with a common understanding best taken by a model like CERN. HYPERION could be the ultimate and best practice example of a large-scale high-speed transportation research facility with also a huge impact on industrial development.

Acknowledgements

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PODIUM DISCUSSION

Podium Discussion
„Hyperloop: where and how can the vision become reality?“

Moderated by
Prof. Dr. Thomas Hamacher
Department of Electrical and Computer Engineering, Technical University of Munich

The following page contains an overview of the participants of the Podium Discussion “Hyperloop: where and how can the vision become reality?” and some key statements on the topic:

- **Prof. Dr. Johannes Klühspies**
  Johannes Klühspies is a transport geographer and serves as the President of the International Maglev Board. His post-doctoral thesis (habilitation) at the University of Leipzig examined the prospects of maglev systems in Europe.

  Hyperloop ideas fascinate young researchers in particular. However, what is often overlooked in this technology development is that the actual prospects for realization depend on everyday factors: on the tube's resistance to aging and weathering, on compatibility with existing urban infrastructure, on demonstrable advantages in operation, on compatibility with ecology and the environment and, last but not least, on the transport-psychological attitudes of potential users. There is still a lot to be done here, and there are scientists who question whether this can ever be convincingly achieved for Hyperloop systems.

- **Dr. Friedrich Loeser**
  Friedrich Loeser is General Manager at thyssenkrupp Transrapid GmbH located in Munich, Germany, also heading the thyssenkrupp TechCenter Control Technology. Beyond Transrapid Maglev - maintenance and engineering seervice for customers in China - his current business activities refer to system development on smart power & control applications in various industries - elevator, automotive, plant, marine. He received the Dipl.-Ing. in Electrical Power Engineering and the PhD (Dr.-Ing.) from RWTH Aachen.

  Hyperloop demands cutting-edge solutions in many fields - a great task for a creative interdisciplinary research team. Such activities are extremely helpful to inspire the well-established transport business.

- **Dr. Stephan Liedl**
  Having completed his studies of mechanical engineering at the Technical University of Munich and the doctorate in the field of cableway systems, Dr. Stephan Liedl joined TUV SUD in 1999. Remaining true to passenger transport systems, he worked as safety assesor in the field of cableway systems and developed TÜV SÜD’s BOStrab Inspection Body to an internationally operating department Metro / Light Rail Systems. Stephan Liedl has completed many cableway, metro and light rail projects in Germany, Europe and overseas as lead assessor or project manager and maintains a long-term relationship with safety authorities, public transport companies and system suppliers. Besides his competence on risk assessment

and system integration level, he is an expert for rolling stock. He has given several presentations on enhancement of rolling stock and on general safety issues of passenger transport systems.
Since 2016 Stephan Liedl has been involved in safety issues in the development of Hyperloop systems. Benefitting from 20 years of experience in different field of passenger transport systems Stephan Liedl was a core member of TÜV SÜD's team to develop the Generic Guideline for Hyperloop applications.

In the initial evolution phase Hyperloop systems may provide short and medium range transportation at a speed level of railways or above. It is more likely that pilot applications of the Hyperloop technology will be realized in regions with weak public transport infrastructure and high commitment to innovations.
Combining established technical solutions and going beyond, Hyperloop systems have to manage new risks. It is crucial to develop the technology with a very high level of safety, finally to gain trust of investors and users. In addition to thorough development and extensive testing, an independent assessment by an expert body can provide a decisive contribution to make Hyperloop technolgy a success.

- **Johannes Spatz**
  Johannes Spatz (*1962) holds a degree in electrical engineering from the Technical University of Munich (TUM). After initial development activities at Daimler Benz AG in Sindelfingen, he assumed various management positions in the development department of Kontron Elektronik, a subsidiary of the BMW AG at that time. He was in particular responsible for system developments in the area of customer-specific test and analysis systems.
  In 1999 Mr. Spatz joined Panasonic Electric Works Europe AG, the former Matsushita Electric Works. After gaining experience in different business fields from sales to various managing director positions, he took the overall responsibility as President in 2011. Throughout the years, he supported various comprehensive restructuring processes within Panasonic and was appointed President of the independent Panasonic Industry Europe GmbH in 2017.
  As President, he drives industrial innovation, synergies and automation with business partners from a wide range of industries including mobility, infrastructure, home & living, production & logistics, and healthcare.

  In order to allow the vision of the Hyperloop to become reality, it is important to consider the Hyperloop as one integrated part of a complete mobility concept. Any passenger transportation concept needs to take the user and investor perspectives and demands under consideration. While users request consistent connectivity, anytime availability, as well as cost transparency, investors focus on proofed technology, easy infrastructural regulations and return on investment.
  The challenge to success (when, where, how) lies in matching these expectations in terms of timing, locations and stakeholders

- **Ana Eloisa Garcia de Gortari**
  Ana Eloisa Garcia de Gortari is a Mexican nanotechnology engineer finishing the M.Sc. in Management at the TUM. Since she was in her last years at the Bachelor's, she noticed her passion for technology transfer and therefore decided to do something a bit out of the ordinary

lab research. She has been part of the TUM Hyperloop team for over 2 years, the first year developing the market and financial strategy. After the last SpaceX Hyperloop competition, she founded the business case subteam, responsible of developing the business plan of our Hyperloop concept.

In our team we truly believe that the technological development must go hand in hand with the business development in order to ensure the success of the new mode of transport. We are researching different areas, from trends and drivers of the transportation industry that will affect the introduction of a new mode of transport, to the costs related to the implementation of the Hyperloop. Performing this previous exploration will ensure that we can use the lessons learned from previous attempts to successfully introduce the Hyperloop technology as the 5th mode of transport.

CLOSING REMARKS

Opening Statement by

Prof. Dr. Agnes Jocher
Assistant Professor for Sustainable Future Mobility

Good morning, good afternoon, good evening.

This has been a wonderful 1st conference on ultra-high-speed transportation. I believe that we have learned a lot from the keynote session delivered by Prof. Welpe on Innovation Ecosystems, each single talk about the fine work in ultra-high-speed transportation that you are doing and finally the exciting Panel Discussion on where and how the Hyperloop vision can become reality. Once again, on behalf of the committee, thank you for delivering such important materials so that all of us can deepen our knowledge about ultra-high-speed transportation and connect expectations and industry needs to research efforts at universities. And thank you to our session chairs today, Prof. Hamacher and Prof. Wunderlich.

Furthermore, I would like to thank all participants who have joined this conference from all over the world.

I hope this conference was a first opportunity to learn from and about each other. Our enthusiasm for ultra-high-speed transportation works like a common language that has brought us and will bring us together in the future. I believe that it is important for us to establish a community and to learn about the excellent research and advances around the world in this emerging topic. Thank you for that and please don't hesitate to contact us, to establish collaborations or other joint undertakings.

Within the coming week, registered participants and speakers will receive an email on how to access the submitted extended abstracts and online presentations.

At this point I would like to point you to our homepage. We are also currently hiring a PhD student to join our team.

Finally, I would like to thank all the committee members for organizing this conference and the administrative and technical staff for ensuring that it proceeded smoothly. Special thanks to Prof. Thomas Wunderlich, Gabriele Semino, and Stephanie Henne at this point. Furthermore, I want to thank the Department of Aerospace and Geodesy for supporting the Hyperloop-Project tirelessly and especially for hosting and supporting this conference. Thank you Prof. Mirco Hornung and Dr. Michael Klimke.

So, hopefully, we will have the opportunity to meet again soon, either online or in-person. Thank you once again for your participation and I wish you all the best and like we have heard in panel discussion "Have fun and continue learning"!

ADDITIONAL CONTRIBUTIONS

Overview of an evacuated-tube transport (hyperloop) system for long distance travel.

F. Lluesma[1], S. Hoyas [2], A. Arguedas [3], J. Vicén[4*]

[1]A. Universitat Politècnica de València (Spain), and Zeleros (Spain).

[2]B. Universitat Politècnica de València (Spain)

[3]C. Zeleros (Spain)

[4]C. Zeleros (Spain)

Keywords: hyperloop, transportation, evacuated tube transport

Introduction

The history of evacuated tube transport begins over 200 years ago, when in 1799 English inventor George Medhurst first proposed moving passenger carriages through a tunnel using variations in pressure levels. Some systems were implemented in France, England and Ireland during the 19th century. The system was called "Atmospheric Railway". A century later, in 1904 Robert Goddard at Worcester Polytechnic Institute (USA) combines the concept of airless tunnels to reduce air friction with the concept of magnetic levitation ("maglev") systems to reduce the ground friction losses. This concept could enable very high speeds with relatively little power in terms of propulsion. Russian inventor Boris Weinberg built his first model in 1909 at Tomsk University. During the following years, the evolution of both technologies (low-pressure tubes and magnetic levitation systems) advanced in parallel. The development of the first superconducting (SC) levitation technologies and linear motors led to the creation of maglev trains. Concurrently, advances in space and pipeline construction led to the development of high-volume vacuum systems, whose most preeminent example is the Large Hadron Collider, with a total of 104 kilometers of piping under vacuum. In the late 1970s, Professor Marcel Jufer from Switzerland combines again both ideas of pressure and magnetism proposing Swissmetro to operate at pressures at which the Concorde SST was certified to fly, but no operational line was implemented. In August 2013, American businessman Elon Musk publishes online an open whitepaper called "Hyperloop Alpha", with a concept of air-bearings for levitation and linear motors at each station for propulsion. In 2015, Elon's company SpaceX organizes a University competition so students all over the world can share new ideas to boost hyperloop development. From this date, hyperloop companies arose globally in order to develop such a system, and cooperation agreements have been announced to enable international standardization ensuring interoperability. It was then when the university team Hyperloop UPV was created. Its aim was to compete against the top technological universities from all over the world and develop hyperloop. After winning two awards on the first edition (Best overall design and Best propulsion system) the team decided to go one step further and create Zeleros, a company independent from the university that is currently fully focused on the development of hyperloop.

Key benefits of hyperloop transportation systems: Although hyperloop was proposed more than a century ago, it is during the last 6 years that has become famous, since Elon Musk's proposal in 2013. The reason is that this concept needs also the technologies available for its actual development. These different technologies are the following:

- **Low-pressure:** Hyperloop requires pressure maintenance of large volumes. However, the Large Hadron Collider, which began operation in 2009, accounts for 54 km of Ultra High Vacuum (around 10-10 mbar).
- **Magnetic levitation:** the first maglev train operated in Birmingham airport from 1984 to 1995. This technology is nowadays sufficiently mature to get the high-speed maglevs operating in China and Japan, as mentioned in the introduction.

* Corresponding author: fellrod@doctor.upv.es

- **Control:** high frequency automation has been put to the test on several applications, such as the reusable Space X Falcon rocket, able to land vertically after completing its mission
- **Composite, new steels, and intelligent materials:** that allow light but extremely resilient fuselages and civil infrastructures.
- **Power electronics and drives:** well developed but still with wide margin for improvement on the railway sector, little by little on the automotive industry and in the next decades on the aviation, where clear progress is being made (E-Fan X).

Apart from the technology readiness, the necessity of a new mean of transport is becoming more and more evident. The trends show an ever-increasing increment for all distances, particularly relevant on the segment where high speed trains and planes share or overlap their market borders. Specially, the congestion of the air space is becoming more and more worrying. By 2050, Airbus expects an increase of 100% in the number of flights. Eurocontrol, the organization that manages the air space in Europe says in one of its reports "for the future, with saturation of airspace resources in long-term, congestion problem cannot be overcome unless airspace structure is re organized". In addition, hyperloop as a 21st century system of transportation will be developed as the greenest among the fastest transportation systems available: fully electric, hence zero direct emissions as a premise. Hyperloop is thus proposed as a solution to the current transportation saturation, as it would mean a new complementary transportation layer, that by its own nature can decisively contribute to reduce pollutant emissions. Demand for air transportation will continue growing, while air traffic congestion at specific corridors already exist. Deploying a hyperloop route could alleviate it by adding a ground transportation system with a performance similar to that of airplanes.

Description of hyperloop: As already described, hyperloop presents several advantages with respect to traditional ground transport. On the one hand, hyperloop concepts is based on levitation. Thus, the rolling problems encountered by the railway at high speeds such as hunting and expensive rail maintenance is overcome, and the efficiency of the system is improved. Apart from that, the partial vacuum environment inside a tube reduces the main drag on a train, the aerodynamic one. The combination between the removal of aerodynamic and friction drag enables this system to be as fast as the plane, with the sound barrier as theoretical main limit (around 1250 km/h). This speed is twice the largest speed ever obtained by a High-Speed Rail and Maglevs, and similar to that of most fighter jets nowadays, with considerably less energy consumption (see **Figure 5**). Being inside a tube also improves the behavior against adverse weather conditions. Cross wind, heavy rain or snow would not potentially affect the operation of hyperloop. However, as hyperloop is a new concept, several approaches have been taken when it comes to its actual development. That is the reason why several companies have emerged in the recent years. Zeleros is one of this companies, whose approach is described in the following section. One of the drawbacks of hyperloop could be though to be the amount of energy consumed by the pumps to reduce and keep the low pressure inside the tube. On the other hand, assuming that an electric power of 40 W/m2 can be extracted from solar panels, and that the tube can be fully fulfilled with panels, a 4 meter diameter tube would give 160 kW/km, which is, for an initial computation, more than enough to energize the pumps on a realistic operation scenario.

Description of Zeleros' hyperloop: The Zeleros concept (see **Figure 1**) can be mainly divided into two different systems. First, the levitation, which is based on Hybrid Electromagnetic Suspension (HEMS). Permanent magnets surrounded by electromagnets are placed on the vehicle. The permanents magnets account for lifting the weight of the vehicle, while the electromagnet is responsible for controlling the gap with the tube. This way, low power is required to energize the coils, as most of the effort corresponds to the permanent magnets.

On another hand, main propulsion is based on a simplified aeronautical engine, in which the combustion chamber has been removed. Thus, a compressor driven by an electric motor captures the air in front of the pod, compresses it, and exhausts it through a nozzle to generate thrust and overcome the drag. One of the main advantages of this proposal is that, as all the technology is integrated in the vehicle, the track complexity is significantly reduced compared to other approaches that based their propulsion on linear motors. As no coils or permanent magnets are required on the track, the infrastructure cost is considerably reduced. Another advantage of this system is that the excess of energy in the flux can be recovered using a turbine, making the whole system more efficient. Regarding the speed, there is a debate not only from the technical perspective but also from the customer and user point of view. As a minimum, any new transportation system to be added to the current portfolio needs to provide better capabilities than existing ones. The fastest mean of transportation for conventional passengers is the airplane. In addition, it is well known that commercial airplanes are the safest mean of transportation. So, the hyperloop should at least match the airplane in these two features. On what refers to the speed, the problem to be solved is not which is its top speed, but what is its average speed for a given corridor. Next it is going to be showcased the true potential of airplanes.

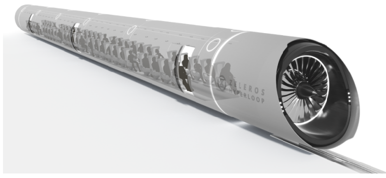


Figure 1. Overview of Zeleros' hyperloop concept. Source: own elaboration.

A visual on airplane average speed can be found on **Table 1**; it clearly demonstrates that despites its top speed (850 - 950 km/h), its average speed (so called "true speed", including taxi), is way lower. On the instances below all flights go from Barcelona non-stop to different locations in Europe. Considering this, a case is made for a system that can sustain a cruise speed of at least 650 km/h, at ground level, for distances where it remains competitive with airplanes (less than 3 hours). The point is what if all these European cities would be linked through a single hyperloop mainline? Strictly in terms of travel time, it means that even a case should be made in terms of whether it is preferable to take a 3h 30' flight from Spain to Sweden or to take a 4h ride on hyperloop under this quick preliminary assumption of sustained 650 km/h cruise speed. This time is not considering any airport or station logistic time on neither case, which has become in many cases a setback on air travel. And does not consider either the fact a hyperloop station could be placed in a city center. In terms of safety, that will be considered more in deep ahead in this text, a quick note to retain is that for a similar average speed, there is no takeoff or landing on a hyperloop.

Destination	Distance [km] (straight line)	Distance [km] (actual flown)	True speed [km/h]	Real travel time (incl. taxi)
Toulouse (France)	267	332	398	53'
Paris (France)	828	900	452	1h 48'
Brussels (Belgium)	1085	1259	567	2h 7'
Amsterdam (Netherlands)	1243	1378	498	2h 26'
Copenhagen (Denmark)	1771	1996	591	2h 57'
Stockholm (Sweden)	2317	2530	680	3h 32'

Table 1. Duration of different flights from Barcelona (Spain) operated by Vueling Airlines on 17th November 2019 using an Airbus 320 aircraft. Source: Flight Aware.

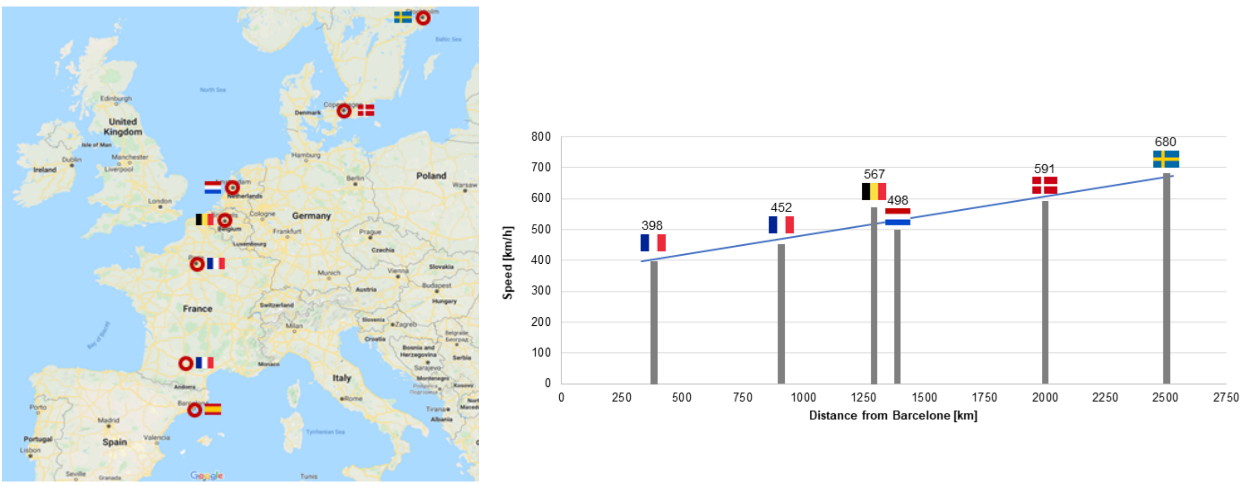


Figure 2. Duration of different flights from Barcelona (Spain) operated by Vueling Airlines on 17th November 2019 using an

Airbus 320 aircraft. Source: Flight Aware.

Electric propulsion for hyperloop: As explained before, hyperloop concept is based on a vehicle circulating through a closed track which has an adequate pressure level to minimise the energy consumption while allowing high safety and reliability. The mission of the propulsion system is to achieve this and overcome the natural drag that the fluid inside the track exerts over the vehicle and other resistances such as the magnetic drag. The vehicle on its movement will transmit kinetic energy to the surrounding fluid, dragging a wake on its movement direction. If the pod velocity is high enough, shock waves will occur, like those that take place on a high-speed train tunnel. However, shock waves in hyperloop tracks cannot be dumbed at the exit of the tunnel by the atmosphere, as is the case for high-speed trains. Shock waves generated in a hyperloop track will be bounced back and forth hitting the vehicles circulating, potentially jeopardizing the vehicle stability. Several hyperloop concept philosophies share the view of using linear motors all along the route in a complete vacuum tube to avoid this effect. Those levels of vacuum may require a more complex and delicate two stage pumps. The high vacuum is mandatorily required to create environmental conditions of no aerodynamic drag. Nevertheless, the adverse effects of atmospheric pressure levels inside the track can be overcome with a potentially better solution, an electric turbofan-like propulsion system. Turbofan engines, which are the most common propelling engine for short, medium and long-haul aircrafts are following the electrification road map of other traditional propulsion systems such as electric cars. Car engines, where the mechanical power was traditionally generated by burning a hydrocarbon fuel, are being replaced by electric power units feed with electric power from battery units. A turbofan engine power with an electromechanical power unit has the advantage of non-generating combustion gas emissions while operating. This fact allows the use of this propelling engines in confined facilities without incurring in recirculating gas problems. The use of an electric turbofan-like system is mandatory when the pressure levels inside the tube are non-space vacuum levels. This is basically due to the vehicle aerodynamic drag. This system has two main effects: first there is a way to cope with the piston effect. The air is removed by being swallowed and transferred after a compression-decompression cycle to the tail end of the vehicle. Second, it is obtained a propulsion system based on compressed air, that compensates the higher air drag now present. A value of 10 kPa is enough to reduce more than one order of magnitude the aerodynamic drag and enables the compressor to properly operate in these conditions. The electric turbofan systems have a considerable disadvantage which is that are only fit to operate at a design point condition when operating in an enclosed environment. However, when operating at design point hyperloop system is extremely competitive from the energy efficiency point of view, compared to aircrafts or alternative piston engine vehicles which operate a significant portion of its mission at off design condition. For short haul routes, meaning shorter than 1500 km, an aircraft only spends at cruise condition approximately a maximum of 70% of the route. The global efficiency of a system of these characteristics normally is quite poor due to the long periods in which the system is required to operate at off design condition. From the point of view of the energy consumption, a significant portion of the total energy of the mission is wasted, especially in the phases of taxi, take off and climb. The advantage that hyperloop offers for missions of this range is that to reach maximum efficiency and cruise condition the system does not require to go through a phase equivalent to climb, which allows to increase the cruise phase of the vehicle up to approximately 95% of the mission. Depending on the size of the cargo and passengers' cabin, the mass flow that the electric turbofan swallows may have to be compressed over the desired pressure ratio from the propulsive efficiency point of view. For such cases, the regeneration through an air turbine is required to achieve high efficiency values. Hyperloop vehicles must keep a very high overall efficiency, otherwise all energy that is not useful for propulsion will be introduced in the track environment altering the optimum operating conditions of the vehicles. From the safety and reliability point of view higher pressures allow the use of this systems with confidence at 10kPa. The Concorde proved successfully that pressurized cabins and turbofans engines could operate successfully at pressures lower than 10 kPa. The technology required to operate at those pressures has a high level of maturity which guarantees its use for passenger and cargo transportation. Below this level of pressure, the inefficiencies of turbomachinery are well studied and therefore an alternative method to avoid the piston effect is required. From the turbomachinery and pressurized cabin point of view the Concorde roof could be established in terms of passenger and cargo transportation as a certified limit. From the safety point of view, a limit could be established at the Armstrong limit 6.26 kPa. Operating at levels of vacuum lower than the Armstrong limit is potentially beneficial from the energy consumption point of view given the almost complete mitigation of adverse aerodynamic effects. However, this potential benefit is offset by the high complexity of the infrastructure required to maintain such levels of pressure. On the other hand, in terms of safety and reliability, cabins certified to operate at those pressures have specific and very restricted safety protocols which would need to be adapted and extensively tested for massive passenger transportation systems.

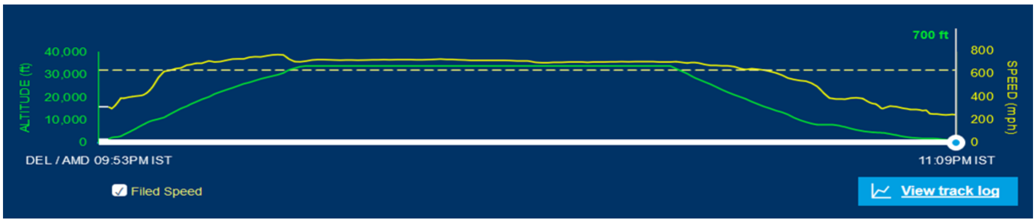


Figure 5. A daily flight from Delhi to Ahmedabad (900km) spends less than 70% of the time cruising.

Currently, existing vehicles operating under the Armstrong limit cannot easily ensure survivability of the crew in case of depressurization, making this approach riskier from a standard passenger safety perspective. Typically, this risk is currently mitigated using space suits like those used in high-altitude flights, which provide military pilots and astronauts a unipersonal breathing environment. Additionally, from the techno-economic point of view Hyperloop is a ground transportation system that requires as such a continuous and fit for the purpose track. Subsequently, the longer the route the more expensive the investment will be. Current maglevs that do not operate on vacuum conditions, have proven that linear motor technology, despite being very effective, entails high investment budgets in the range of 40 M€ to over 100 M€. The high price of current maglevs comes from the required electric installation along the track to allow the movement of the vehicle. The integration of maglev technology along with high vacuum condition makes even more expensive the potential hyperloop track following this concept than the maglev original line track. Additionally, previous studies made by the Korean Railway Research Institute (KRRI), suggest that no benefits from the drag and the aerodynamic point of view will be achieved over pressures of 30 kPa, compared to a maglev train operating at atmospheric pressure. Finally, the vehicle will be autonomously driven. This enables fully automatic operation commanded from a control center, which eliminates both the human factor from the safety perspective and helps to reduce the operational cost, including long training periods, simulators, and manuals.

Main operational characteristics of the proposed hyperloop transport system

Capacity: It has been proven through simulation that vehicles can be built to accommodate up to 200 passengers, so the vehicles are being designed to carry between 50 and up to 200 passengers. The largest and most common regional airplanes, A320 and B737, can carry up to 185 passengers. Thus, the system is aligned with true market needs in this respect. In addition, for the proposed range and design the more passengers the vehicle carries, the more efficient the vehicle becomes in terms of consumption per seat. Nonetheless vehicle capability can be adjusted to the specific need of operators, to accommodate 50, 75, 100 or 130 passengers to say a few. Most likely, the first to be deployed will be the smaller version of 50 passengers, since the overall power requirements can more easily be met and will be enough for most of the potential corridors. Considering a single tube per direction and 16 hours of daily operation, and a tentative minimum headway at cruise speed of around 5, a potential of 38,400 passengers a day per direction will be obtained, and a flow of 2,400 passengers on a peak hour. For a point-to-point mean of transportation targeting distances in excess of 500 km these figures are enough in most cases, and there is still reasonable margin for improvement. Furthermore, one key benefit of the proposed system is how it could complement the current air traffic. It has the potential to add highly required capacity in already congested corridors. While the transition to full electric airplanes will rapidly escalate after 2040, the demand for air transportation will grow and continue growing well beyond that horizon, hence stressing even more air routes and airport traffic, some of which live nowadays in the verge of saturation. Even green e-planes will not be enough to fulfill the demand increase. The proposed system, travelling at the same average speed than an airplane, can provide the much-required additional capacity needed on the 1,000 km range, also ensuring a more accurate hourly schedule reliability.

Energy efficiency: All hyperloop system will benefit from the progresses made in electrical technology in order to offer a zero direct emission system. It will be designed from its foundations to be a green mean of transportation, free of direct emissions. This includes not only fossil-fuel free, but also noise free since most or all noise produced will be kept inside the tube. Solar panels and windmills will be the preferred source of energy whenever possible. Tunnels will be narrower, and the tubes could be placed over pylons, thus leaving open paths under it, hence creating minimal disturbance to urban citizens, farming facilities, wild animals or vegetation. Finally, the tube creates an internal environment where transit will be unaffected by external weather, such as cross winds, sandstorms, or heavy snow. Also, for the present paper a dynamic simulator was developed to estimate the cost in time and energy that our concept requires. In **Figure 5** the train is the best one. However, as we discussed previously, the train competitiveness in these distances is limited due to its average speed. When it comes to compare Zeleros and current air services, improvements between 66% and 75% can be seen in the present routes. The main reason, as previously said, is that the efficiency of the plane is very poor in the proposed range, mainly due to the climb and descent phases covering almost the whole trip. Although Hyperloop will be also required of an acceleration and deceleration phase, it will travel horizontally, which makes a large difference compared to the plane.

Travel time: In **Figure 6** the travel time from the developed simulator is compared with plane and trains for three different routes covering three different continents (Europe, North America and Asia). Also, each of them is representative of three different distances, ranging from 600 km to 900 km. Based on the speed assumptions of the analysis of **Figure 4**, Zeleros‘ hyperloop is able to match the speeds from the plane setting a cruise speed of at least 650 km/h and is far better than any rail services covering the same distance, even compared to the HSR as it is the case between Paris - Frankfurt. Note that the acceleration and a phase equivalent to taxi has been included on the hyperloop case too, for a fair comparison. However, side effects like the logistic time in the airport and the fact that hyperloop is potentially a city center to city center solution are not reflected.

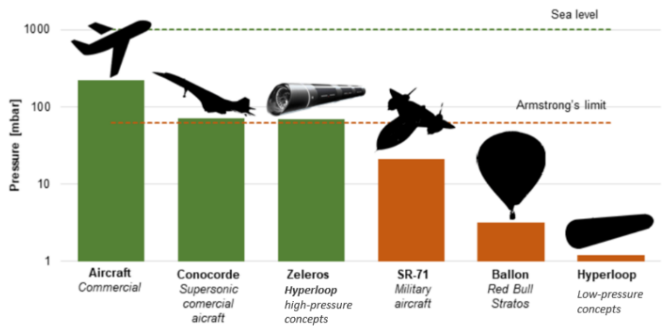


Figure 3. Operating pressures for different vehicles. Source: own elaboration. Reference SR-71: https://www.sr-71.org/blackbird/sr-71/. Reference balloon: http://www.redbullstratos.com/technology/high-altitude-balloon/index.html

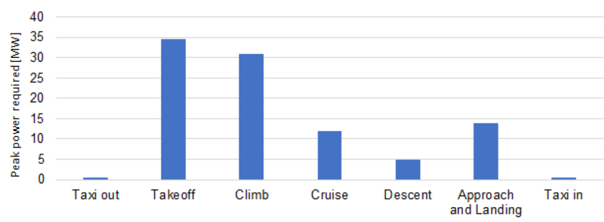
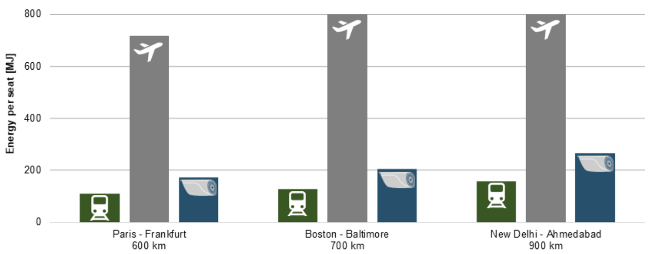


Figure 4. Power required for a generic 150-passenger short haul aircraft designed for a maximum range of 3000 nm and a 1000 nm (1800km) mission. Reference [18].



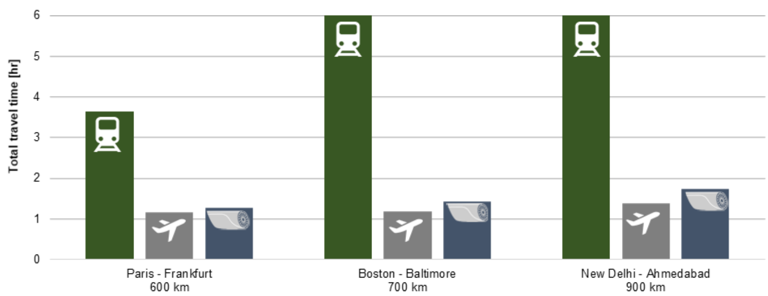


Figure 5. Energy consumption per seat for different transport modes (one way). Source: own elaboration. Reference for train:https://www.siemens.com/press/pool/de/materials/industry/imo/velaro_cn_en.pdf. REFERENCE FOR PLANE: FLIGHT AWARE.

Figure 6. Point to point time with different transport modes. Source: own elaboration. Reference for train: SNFC, DB, Indian Railways and Amtrak. Reference for airplane: Flight aware.

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Thermal Analysis of a Cryostat for High Temperature Superconductors in a Hyperloop Transportation System

Á. Németh[*, 1, 3], D. Radeck[2, 3], A. Jocher[2], O. J. Haidn[1]

[1]Department of Mechanical Engineering, Technical University of Munich, 85748 Garching, Germany

[2]Department of Aerospace and Geodesy, Technical University of Munich, 82024 Taufkirchen/Ottobrunn, Germany

[3]NEXT Prototypes e.V., 85748 Garching, Germany

Keywords: Hyperloop, Propulsion, Liquide Nitrogen Cryostat

Introduction

In recent years, the development of a Hyperloop Transportation System has gained increasing interest globally. While a detailed vision for use cases of this ultra-high-speed transportation system exists, the technical feasibility has not been demonstrated yet. The propulsion system is an essential element of a technically feasible Hyperloop Transportation system, which will be the focus of this study.

For several decades it has been well established that superconductors are enhancing the propulsion of ultra-high-speed transportation systems because they improve reliability and reduce energy and the maintenance costs compared to existing alternatives (Ono 2002). In this work, the Preliminary Cryostat Design Tool (PCD-Tool) is developed for a cooling concept for superconductors in a Hyperloop system and its results are compared to a finite element method simulation for validation purposes.

The inspiration for a system, which contains superconductors comes from the TUM Hyperloop student initiative. The team has conducted an extensive comparison on possible propulsion systems and decided on a long stator linear synchronous motor [Radeck 2020]. This motor consists of an excitation system inside the pod and armature windings. While the three phase armature windings produce a travelling magnetic field, the excitation system produces a static one. The propulsion force is created through the interaction of these two fields.

There are three options to create the static field at the pod: electromagnets, permanent magnets and superconductive coils. In the long-term it is more important to reduce costs on the track side, because these scale with the distance. A possibility is to use less armature windings, which results in weaker magnetic fields. This can be compensated through a stronger magnetic field at the pod. Superconductors are highly appropriate for this solution, since they can create higher magnetic fields with less power consumption than electromagnets and can be turned off unlike permanent magnets making the handling of the pod easier.

Development of a preliminary design tool for a cooling concept for superconductors in a Hyperloop

The PCD-Tool, implemented in MATLAB [MATLAB 2020], defines a liquid nitrogen cryostat by two containers: one filled with liquid nitrogen and the superconductor coils, the other one serving as an outer shell to maintain a near-vacuum condition around the inner container. The PCD-Tool considers material properties, electric current, geometry and operating conditions as subsequent steady states. In addition, it provides an optimal value for the ratio of length to cross-sectional area of the electrical feedthroughs where the heat input is minimal, based on material properties, temperature difference and electrical current.

Three factors were considered for the heat transport between the environment and inner container: radiation between the two containers, heat transfer through the mechanical attachment and heat transfer through the electrical feedthroughs. Natural convection and conduction through residual gas between the two containers is neglected due to high quality vacuum.

* Corresponding author: aron.nemeth@tum.de

Electrical feedthroughs

As electrical feedthroughs we define the portion of conducting material that connects the superconductors with the power supply and are between the two containers, as shown in red in Figure 1. There is ongoing research and some applications of persistent-current switches [Dong et al. 2019], that allow to eliminate this type of heat transfer into the system during operation, but they are not yet widely used. For this reason and considering that electrical feedthroughs cause most of the heat transfer electrical feedthroughs are implemented in the PCD-Tool.

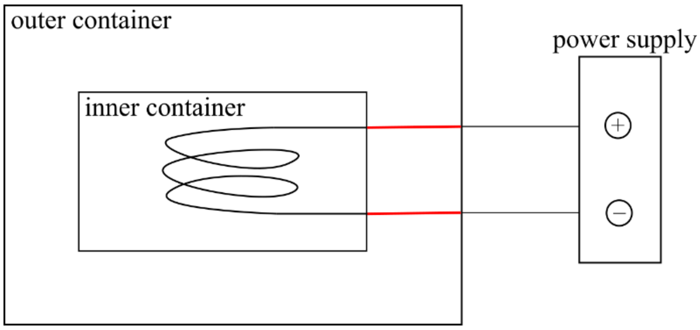

Figure 1: Schematics of a cryostat with power supply highlighting the location of electrical feedthroughs in red color

The PCD-Tool takes two phenomena into account: the heat generation due to electrical losses and the heat transported due to different temperatures on the cable's two ends. It also assumes that the heat caused by both phenomena is transferred into the inner container.

The Joule heating is proportional to the cable's cross section area and inverse proportional to its length. The heat transferred due to the temperature difference is inverse proportional to the cable's cross section area and proportional to its length. This results in an optimization problem for which the PCD-Tool provides the length to cross section area ratio with the minimal heat transferred into the inner container.

Mechanical attachments

The mechanical attachments are responsible for keeping the inner container in place while maintaining a minimal heat input. In the process of choosing a design it is important to minimize the cross-section area and the thermal conductivity of the used material and still maintain sufficient strength. For example, one material with appropriate properties for this application is fiberglass reinforced plastic.

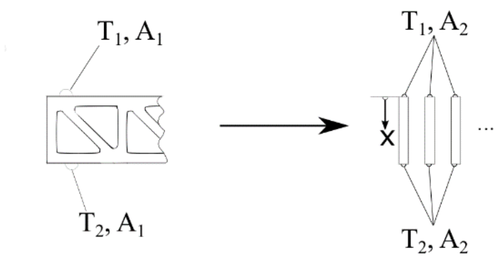

Figure 2: Abstraction of mechanical attachments. On the left-hand side, a possible design for the mechanical attachment with temperature T_1 and T_2 on either sides and cross section area A_1. On the right-hand side its abstracted model as multiple quasi-one-dimensional uniform bars with the cross-section area A_2 and heat transport only in x direction.

The PCD-Tool requires as input the number of abstracted bars along with their cross-section area and the temperatures on both ends. It also requires the thermal conductivity of the used material at the two temperatures.

The PCD-Tool calculates the heat with a linear approximation of the thermal conductivity and temperature profile along the bar.

Thermal radiation

Every object above the absolute zero temperature emits thermal radiation. The heat exchanged between two objects is proportional to the difference of the temperatures to the power of four and an exchange coefficient [Polifke and Kopitz 2009]. The latter takes the geometry and emissivity into account. The PCD-Tool uses an exchange coefficient used for a convex object in a closed space as shown in Figure 3. Real cryostats rarely have a convex inner container, but as shown in the next section this assumption provides an adequate approximation.

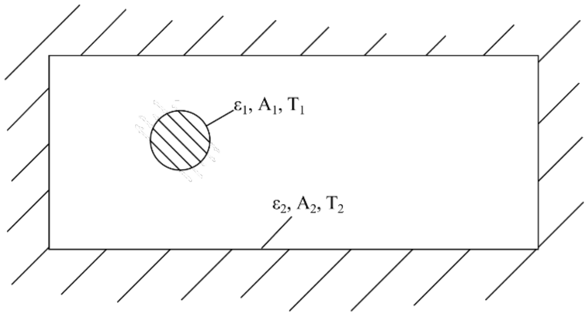

Figure 3: Radiation model existing of two objects with emissivity ε_i, surface area A_i, and temperature T_i

Comparing the results of the developed tool with a finite element method simulation

To test the performance of the developed PCD-Tool, a liquid nitrogen cryostat was created using a finite element method (FEM) [Ansys 2020]. The 3D model contains all components described in previous steps with eight shaped containers for compatibility with an iron core. The results suggest that the PCD-Tool is adequately accurate for preliminary designs while allowing for quick comparisons between different preliminary designs.

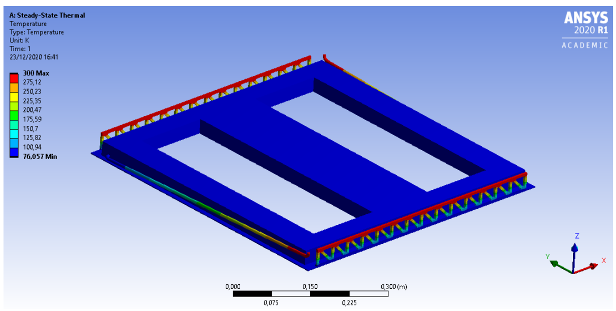

Figure 4: Rendering of the cryostat's 3D model without outer container in FEM

Components	**FEM** [W]	**PCD-Tool** [W]	**Difference** [%]
Mechanical Attachment	3,2	3,32	+3,75
Electrical Feedthrough	13,47	13,96	+3,64
Thermal Radiation	2,6	2,82	+8,46
Overall	19,27	20,10	+4,3

Table 1: Heat transferred into the inner container calculated with FEM and the PCD-Tool and their differences

Conclusions

This work proposes a Preliminary Cryostat Design Tool to help the development of superconducting excitation systems for ultra-high-speed transportation systems. The tool considers three factors for heat transportation: radiation, heat conduction in mechanical attachments and electrical feedthroughs.

The three major achievements documented in this extended abstract are the development of the design tool, the comparison of the design tool results with a FEM simulation and the identification of the tool as adequately accurate for quick preliminary designs.

Future work should be done to extend the PCD-Tool, so that it considers the cooling process of the cryostat and not only the operation. Furthermore, a user-friendly graphical user face could be implemented to simplify the usage.

Acknowledgement

The author thanks the TUM Hyperloop Team for the incredible passion and commitment towards building a new mode of transportation. Most of the experience and knowledge that influenced this work arose from the team spirit.

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Conception and development of an operation control system for an hyperloop testtrack

T. Klose[*,1], Prof. B. Vogel-Heuser[2], E. Trunzer[2]

[1]Department of Aerospace and Geodesy, Technical University of Munich, 82024 Taufkirchen/Ottobrunn, Germany

[2]Department of Mechanical Engineering, Technical University of Munich, 85747 Garching, Germany

Keywords: Hyperloop, Operation Control System, function tree, linear synchronous motor

Introduction

In 2013, Elon Musk presented the idea of transporting capsules with high-speed in a low-pressure tube in his white paper "Hyperloop Alpha" [1]. Because of the low-pressure inside the tube an Hyperloop capsule is supposed to be able to reach a maximum speed of 1220 km/h efficiently. Since a rail to wheel connection tends to become unstable at these speeds, a levitation system is used instead. A linear motor integrated in the track is used as the propulsion system. By integrating the propulsion system into the track, the stored energy required in the vehicle is reduced and higher accelerations can be achieved [1]. To advance the development of the Hyperloop system, the Technical University of Munich (TUM) initiated the TUM Hyperloop project in which a 24 m long test track is to be built and a prototype of the Hyperloop system in full size is to be developed.

In this extended abstract the design of the architecture of the operation control system for TUM Hyperloop's 24 m test track will be presented. In a first step, existing operation control systems of comparable systems will be described. Afterwards the required functions for the operation control system will be identified. Based on the identified functions, the hardware and software architecture can be determined. Subsequently, a system model of the 24 m test track is created to validate the architecture. The validation is done by a "hardware in the loop" simulation.

Operation control systems of existing ground transportation

The high speeds and the low-pressure tube are the unique selling points of the Hyperloop concept. These features place special demands on the operation control system. For example, the tube must be constantly checked for leaks and the pressure must be controlled. Because the linear motor is mounted in the track the operation control system must also control the propulsion system. To ensure that the drive control is still functional at 1220 km/h a fast data communication is required. Additionally, fully automatic operation is required to guarantee safety at these speeds. These characteristics are summarized below:

- Top speed of 1220 km/h,
- long-stator linear drive,
- travel in a low-pressure tube,
- fully automatic operation, and
- centralized control of all vehicles.

There is no existing system that has all the features mentioned above in their entirety. Thus, existing operation control systems are not readily transferable to the Hyperloop system. However, some of the operation control systems solve partial problems that must also be solved by an operation control system for a Hyperloop. For example, the train control system of the railroad guides the trains on a route through the track network and avoids collisions between the vehicles [2-4]. Concepts of this control system can be adopted for the Hyperloop. Since the degree of automation of the railroad is very low, only the concepts are transferable, but not the systems used.

Autonomous rail systems, such as the RailCab [5], have a high degree of automation, but have different requirements for the operation control system due to the low speed of the systems. In addition, the vehicles are not controlled centrally by the operation control system, instead the vehicles can determine their own direction by means of steerable axles [5].

* Corresponding author: tim.klose@tum.de

The most comparable system to the Hyperloop is the Transrapid. This system is centrally controlled by an operation control system and uses a synchronous linear motor which is mounted in the track [6],[7]. The big difference to the Hyperloop concept is the achievable speed. While the Transrapid can reach a maximum speed of 501.5 km/h [8], the Hyperloop is said to be able to reach 1220 km/h.

Table 1 compares the existing systems presented above with the Hyperloop concept. Here, "x" represents a fulfilled property and "-" a non-fulfilled property.

Table 1: Comparison of operation control systems for existing ground transportation systems with requirements for Hyperloop.

	850 km/h max. velocity	Linear Motor	Low-pressure tube	Automatic operation	Centralized control
Hyperloop	x	x	x	x	x
Railway	-	-	-	-	x
RailCab	-	x	-	x	-
Transrapid	-	x	-	x	x

Functional requirements of a Hyperloop operation control system

As described in the introduction a linear motor in the configuration of a synchronous longstator linear motor is used as the propulsion system for the Hyperloop demonstrator built by TUM. Because the synchronous longstator linear motor is integrated into the track and not into the vehicle, the propulsion system is directly controlled by the operation control system and not by the vehicle. The ideal architecture for the propulsion and operation control system is modular. By independent autonomous operation of each module, redundancy is achieved which increases reliability. A communication interface between the modules enables them to cooperate to achieve the goal of safely driving the Hyperloop capsule along a track several kilometers long. For the 24 m Hyperloop testtrack only one module is to be built. This module will be tested and can be reused for a longer Hyperloop testtrack.

To identify the functional requirements of the operation control system for the 24 m Hyperloop testtrack a function tree analysis has been carried out. In the function tree analysis, general main functions are divided into subfunctions. The subfunctions are in turn divided into subfunctions. The process is repeated until the functions cannot be divided any further. This process ensures that no functional requirement is forgotten. Figure 1 shows the main functions of the 24 m test section.

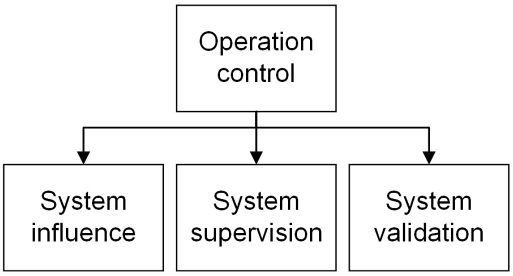

Figure 7 Representation of the two highest levels of the functional tree analysis carried out for the 24 m TUM Hyperloop testtrack.

The function “system influence” combines the drive of the vehicle, the pressure control in tube and the power supply of the vehicle. The function “system supervision” summarizes the acquisition of sensor values, the evaluation of the sensor values and the graphical representation of these values. The system validation function comprises the acquisition and storage of sensor values that are not required for condition monitoring but for the subsequent validation of simulations.

System architecture of the TUM Hyperloop demonstrator

The system architecture developed for the TUM Hyperloop demonstrator is presented in Fig. 2. In the developed architecture, there is only one "ground station" called “HMI”, which is operated by one operator. The “HMI” visualizes the sensor data and transmits the inputs from the operator to the “main system”. On the "main system" a state machine is implemented in software, which puts the system into discrete states. Depending on these states, the outputs are set and thus the subsystems are controlled. The operator's commands are requests to the "main system” to change the state. Since in a state machine not all states can be reached directly by all states, the inputs of the operator are accepted or rejected depending on the current state. In addition to the operator input, the "main system" can process sensor values and use this data to monitor the state of the system. The "main system" can communicate with the drive system and the vacuum system via an EtherCAT bus. While the drive system controls the drive, the vacuum system controls the pressure inside the tube. The safety system observes the state of the whole system separately from the “main system”. If a safety critical state occurs the safety system communicates with the main system and takes over control. This way only the safety system has to be certified according to safety norms and not the whole system itself.

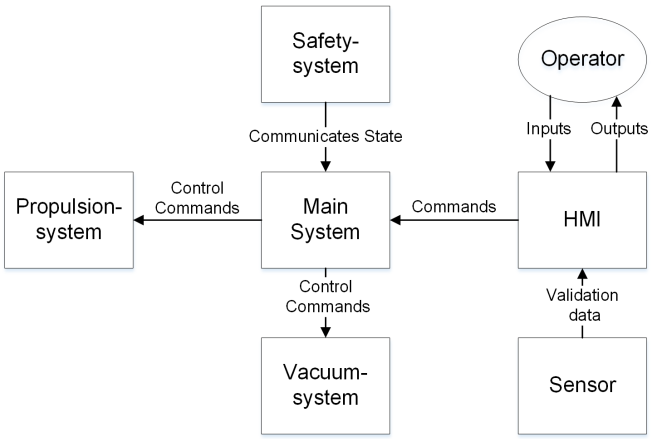

Figure 8 Schematic of the TUM Hyperloop demonstrator’s system architecture.

Evaluation of the developed system architecture

For the evaluation of the presented architecture a hardware in the loop simulation has been conducted. During this hardware in the loop simulation an industrial pc running the software for the operation control system has been connected to a realtime pc running a simulation of the 24 m test track. Special focus was placed on the modelling of the drive system. For the control of the drive system the current position is needed. Since the position is measured by the vehicle and transmitted to the propulsion system via a communication system, latencies are introduced. The influence of these latencies on the propulsion control have been evaluated using the hardware in the loop simulation.

For the drive control a field-oriented controller has been implemented on the realtime pc. The hardware in the loop simulation showed that latency did not affect controller stability, but it did induce vibration. This vibration can be seen when looking at the acceleration plot below.

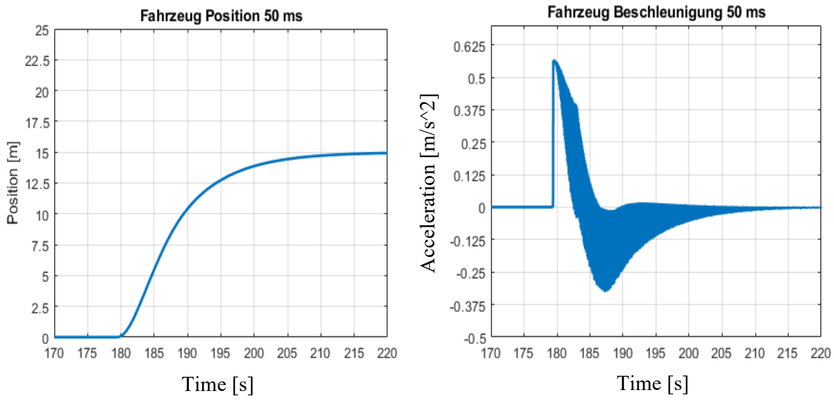

Figure 9 Results of the hardware in the loop simulation. a) displays the position of the capsule over time and b) displays the acceleration of the capsule over time.

The vibration is caused by the delayed update of the phase currents. The delay of the phase currents causes the vehicle to overtake the magnetic field in the long stator and then to be decelerated by the magnetic field. This circumstance can be understood from the pole angle. The pole angle represents the angle between the rotor, in this case the vehicle, and the magnetic field. The force on the vehicle is at maximum when the pole angle is 90 degrees. The direction of acceleration also changes with the sign of the pole angle. As can be seen in Fig. 4, at a latency of 50 ms there is a point at which the pole angle changes between a positive and a negative value.

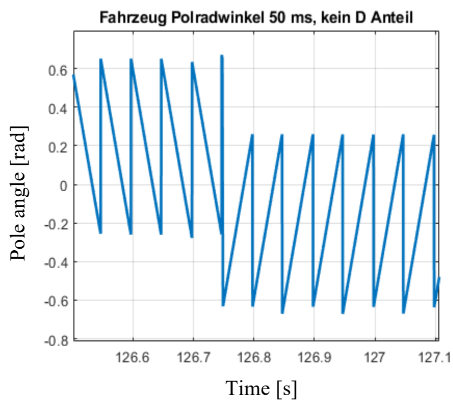

Figure 10 pole angle of the vehicle

For the vehicle speed which is supposed to be achieved on the 24 m test track a maximum communication latency of 10 ms at which no vibrations occur has been identified.

Conclusion

In this work, the fundamentals for an operation control system for a 24 m Hyperloop testtrack were investigated. During this research, existing operation control systems were investigated, the functional requirements were defined, an architecture was designed and a simulation model of the vehicle, the low-pressure tube and the drive system was created. From the investigation of existing operation control systems, it was found that the Transrapid is the most comparable system to the Hyperloop due to the propulsion system integrated in the track and the high speeds. However, since the Transrapid's speeds of about 500 km/h are significantly lower than the Hyperloop's 850 km/h and the Transrapid does not use a low-pressure tube, the Transrapid's operation control system cannot be used directly for the Hyperloop.

A function tree analysis was used to analyze the functional requirements. In this functional tree analysis, the main functions were divided into sub-functions. From these functional requirements, a system architecture consisting of a "Main System", an "HMI" and individual subsystems was subsequently defined. To validate this architecture, a hardware-in-the-loop simulation was performed. The simulation focused on the effects of communication latencies on the drive system. The simulation showed that the controller of the drive system remains stable despite high communication latencies. However, it was shown that vibrations are induced for latencies above 10 ms. These vibrations can be attributed to the delayed update of the phase currents and the resulting fluctuation of the pole angle.

Since the possibility of sensorless control was not considered in this work, sensorless control should be implemented in future work. Simulations can then be used to identify the speed above which sensorless control performs well. This speed can then be used as a benchmark to calculate the maximum allowed latency of the communication.

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