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Potential Analysis for Vacuum Transport Technologies in the Public Transport Infrastructure of Switzerland

Phase 1:
Life-Cycle Analysis with Focus on Energy Consumption and Environmental Impact of a Vacuum Transport Infrastructure

Technical Summary

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Executive summary

The availability of a high-quality public transport system has become key to Switzerland's high living standards. At the same time, the increase in population and economic growth inevitably leads to a higher demand for transport. As the impact of the changing climate is becoming increasingly more pressing, the need for reduction of emissions is inevitable also in the transport sector. In Switzerland in particular, the transport sector contributes to almost 40 % of all CO_2 emissions [BAFU 2022]. It is therefore apparent that today's transport infrastructure needs to adapt to live up to both the societal and environmental requirements at the same time. New modes of transport, in combination with extension and improvement of the existing ones, are required.

Hyperloop is a concept that addresses transport at a range between a hundred and a thousand kilometres, by travelling at speeds comparable to aeroplanes, but with a considerably lower ecological footprint. The system, as it is thought, strongly mitigates the limitations of current rail, aerodynamic and rolling resistances, by magnetically levitating above the track in a tube with a partial vacuum. Therefore, not only it could be possible to add a new mode of ultra-high-speed rail to the current network, but also to shift large parts of emission-intensive short-haul flights to sustainable, fully electric ground-based transport. However, the promising vision of hyperloop will only have a chance at becoming reality if it can guarantee benefits to the society in terms of capacity, comfort, travel time and mainly ecological impact.

In this study, the feasibility of the introduction of a hyperloop system to the Swiss transport infrastructure is assessed, both from technological as well as environmental aspects. Therefore a methodology is developed to flexibly assess capacity, energy consumption and environmental impact of a hyperloop system depending on the chosen design parameters. Additionally, a framework is provided to address some of the most pressing questions of hyperloop technology. This includes a software that is able to evaluate the influence of numerous parameters and assess the requirements on the power grid, as well as an interface with the life-cycle inventory database *Ecoinvent*, which is widely used in academia and industry to assess the environmental impact of various products and processes.

This work aims at presenting and assessing the environmental and energy-related impacts of a feasible concept of hyperloop system, focusing on a coherent synthesis of all its parts rather than on a detailed development of any component in particular. Every technological principle included and modelled is either already in use or has seen a proof of concept in industry or academia. Therefore, it is shown that already today's technology is sufficient to build a functional hyperloop system. Furthermore, with the expected technological advancements through cumulative investments and the developments in the construction sector, hyperloop systems are expected to be built at substantially lower energy and environmental footprint in the years to come. Hence, not only will it be feasible, but also it will represent an improvement in terms of capacity and environmental impact compared to other modes of transport.

With a reasonably conservative configuration, which approximately displays the energy efficiency of trains, hyperloop would be able to cover the full rush hour traffic between Zurich and Bern and reduce travel time over this distance to approximately ten minutes. The hyperloop configuration used to prove this includes safety distances large enough to brake behind an instantly stopping vehicle.

The key challenges and potentials for improvement from a technological point of view are addressed, both for technical feasibility and for environmental impact: a more detailed knowledge of the aerodynamic drag, launcher power management, improvements in thermal storage systems and more economical designs of the tube as well as rail cross section would substantially reduce construction and operational emissions. Key technological concepts that are needed to establish a full (potentially European) hyperloop network are provided.

Overall, the study demonstrates that a hyperloop indeed can provide the speed of a plane at the ecological impact level and capacity of a train, therefore closing a large gap in the future network of transport. The impact of tunnelling will be included in the second part of the study.

1 Introduction

Hyperloop is a concept proposed first in the late 18th century [IEEE 2021] and made popular again in the beginning of the 2010s. The vision of hyperloop consists of vehicles levitating in a tube with a reduced air pressure, which enables fully electric ground transport at the speed of planes or higher, opening a potential addition to the existing transport infrastructure. With hyperloop the travelling distances between Zurich and Berlin would shrink to mere 48 minutes and a trip between Zurich and Geneva would take less than half an hour.

1.1 Why hyperloop now?

Apart from the appealing, futuristic vision and reduction in travel time, there are strong reasons that advocate for the introduction of a hyperloop infrastructure now.

The predicted future of transport

The combination of population growth and economic expansion will inevitably lead to a higher demand for transport, i.e. *more* and *faster* passenger-kilometres (pkm) will have to be served by some sort of transport infrastructure [Schafer&Victor 2000; Marchetti 1994]. At the same time, climate change has begun showing its alarming impact on human activities and the need to reduce greenhouse gas (GHG) emissions of the transport sector is as imperative as ever [IPCC 2022]. This reduction can either come from less movement or from smarter ways of transporting people and goods: plausibly, it will result from a combination of both. Among other goals, hyperloop aims at capturing a part of the volume of short-haul or domestic flights to reduce emissions.

The potential of hyperloop

Most likely, the aforementioned modes of transport will complement each other to build tomorrow's transport system: an extension of the current rail network in Europe is unavoidable, and intercontinental connections are unlikely to be connected on ground any time soon. However, hyperloop comes with certain characteristics that justify its inclusion into the transport landscape of tomorrow:

- **Speed regimes:** to increase capacity, a disentanglement of the infrastructure for fast (long-distance) and slow (local) modes of transport is necessary. This means that new routes eventually have to be constructed to increase the volume of transported passengers. Compared to high speed railway (HSR), hyperloop however has the potential to run at more than twice the speed of the most advanced HSR trains with similar environmental footprint.
- **Aerodynamic drag:** the major share of the energy consumption for a HSR is aerodynamic drag. Hyperloop mitigates to the highest possible extent the remaining drag.
- **Saturation of current networks:** airports are reaching their saturation point in terms of volume [ITF 2017, EuroControl 2018]. Since an extension of the airport infrastructure in the context of climate change is somewhat inadequate, the addition of hyperloop to the aviation network could provide additional capacities.

- **Issues with sustainable alternatives:** sustainable aviation fuels (SAF) are suggested as a key solution to decarbonize aviation, but their diffusion is hindered by the competition with other sectors for biofuels [Mission Possible Partnership 2022] and by the low technology readiness level (TRL) and scale of power-to-liquid (PtL) fuel production [IEA 2021, IEA 2021]. In addition, the low well-to-tank efficiency of PtL fuels implies that the (renewable) electricity required to fly on SAFs will always highly exceed the direct use of electricity in a hyperloop system. Finally, non-CO_2 climate forcers related to aviation (primarily contrail cirrus) would also not necessarily be abated by SAFs [Brazzola 2022].

Switzerland's role in pioneering transportation technologies

Switzerland has shaped the future of transportation many times before, by pioneering railways and completing flagship projects unique of its kind, such as the alpine base tunnels. As the European movement for Hyperloop is taking momentum, another unique opportunity is arising for Switzerland to continue their role as world leader in public transport.

1.2 Scope of the study

The goal of this study is to examine the feasibility of hyperloop with focus on environmental metrics. It shall not be read as a blueprint or design suggestion, but rather as a collection of proven technical solutions that show the potential of hyperloop even without a system design optimization. A more extensive list of omissions and assumptions can be found in the full report which will be published at the end of the follow-up phase of the project in 2023.

Financial situation

The cost of a hyperloop infrastructure is to be determined during the follow-up phase of this project in early 2023. However, it is clear that cost figures for an entire European network will be in the three-digit billion range. It is noteworthy that already now the financial means invested in hyperloop on a European level are remarkable. In Northern Italy, a 800 M€ tender for the construction of a first hyperloop track has been published [Hyper Transfer Project].

2 The hyperloop system

2.1 What is the hyperloop system?

Fig. 2.1 shows an overview of the different parts of a hyperloop system from a functional perspective, outlining the key elements independently of their specific technical designs. There are three main physical subsystems: track, vehicle and station.

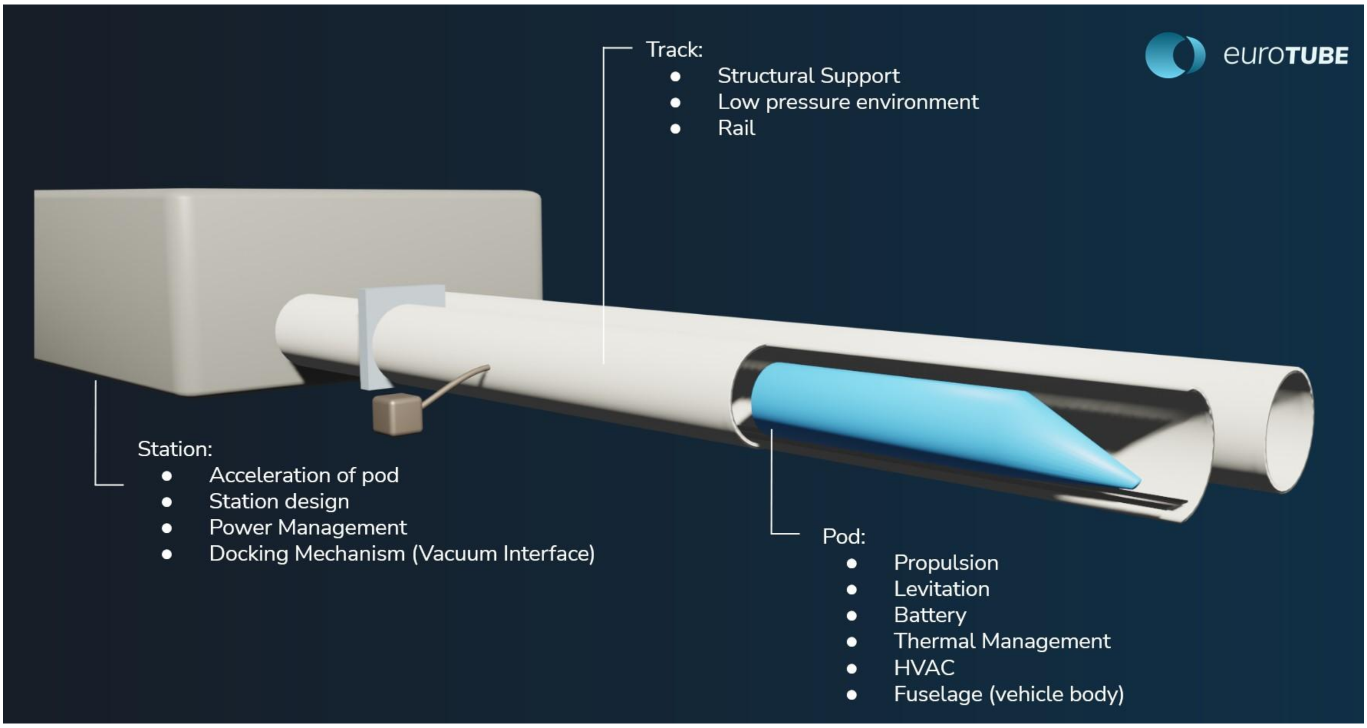

Fig. 2.1. *Main subsystems of a hyperloop system with the corresponding components*

The hyperloop vehicle (frequently also called “pod” or “capsule”) is travelling in a tube which provides structural support as well as a low pressure (1-100 mbar) environment. A mechanism needs to be provided to accelerate the vehicle within reasonable time to its maximum speed. Once at top speed, a propulsion system of the vehicle is needed to counteract the resistive forces still acting on the pod. In addition the vehicle is levitating without contact to the track, thus allowing for much higher speed and almost no wear and tear of the guideway material.

2.2 Modelling of technical components

For each of the above mentioned functionalities of a hyperloop system, there are various approaches and technical solutions which are explored and also intensely discussed among the key players in the hyperloop field. The modelling choices made in this study are not yet definitive answers and are subject to change as data is collected and the model is expanded in the future.

Pod

- **Propulsion (during cruise)**: The vehicle is equipped with a linear motor acting on a passive track and this mainly saves many emission-intensive materials by avoiding an active track (e.g. the Japanese Maglev).
- **Fuselage:** For this model, the fuselage is assumed to be similar to a small aircraft, having the same requirements of temperature insulation, air-tightness and structural integrity.
- **Aerodynamic drag:** The modelling of the aerodynamic drag in an enclosed system at very high speeds is a highly complex and computationally exhaustive task, which is not yet well determined. Compared to slow-speed applications, in a hyperloop setup the drag coefficient becomes also a function of the speed. For this study, a 2D numerical simulation is built and run on a commercial software for a reference case.
- **Magnetic levitation:** In this work an electrodynamic suspension system (EDS) was chosen. Strong magnets on the pod-side move over a conductive plate on the track side, inducing eddy currents due to the change in magnetic field in the rail, which again counteract this change and create a repelling force. To improve the self-weight of the system, the model includes the use of ReBCO superconducting tapes submerged in liquid nitrogen. The technology to store liquid nitrogen safely is well established and used in various industries, and the cost of ReBCO-tapes is relatively low.
- **Thermal management:** Due to the vacuum environment, any thermal exchange with the tube or partial vacuum is highly dampened. There are considerable heat sources onboard the vehicle that have to be dissipated. The most promising technologies currently available are phase-change materials (PCM), e.g. water-ice or salt hydrates.

Track

- **Tube:** In the context of the current energy and raw materials shortage, both availability and cost of large steel pipes are questionable. A second major disadvantage is the specific manufacturing of such parts which is limited to a few specific geographic locations. These pipes would then have to be transported over large distances, complicating transport and increasing cost and environmental impact. The main advantage of local construction materials like concrete is that it can be produced efficiently and casted on site. Concrete is more cost-efficient and has the potential to be produced from fully recycled composite materials in the future. While the steel provides air tightness intrinsically, in a standard concrete solution a vacuum-proof liner has to be applied to the tube.
- **Leakage & vacuum assurance:** EuroTube engineers have been estimating the leakage through the concrete-liner hybrid system and designed a pumping design for both the first pump down and the continuous maintenance of the vacuum.
- **Switch:** Hyperloop switches have to work contactless (allowing the levitation to be maintained) and passively, since at high speeds they will be several hundred metres in length. The levitation technology modelled in this project allows for a fully passive switch.

- **Tunnels:** The life-cycle assessment (LCA) of the tunnelling process will be part of the second phase of the project. The complexity of modelling costs and grey emissions in construction prevents any fast approach. Extensive investigation and deep industrial feedback is needed to avoid distorting the results and providing a state-of-the-art projection for the expected time horizon.
- **Vacuum interface**: As part of an *Innosuisse* project with industry, EuroTube has developed a valve that is capable of isolating vacuumed sections even with tubes several metres in diameter, allowing for the efficient use of airlocks.

3 Methodology

In order to derive environmental and other key performance indicators (KPI) of the hyperloop infrastructure, two subsequent steps are necessary:

- Determine the physical design of the system such that it can adequately perform the desired transport service;
- Build the life-cycle inventory and perform the impact assessment considering the material and energy requirements for the construction and operation of the system designed in the previous step.

Fig. 3.1 shows a schematic representation of the approach used to model the hyperloop system and compute its KPIs. The following steps are iteratively repeated to evaluate the system:

1) The set of independent input parameters is fixed.
2) The passenger demand for the line is either assumed *a priori* or taken from an exogenous transport demand model.
3) Experts from the civil, mechanical and electrical fields provide scale-up models of the functional components of the hyperloop system for a large-scale system in the future.
4) A mathematical model derives the physically possible hyperloop configuration and evaluates all the necessary system specifications: onboard battery size, weight of the pod, the specific energy consumption, etc. A more detailed description is presented in the next section.
5) The life-cycle inventory (LCI) is then built up starting from the design model outputs (e.g. size of needed onboard propulsion motor) with the inclusion of other non-automated system components (e.g. metallic materials needed for rail) and of all upstream processes (e.g. cement production).
6) Once established, the LCI is then evaluated through the life-cycle impact assessment (LCIA), which returns several environmental metrics, such as the global warming potential (GWP) expressed in gCO_2-eq./pkm. As the underlying LCI, the LCIA includes construction, operation and end-of-life of all parts of the system.
7) Based on energetic and environmental KPIs, other system hyperloop configurations are tested by adjusting some of the independent input parameters.

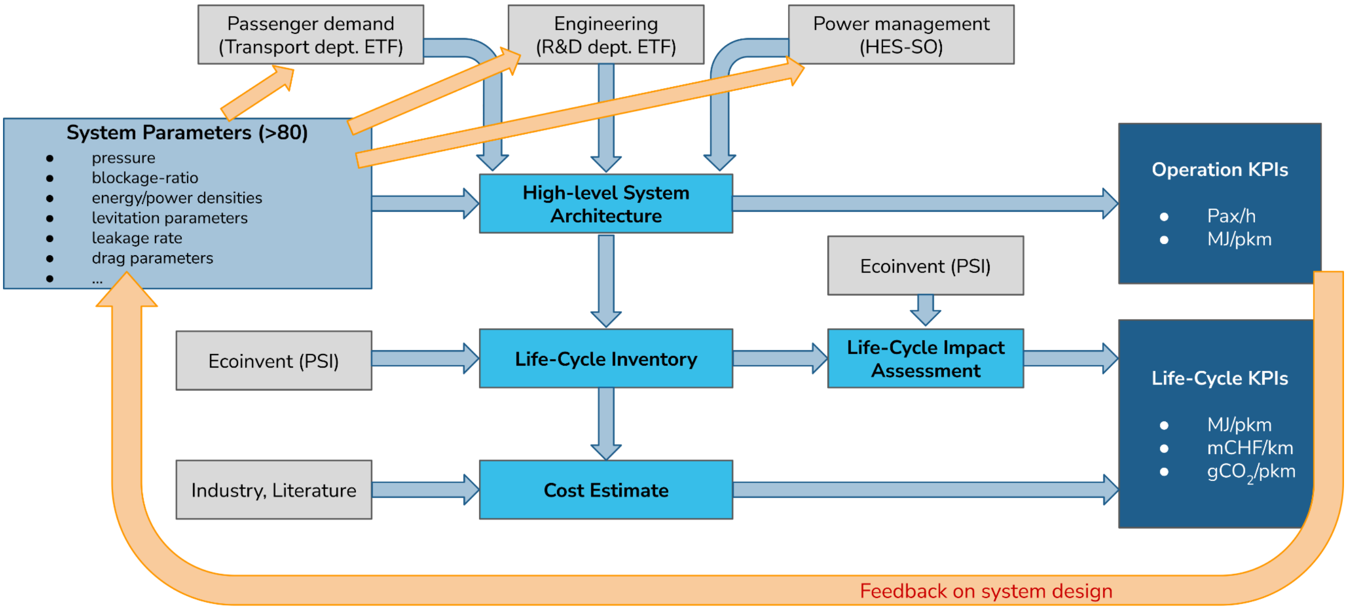

Fig. 3.1. *Schematic representation of the methodology employed to size the hyperloop system and estimate its KPIs.*

Hyperloop modelling tool

The system model is written in Python. Most system parameters are chosen *a priori* by the user. However, several properties of the pod cannot be chosen independently (e.g. weight of vehicle, size and power of levitation and propulsion systems, amount of coolant needed, etc.) since they influence each other. The model is not an optimization process but is a system of equations solver that returns the only physical solution possible. This approach ensures short computational times and to draw logical connections between changes in input parameters and the resulting system performance. An extensive sensitivity analysis on specific parameters is in fact performed and presented in this report.

4 Hyperloop energy consumption and environmental footprint

4.1 Simulated scenarios

Before exploring different hyperloop system configurations a reference case is defined: its input parameters are set in a conservative way in order to present an impartial assessment, but the model suggests that the resulting system would also be technically plausible and environmentally sound. Table 4.1 shows the main relevant parameters.

Table 4.1. *Main parameter values for the reference case.*

System Parameter	Value	Unit
Cruise speed	250	m/s
Acceleration/Deceleration of pod	1	m/s^2
Capacity of the lines	84’330	px/day
Average load factor	80	%
Network length	300	km
Passengers per pod	70	px
Blockage ratio (BR): area of tube obscured by pod	0.6	
Pressure in tube	10	mbar
Onboard battery cell energy density	500	Wh/kg

4.2 Capacity of the system

With a 70 passengers pod, throughput capacities of 5’000-10’000 pax/h per direction can be unlocked, while with 200 passengers per vehicle the maximum capacity stretches to 28’000 pax/h per direction, achieving the levels of conventional modes of transport. In this study the infrastructure is assumed to be between the Swiss cities of Zurich and Geneva, for a total distance of approximately 300 km. For the passenger traffic the forecasted flow in 2050 between Zurich and Bern is instead assumed, since this is the busiest segment of the Zurich–Geneva corridor. As a potential showcase, the hyperloop system is thus sized to accommodate the entire 2050 traffic on both road and rail between Zurich and Bern [ARE 2022].

4.3 Energy consumption during operation

Figure 4.1 shows the breakdown of the system energy consumption for different system configurations in terms of tube’s pressure (p) and blockage ratio (BR).

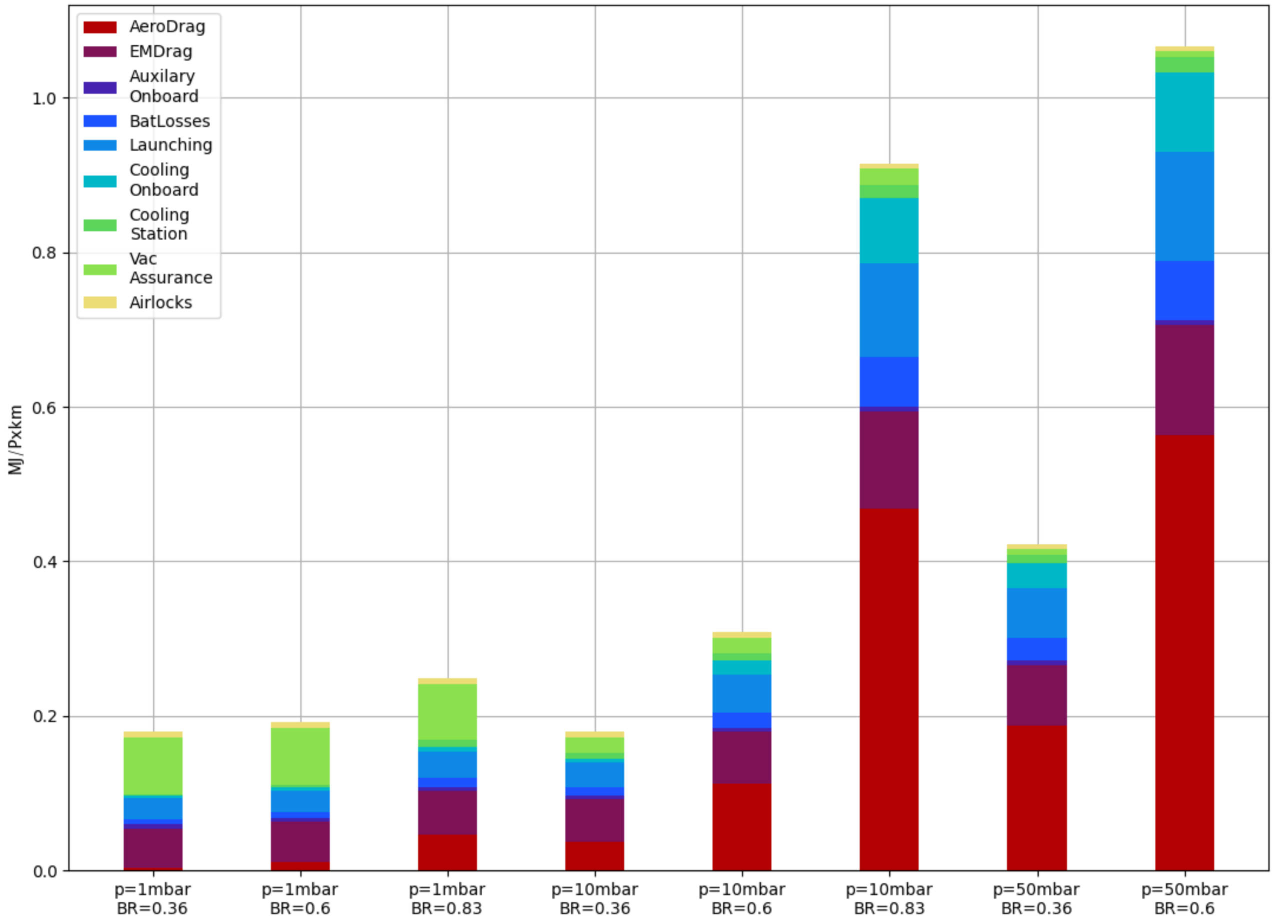

Fig. 4.1. *Operational energy breakdown for different combinations of blockage ratios (BR) and tube air pressure (p). The combination with p=10 mbar and BR=0.6 corresponds to the reference case.*

Despite the lower tube pressure, aerodynamic drag is still a major contributor to the energy consumption due to the piston effect that materialises when travelling at high speed in a tube. For this reason, Figure 4.1 displays the importance of achieving low pressures and choosing adequate blockage ratios. Other important sources of energy consumption are the electromagnetic drag and the pod's acceleration (also called "launching phase"). Airlocks are optional in a hyperloop design, but can already be identified as no major problem in terms of energy consumption. With these results, it seems clear that the major improvements in hyperloop in terms of operational energy consumption can be made with more detailed knowledge of the aerodynamic behaviour of the vehicles under reduced pressure.

Sensitivity Analysis

Fig. 4.2 shows the specific energy consumption during operation for different system designs. It is visible that, although many uncertainties in the technical understanding of some components persist, the choice of suboptimal designs is what mostly penalises the system. For instance, the selection of small pods (28 passengers) or high blockage ratios (0.83) has a much worse impact than if the development forecast of linear motor or battery has been overestimated by a factor of 2.

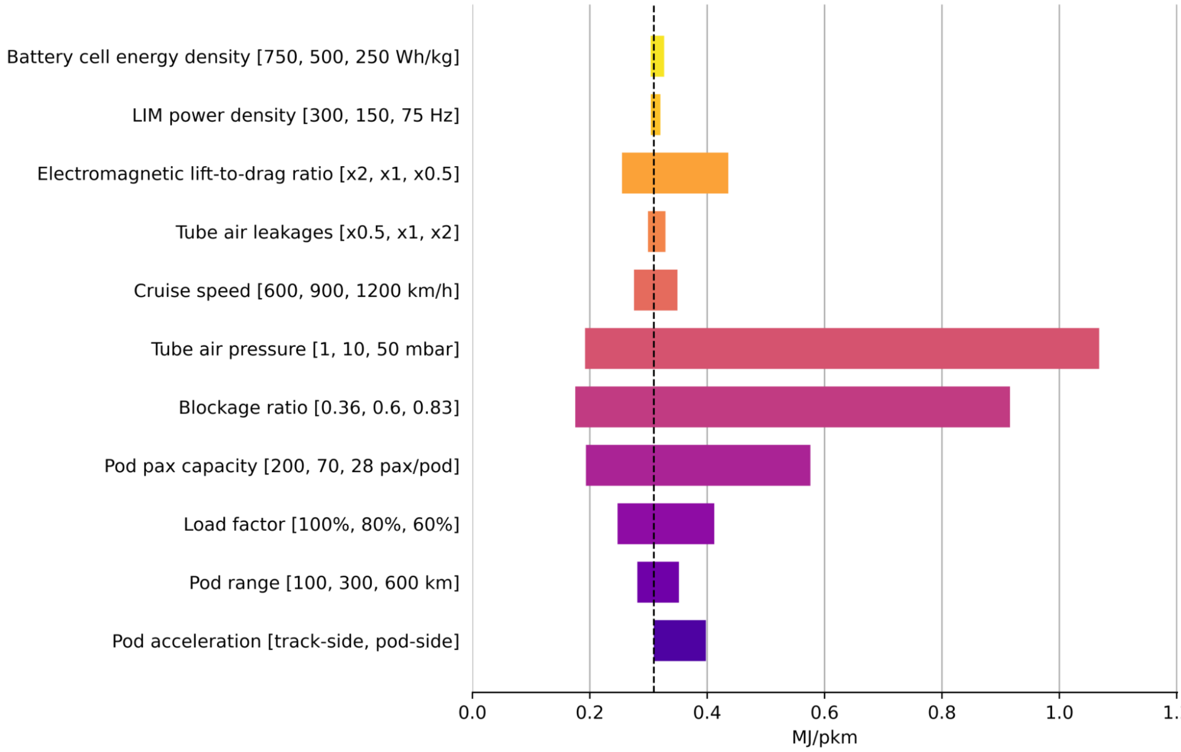

Fig. 4.2. *Specific energy consumption of the hyperloop system (in MJ/pkm) for various input designs settings. Each row explores a different dimension: first and third values correspond to the left and right margins of the bars; the second value is captured by the dashed line and indicates the reference case.*

4.4 Life-Cycle Assessment

The life-cycle assessment evaluates the total cradle-to-grave environmental footprint for the whole infrastructure. Rather than on parametric sensitivities, the following analysis focuses on few significantly divergent design choices since this is where the LCA's capability to capture upstream emissions is more vital. Three cases are thus defined:

1. Reference case: as described in Table 4.1 with track-side acceleration and recuperation.
2. Pod-side acceleration and recuperation: neither launcher nor recuperator on track.
3. Steel case: analogous to the reference case with the concrete tube replaced by steel.

While the significant contribution of the rail is equal for all designs, there are fundamental differences in the tube construction between concrete and steel, with the latter contributing to almost half of the entire GWP of the steel case. The omission of launcher and recuperator saves substantial amounts of emission-heavy metals compared to the reference case, but it leads to larger pod batteries and slightly higher energy consumption. However, the overall LCA seems to favour the self-propelled design.

It is important to highlight that the total GHG emissions would be higher for sections placed underground due to the energy and material investments involved in the tunnelling process. However, the comparison between the cases here described is still valid.

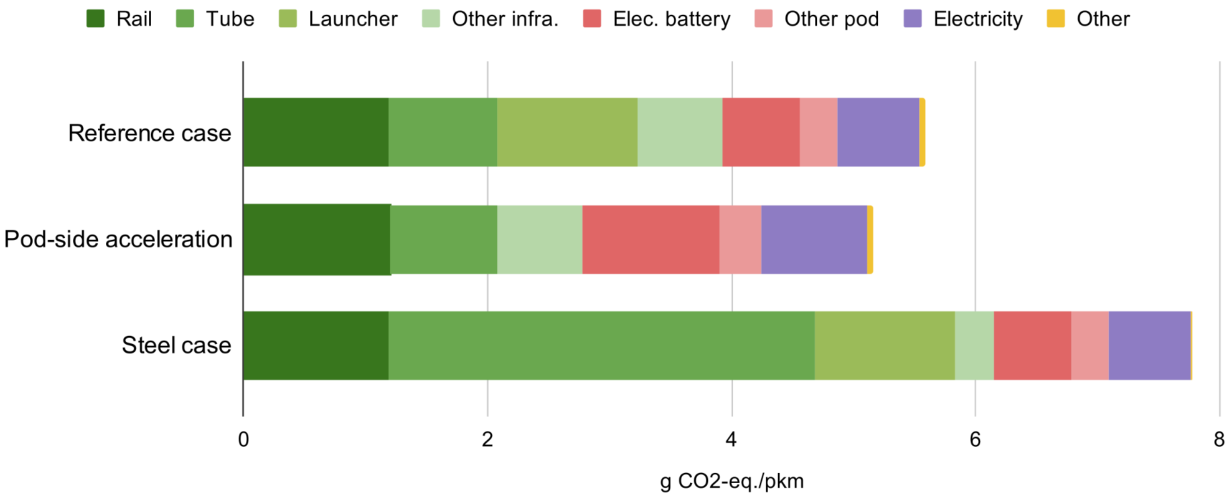

Fig. 4.3. *Total life-cycle impact of three different hyperloop designs on the GWP (measured in kg of CO_2-equivalent per pkm).*

5 Benchmark with alternative modes of transport

The comparison of the life-cycle GHG emissions between hyperloop and other modes of transport is displayed in Fig. 5.1. For aviation two comparisons are provided: with conventional fossil jet fuel and with synthetic kerosene. All electricity needs for e-kerosene production are supplied by wind generation, while all other modes employ local electricity, specifically assumed to be today's consumption mix of the Swiss Federal Railways (SBB) [Ecoinvent 3.8]. For each mode of transport the GWP is split by source of emissions: infrastructure (stations, airports, tubes, rails), vehicles (pods, planes, trains), electricity during operation (and for e-kerosene production), upstream fuel supply (especially for aviation) and other emissions during operation (SOx, NOx, SF6 refrigerants).

Aircrafts running on e-kerosene solve the problem of inflight emissions since the CO_2 emitted during operation matches the CO_2 absorbed by direct air capture (DAC) to generate the fuel: for clarity, the lower magnified barplot cancels out these two components of the life-cycle. However, these aircrafts still require the same energy intake as their predecessors. In addition, the low electricity-to-fuel conversion process for e-kerosene makes the net electricity consumption of these aircrafts considerably higher than trains or hyperloop.

The GWP related to electricity consumption is rather comparable for train and hyperloop. We further can conclude that hyperloop and railway consume on average a comparable amount of electricity *per pkm*. Regarding the vehicles' GWP, hyperloop's pods show the largest relative footprint and this is primarily due to the central role that electric batteries have in the pod life-cycle.

The infrastructure footprint for all modes of transport is surprisingly similar: in the case of aviation, despite the no need for a connecting infrastructure, airports still display a large environmental impact. This comes from their extensive land use, the substantial consumption of heat and electricity for the buildings, the fuel consumption for ground operations and the resources needed for aircraft maintenance.

The difference between rail and hyperloop infrastructure is instead primarily due to the assumed utilisation of the lines. On one hand, the average seat offer of railway is about 36% lower than for hyperloop, because the latter is sized to serve the most crowded Swiss corridor (Zurich-Bern), while the former comes from an average of Swiss long-distance train services [Ecoinvent 2007]. On the other hand, the load factor employed for long-distance trains is 28% [Ecoinvent 2007] while for hyperloop an utilisation rate of 80% is predicted. The latter estimate can be considered achievable thanks to the higher modularity of the vehicles and their more frequent departures, which may allow for a better demand-following timetable and a higher occupancy rate. In addition, load factors of 80% are typical for aviation [ICAO 2022, Notten et al. 2018].

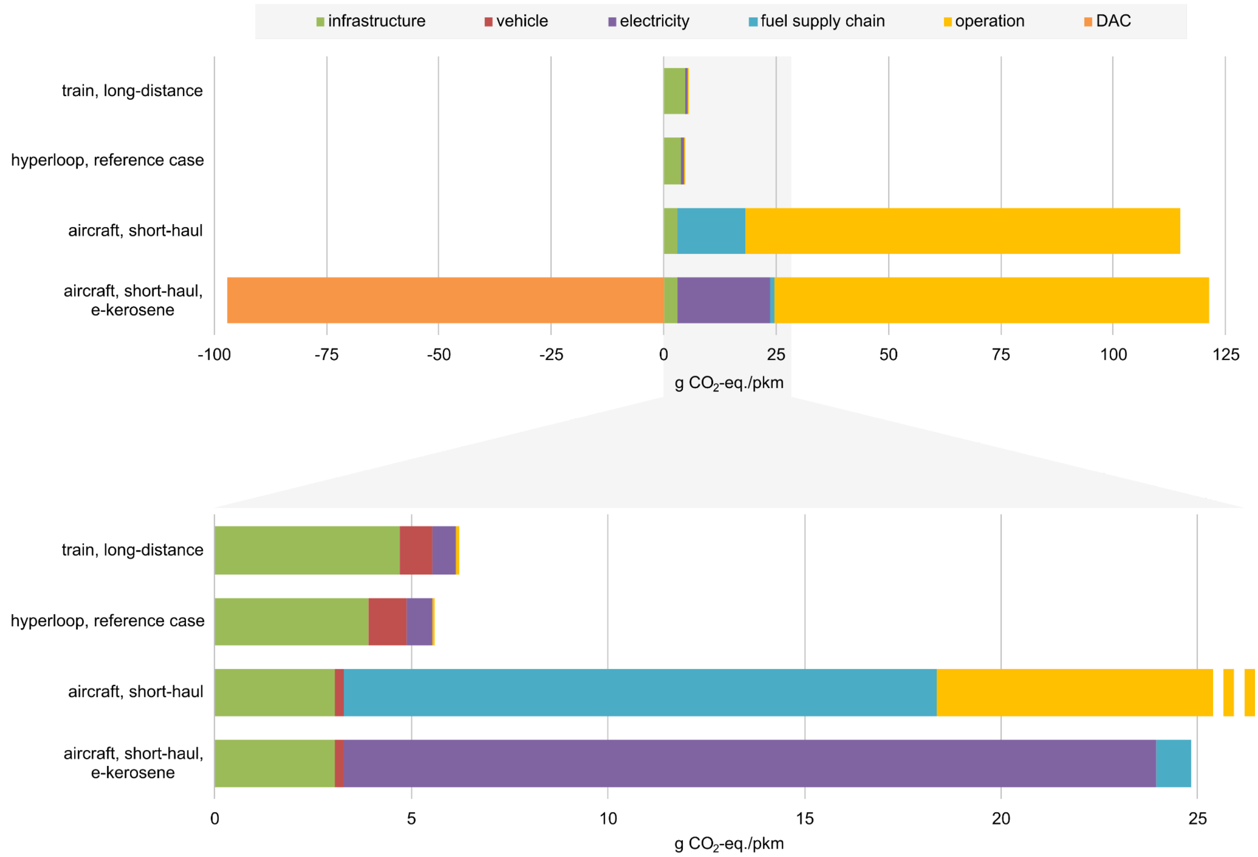

Fig. 5.1. *GHG emissions along the life-cycle of different transport systems, normalised per pkm. The lower plot displays a magnified section of the above between 0 and 25 g CO_2-eq./pkm. For e-kerosene aircrafts the CO_2 absorbed by DAC can be discounted from the CO_2 emitted in operation.*

6 Detailed study on launcher power management

The study includes the detailed modelling of a power management system for an hyperloop station: vehicles are accelerated from the track on a so-called “launcher” (similar to an aircraft carrier, but using electromagnetic force and being several kilometres long). The vehicle reaches the maximum speed at the end of the launching process. During cruise, the vehicle is supplied by an on-board battery to maintain the maximum speed. Finally, when the capsule arrives at the destination, it will be braked by a recuperator section. The regenerative braking energy can be harvested for further acceleration of other capsules running in the opposite direction. However, the total power from the substation is often limited, which is defined in the contract with the transmission system operator or the local distribution system operator. A high-power storage (HPS) module is thus studied to shave the peak power in the morning and evening traffic peak periods.

In the acceleration and deceleration areas, there are several challenges to be addressed. Firstly, the loads change sharply as the demanded power can be very large at the end of the acceleration area and in the beginning of the deceleration area. Secondly, there are multiple capsules running in the launcher and recuperator simultaneously in the morning and evening peak time. The peak load would be larger than the maximum power that can be supplied by the substation, which would result in financial penalties. In the most extreme case, it was tested whether hyperloop could serve the full demand at rush hour between Bern and Zurich predicted for 2050. Without any buffer mechanism, the power demand at the substation reaches a maximum peak of 39.6 MW. However, for the largest part of the day, the power demand would be much lower. To limit the substation and contract expenditure, it would thus be beneficial to install a high-power storage (HPS) system — such as a supercapacitor — that could shave the peak load at rush hour. Fig. 6.1 shows that a 5.2 MW HPS could already reduce the maximum power by 5 MW: this solution would be more economical than raising the maximum power available from the energy provider. It is important to underline at this point that the power needed is significant but still in the range of current technology and power grids.

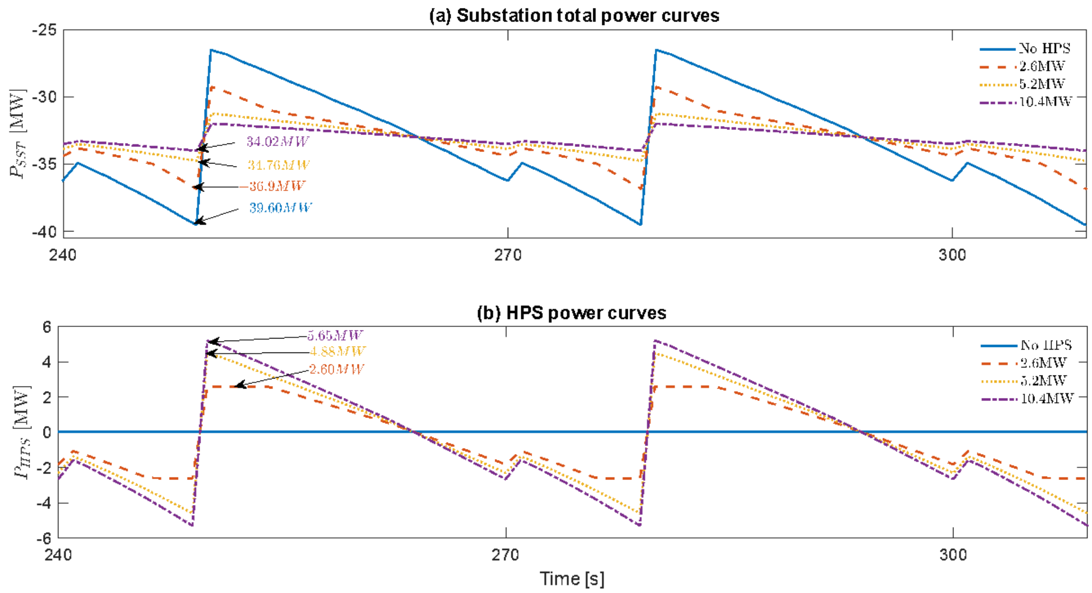

Fig. 6.1: *Effect of peak shaving for different high-power-storage (HPS) capacities.*

7 Conclusion

7.1 Summary

In this study, the following key statements are established:

- **Capacity:** With the vehicle defined in the reference case and a safety distance that allows for braking behind an instantly stopping vehicle, a capacity to cover the full rush hour between Zurich and Bern can be achieved. This capacity can also be served from the electrical grid side. Therefore, doubts about the capacity of hyperloop are mostly unjustified, especially in view of the EU working on standards for the introduction of the virtual coupling model [MOVINGRAIL D4.3, 2020]. Since the aerodynamic drag only marginally depends on the vehicle length, increasing the vehicle capacity almost proportionally reduces the operational energy consumption per passenger (MJ/pkm).
- **Technology:** Already today, all the key technologies needed to construct a hyperloop exist and have undergone proof of concept. With the improvements to come in the next few years, the key performance indicators of hyperloop have the potential to significantly improve, especially those closely related to other e-mobility trends like energy storage systems.
- **Framework (hyperloop modelling tool & substation model):** A framework has been established to evaluate different design configurations and to address fundamental hyperloop design questions. This method can be used (and extended) in the future to further investigate the many design choices yet to be made and to identify the most pressing topics for further research.
- **Environmental impact:** It is demonstrated, using in-depth life-cycle assessments, that hyperloop is indeed at the same level of conventional high-speed trains in terms of greenhouse gas emissions as well as operational energy consumption.

In conclusion, the study demonstrates that a hyperloop indeed can provide the speed of a plane at the ecological footprint and capacity of a train, therefore closing a large gap in the future network of transport.

7.2 Outlook about the second phase of the project

The second phase of the project will revolve around the following topics:

Economic assessment

Being an entirely new infrastructure, hyperloop will come - like other similar infrastructure of this scale - at a considerable price tag. A cost figure will be the main result from the follow-up phase of the project and to be published in the first half of 2023.

Modelling of tunnels

LCA of tunnelling requires an extensive and *ad-hoc* modelling approach since the framework used in this study is missing the necessary data sets and the construction of vacuum-proof tunnels is still at a conceptual phase. Studies with major players in the field are ongoing and will be part of the follow-up work of this project.

Study of networks

This study proves the feasibility of a point-to-point hyperloop system. Naturally, even in a plausible Swiss use case, one would develop a network with intermediate stops as well as a sensible international integration to the on-going European plans, to increase the positive impact of the new transport infrastructure. Concretely, network design and effects could be investigated, such as demand modelling, reachability of regions, pod sizing and fleet design.

Further levitation and propulsion systems studies

Even though there exist already fully functioning and commercially implemented levitation systems, further work is needed to find the optimal (economically viable, most ecological, most reliable and switch-compatible) solution for a completely new large-scale infrastructure. The same reasoning holds for the linear propulsion system.

Aerodynamics

Despite the extensive work undertaken on the system aerodynamics, there remain many challenges that should be investigated further, such as shock wave propagation, drag-induced lift effects and heating of the system due to friction.

7.3 Further Information and Disclaimer

A more detailed report about the study will be published upon the completion of the second phase in 2023. It shall be clarified at this point that the purpose of this study is to investigate the feasibility of vacuum transport and deliver a valuable benchmark including a first-of-a-kind LCA. The work should not be understood as a design suggestion or blueprint of any kind and the data used in this work need to be further validated by extensive simulations and large-scale tests.