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HeliRail: A railway-tube transportation system concept

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ABSTRACT

Helirail is an energy efficient mass transit transportation system concept, which combines developments in low-pressure tube transport with existing high-speed railway infrastructure. It addresses the problem that, currently at low speeds, steel wheel railways are an energy efficient transport mode, however at high speeds, >80% of energy is used overcoming drag. This means minimising these resistances presents a high-impact opportunity for reducing railway energy consumption. To reduce resistance, HeliRail consists of an airtight tube-track structure that allows existing steel-wheel trains to travel on existing railway corridors where slab-track is suitable, with minimal drag. The running environment is low-density heliox gas, held inside lightweight tubes, slightly below atmospheric pressure to minimise species transport. HeliRail captures this energy saving as an operational reduction, thus improving the energy efficiency of high speed rail by 60%. On a high capacity route, annually this could save enough energy to power 140,000 homes. Deploying Helirail on an existing line does not increase train cruising speeds, however a secondary benefit is journey time reduction, achieved using a small part of the energy saving for improved train acceleration. Unlike previous evacuated tube transportation embodiments, the system is interoperable with traditional rail lines/trains meaning vehicles can pass through HeliRail sections and onto traditional steel-rail networks. This also reduces land-purchase requirements. Further benefits include improved safety compared to vacuum transportation and fewer service disruptions compared to rail. Capital cost is low compared to a new rail or pressurised transportation line, and is recovered after a period competitive with renewable energy technologies.

1. Introduction

Approximately 20% of the world's energy is used for transport [1], and this is predicted to increase by 31% by 2050 [2]. Further, considering Europe as an example, transportation is the single largest emitter of greenhouse gases (30.8%) and the only sector to have experienced a growth in emissions since 2007 [3]. When considering approaches to reduce transport energy consumption and emissions, rail is attractive compared to road and air because the rolling friction between steel wheels and rails is low. This is true when moving at low train speeds, however, as train speeds increase, air resistance and drag increase rapidly. Therefore railway transport becomes significantly less energy efficient, even at moderate speeds, as shown in Fig. 1, which is plotted using Eq. (1). This is particularly important considering current plans to expand the global high-speed rail (HSR) network.

Aerodynamic resistance is a well-known challenge in aviation, and to overcome it, airplanes climb high where the air density is low, thus reducing air resistance and improving energy efficiency. This concept of reducing the air resistance on vehicles is more challenging for land transport, however the desire for faster travel continues to inspire research in this area.

For example, one of the first concepts for pressurised land transportation was proposed by Medhurst in 1799. It was expanded upon by a variety of engineers, including by Brunel who built an 'atmospheric railway' in 1847. The underlying concept was to use a differential air pressure to power a vehicle. Later, Goddard [4,5], proposed an alternative, where vacuum pumps reduced pressure in a tunnel guideway, while the vehicle was magnetically levitated.

These implementations were ultimately commercially unsuccessful, however recent advances in vacuum pump technology have led to renewed vigour into pressurised transportation systems. These included concepts from [6–8], which like Goddard, proposed using reduced running environment pressures to minimise resistance, rather than differential air pressures as propulsion. Thus, research efforts have shifted towards constructing new, dedicated transport infrastructure networks that move magnetically levitated, battery powered pods inside vacuum tubes at speeds ≈1000 km/h. The attractiveness of this comes from the speed increase and energy savings primarily afforded by minimising air resistance.

This mode of transport is often colloquially referred to as 'Hyperloop' and thus, hereafter the term is used loosely to simply refer to the general concept of vacuum transportation. Significant research ef-

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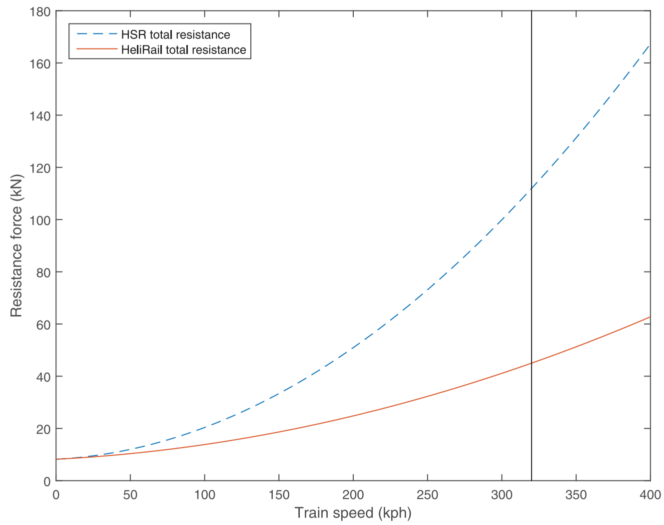

Fig. 1. Typical resistance on a high speed train (black line=320 km/h).

forts have been placed on developing Hyperloop vehicles, for example [9,10]. Additionally, researchers have investigated bridge dynamics [11], ground dynamics [12], aerodynamic design [10, 13] and earthquakes [14].

Regarding commercialisation, there has been the development of test tube tunnels [15], and scaled test runs in absence of human passengers, to speeds of 457 km/h [16]. Further, generic Hyperloop guidelines for design, operation, and certification have been proposed [17]. Thus far, most implementations focus on reducing drag via low pressure air environments, however it has also been proposed by [18] to fill a tube with low-pressure heliox (a helium and air mix [20]). The advantage of helium is that it has a significantly lower density than air, thus reducing drag. Therefore it was proposed for the purpose of slightly relaxing the low-pressure tube environment, thus reducing costs and improving safety.

A challenge with these approaches however (even for the pressure range proposed in [18]), is that it is costly to maintain a very low-pressure environment over long distances. This is because the pumps required are at the limit of current technology, making them expensive and energy intensive to run. Further, it is challenging to overcome the safety issues associated with placing people in a near-vacuum environment, without building significant additional protective infrastructure. Therefore [19] proposed replacing the low pressure air within the evacuated tubes [19], with heliox held at atmospheric pressure. This provides reduced resistance because heliox has a lower density than air and dispenses with many of the safety concerns associated with operating at low pressures. Further, the capital and operational costs associated with high performance pumps are not required.

A challenge with using heliox at atmospheric pressure though is that the piston effects due to high-speed vehicles running in a narrow diameter tube is high [21], thus cancelling many of the energy efficiency benefits achieved when operating at low pressure. Considering the energy consumption trade-off between piston effect resistances and maintaining a low-pressure tube, it has proven challenging to find an environmentally friendly solution to achieve ground transport at speeds of ≈1000 km/h. Instead, from an energy requirements standpoint, Hyperloop has been shown to offer similar performance to existing HSR [22], but possibly carry fewer passengers (for example, 30 people per pod [23]).

A further challenge with most current embodiments of vacuum transportation is that they propose using the magnetic levitation of vehicles. This makes interoperability between vacuum transport and existing transport infrastructure challenging. Even if steel wheel-technology was adopted instead of magnetic levitation (e.g. the 'Vacuum Railway' [4]), the vehicle design and dynamics needed to operate at 1000 km/h are vastly different compared to operating in the region of 300 km/h. These considerations mean Hyperloop-type vehicles are incompatible with traditional railway networks, thus requiring entirely new transport corridors and networks to be constructed. The prohibitive cost associated with this is one reason why alternative market disrupting guideway technologies such as 'Tracked Air Cushion Vehicles' (e.g. [24,25]) failed to trump incremental advances in steel-wheel railway technology.

Considering the challenges associated with the high speed transportation of people/goods at near-vacuum conditions over long distances, this paper presents a concept solution that combines the advantages of HSR and Hyperloop within a single system. The concept uses heliox filled tubes to reduce drag on steel-wheel high speed trains. First the general concept is presented, including the key details of the proposed guideway and vehicle design. Then the benefits of the system are discussed. Finally, practical application and key risks are explored. It should be noted that the present embodiment of HeliRail is not presented as a finalised system, but instead as a concept to be built upon and refined by others.

2. HeliRail transport system design

2.1. General concept

HeliRail builds upon previous vacuum transportation related research, but instead of offering an alternative transport mode to HSR, key tube-transportation concepts are integrated with HSR, thus creating a hybrid system. This system consists of sealed tubes filled with heliox, that enclose steel-rail, concrete slab HSR trackforms, serving to reduce aerodynamic forces on running trains. This results in a significant reduction of energy usage during train operation. The key components of HeliRail are shown in Fig. 2, and the main technical points for understanding are:

1. HeliRail can be used for either new lines or for retrofitting existing HSR lines. When deployed to retrofit a concrete slab track, pre-formed tubes are fixed to the existing trackform. Alternatively, when deployed on ballasted lines, the ballast track superstructure is replaced with pre-formed tube-slab integral units
2. Tubes are used to enclose double-track railways only, which are the most common HSR track type. Compared to enclosing single tracks, this reduces the blockage ratio by maximising effective tube area, and thus minimising the piston effect
3. Post-construction, a ducting system extracts the ambient air from inside the tubes and replaces it with heliox. Once complete, the heliox is held permanently at marginally below atmospheric pressure (≈95–99%) during train running. The ducting system maintains pressure and recycles heliox to ensure it meets the required level of purity. Solar panels power the ducting system.
4. High speed trains are sealed by design, however the pressure differential between train and tube minimises heliox contamination via air passing across vehicle car body seals. Also, although heliox is breathable, the pressure differential minimises heliox contact with passengers
5. Due to the minimal tube-vehicle pressure differential, compared to evacuated tube transportation, only lightweight tube infrastructure and seals are required. Therefore a range of materials (e.g. transparent plastics) are viable candidates for the tube structure. Lightweight materials help reduce capital costs, while reduced leakage rates help reduce operational costs
6. Trains can transition from HeliRail to/from existing steel-rail networks seamlessly. Fast-deploying air-locks allow trains to enter/exit HeliRail sections without a loss of heliox, thus maintaining pressure and density. An example HeliRail journey is shown in Fig. 3

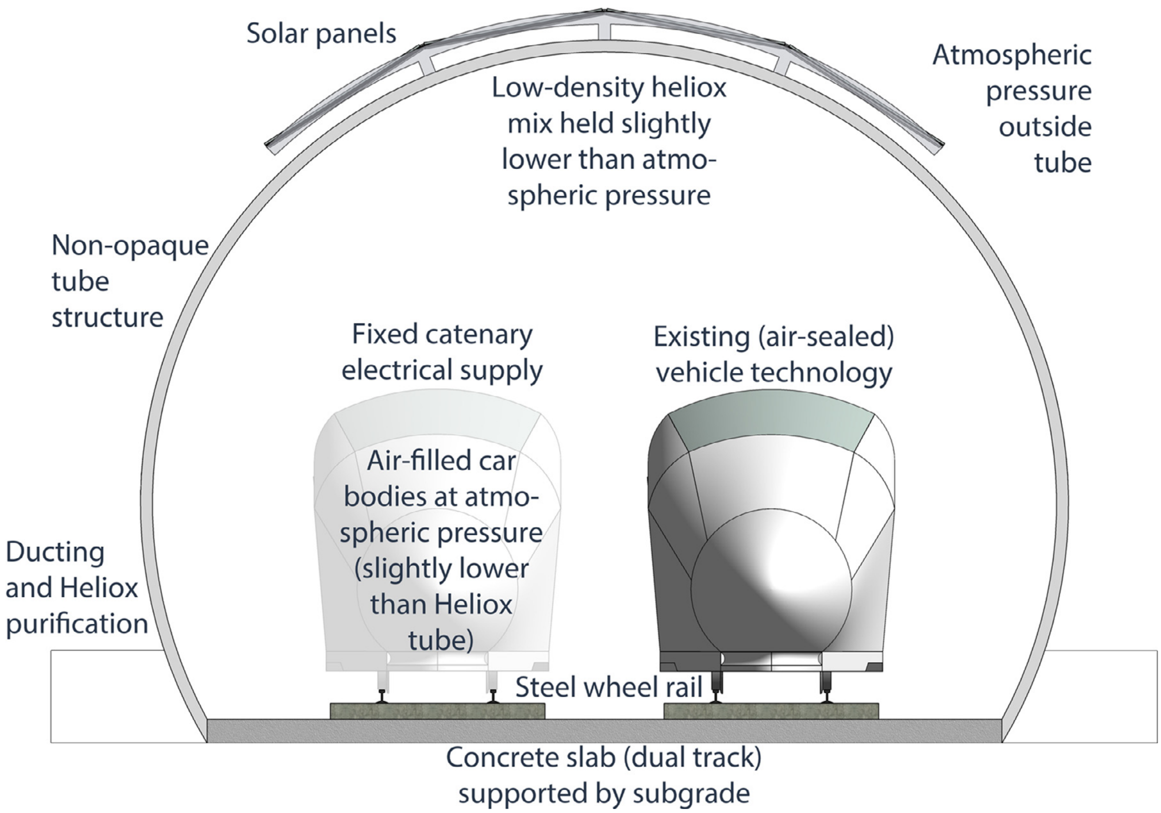

Fig. 2. Key HeliRail components (not to scale).

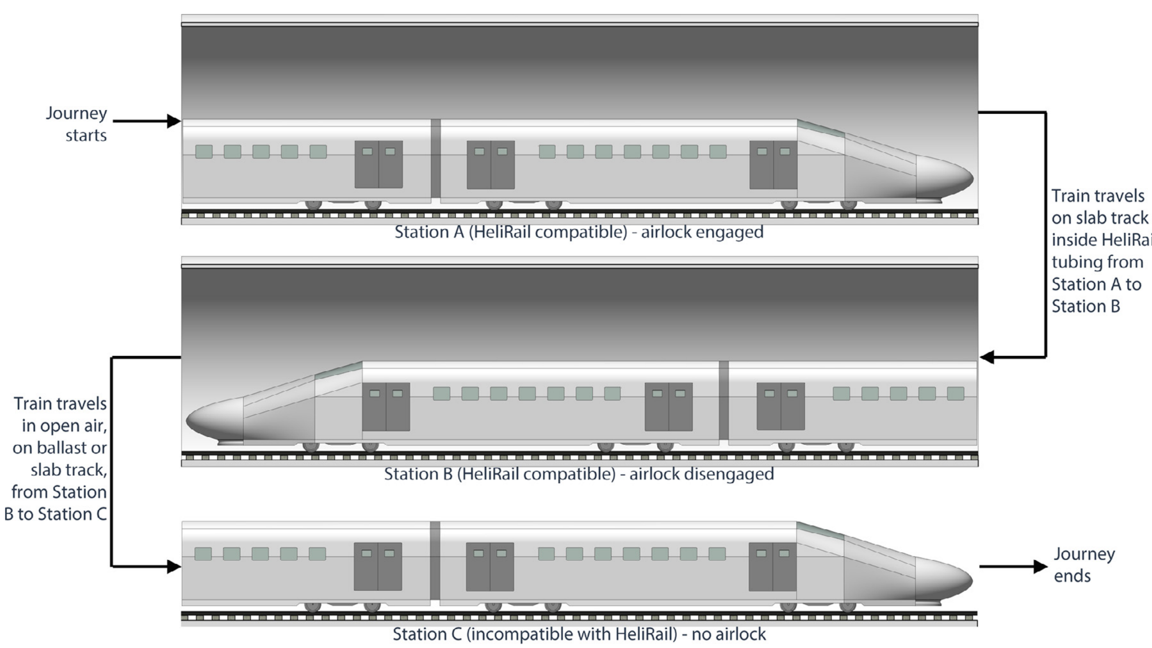

Fig. 3. An example HeliRail vehicle journey (top=start, bottom=end).

Considering predicted changes to our climate and the need to preserve resources, HeliRail shifts the focus of pressurised land transportation from increased speeds, to energy efficiency. The system is compatible with existing rail corridors, transporting passengers at the same speed as existing High Speed Rail (HSR) technology, however with 60% less energy than that used by either HSR or Hyperloop. This facilitates: high interoperability, high line availability, low capital/operational costs and minimal maintenance requirements.

2.2. Guideway structure design

At low train speeds, the majority of a train's energy is used to overcome rolling resistance (Fig. 1). However, aerodynamic resistance has a squared mathematical relationship with speed (e.g. Eq. (1)), meaning at high speeds, much greater energy is required to move the train. For example, based upon Eq. (1), at 320 km/h, 84% of energy is used to overcome aerodynamic resistance. Alternatively, if the guideway provides a

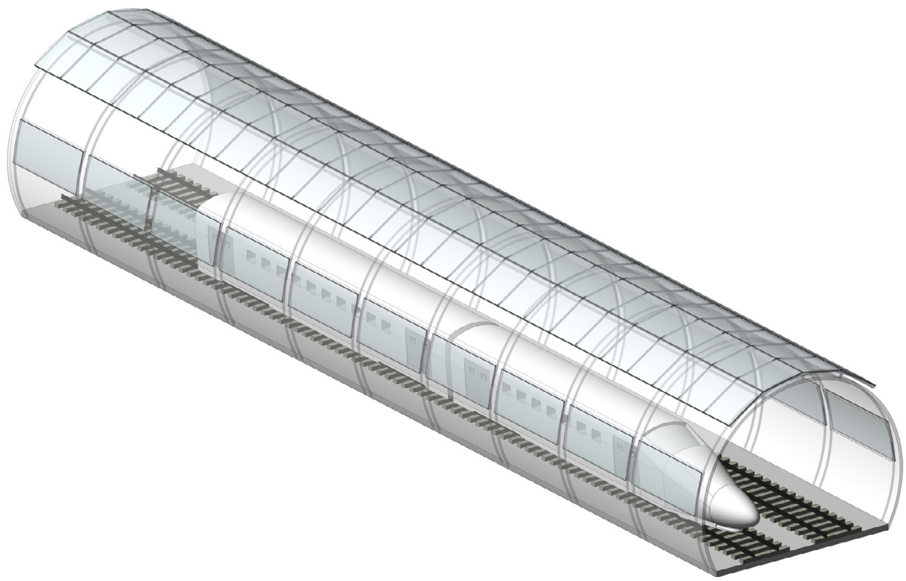

Fig. 4. 3D view of HeliRail.

vacuum condition within which the train can move, this aerodynamic drag is close to zero, thus allowing the train to move using minimal energy.

Vacuum conditions however are very challenging to achieve/maintain in practise, so alternatively air resistance can be minimised via either placing the tube in a state of low pressure, lowering the gas density within the tube, or a combination of both. A consequence of this however can be the creation of the 'piston effect', which occurs when an object moves in a confined gaseous space. The piston effect creates additional resistance, potentially counteracting the energy benefits achieved by running a train inside a low pressure environment.

To overcome this, HeliRail will be deployed solely on dual track arrangements rather than single tracks, and thus the main tube will have a large cross-sectional area (Figs. 2 and 4). This will reduce the blockage ratio compared to individual smaller tubes, as is commonly proposed for evacuated tube transportation, thus minimising the piston effect [21]. A challenge with dual tracks however is that vehicles typically travel in opposite directions, thus changing the effective cross-sectional area and possibly creating a highly turbulent zone. Therefore, when trains pass each other inside the same tube but in opposite directions, a pressure relief arrangement to minimise train-train interaction will be used. It will operate automatically during carefully timed vehicle passages.

The tube will be held at slightly lower than atmospheric pressure to minimise heliox seeping into HeliRail vehicles, rather than for the aim of reducing drag. To achieve this, only a small reduction in pressure is required, estimated to be in the range 95–99%. If the pressure differential is too high, then gas seepage from the vehicles into the heliox tubes will accelerate, thus contaminating the heliox mix with nitrogen. To achieve the differential, fan technology will be used rather than compressor technology because it is suitable for marginal pressure reductions, yet has a lower cost.

Trains moving within HeliRail tubes will inevitably induce gaseous compressions. Although the heliox will be held at a reduced pressure to minimise air contamination, compressions will increase the probability of the transport of species across the tube and vehicle seals. This is particularly true considering the small size of helium atoms, meaning that over time, the heliox running environment will become less pure. To manage this, the fan technology used to maintain the pressure differential will also be connected to a ducting system that will maintain contamination at a percentage that balances the need for low density with the cost of purification.

The tube structure must be durable, cost-effective to manufacture, able to handle high-speed pressure forces, air-tight and resistant to weathering. Although steel has been proposed for Hyperloop during initial trials [16], it has challenges with impact loads, corrosion, repairability, thermal expansion characteristics and cost. Therefore alternative materials will be used for HeliRail.

Firstly, considering structural design, HeliRail tube pressure will only be marginally different from atmospheric, meaning the static pressure forces on the tube lining will be much lower compared to an evacuated tube. Instead, dynamic forces on the lining are likely to be more dominant, arising due to the fluid-structure interactions during train passage caused by gaseous compressions. However, vehicle speeds will be significantly lower than Hyperloop, meaning that the dynamic forces will also be much lower. Therefore alternative, more lightweight and cost effective materials, constructed using more relaxed tolerances are viable.

In particular, transparent plastics are a viable choice for HeliRail. They will provide an enhanced passenger experience compared to an opaque/translucent structure. Further, passengers are typically satisfied with a 50% field of vision from within trains. Therefore the tube can be constructed from a combination of materials, including these plastics. For example, transparent plastic windows can be combined with novel precast concretes (e.g. carbon-fibre textile reinforced concrete as proposed by [26] and intermittent steel bracing). An example of this is shown in Fig. 5. Using a hybrid structure will allow for the optimisation of parameters such as strength, cost and carbon footprint.

Perhaps more importantly though, a hybrid tube structure will allow for greater design flexibility for expansion joints and seals. These interfaces will be more straightforward to design in comparison to an evacuated tube because the tube pressure (static and dynamic pressures) are much less onerous. The number and location of seals depends on whether the install is a retrofit or new-build, because new-builds will be pre-cast track-tube units meaning expansion joints will be the main location of seals.

For the case of new lines, track slabs will be assembled together with the tube to create a single standalone integral unit. This allows for higher precision sealing compared to retrofitting existing lines. On existing lines, the method for fixing the tube to the slab depends upon the track type, however a universal method could be developed. A heliox impermeable sealant will be applied at all joints as a safeguard to minimise seepage.

2.3. Vehicle design

The trains used on HeliRail are steel-wheeled and operable both inside tube sections and on standard rail routes without tubes. This maximises integration with existing networks, yet can be achieved via mod-

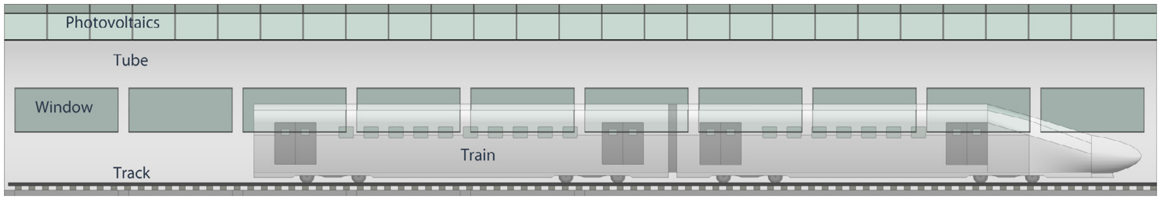

Fig. 5. Semi-transparent HeliRail side-view showing an example tube window solution.

ifications to existing train technology. Compared to developing new trains and new technologies, this saves the significant time and cost associated with building and commissioning new rolling stock. HeliRail operates using steel-wheel vehicles at similar speeds to existing lines meaning modifications are not required to alter track alignments, cant, wheel-rail contact characteristics, vehicle dynamics…etc. Until battery train technology becomes more commonplace, current collection is achieved via an overhead rigid catenary electrical supply, as commonly used in tunnels, and is again compatible with most existing train technology. For existing networks operating solely using battery trains, HeliRail will not require catenary equipment.

A difference in requirements between a train running in air and within heliox is the need to seal cabins from the transport of species between tube and train. Although sealed trains (e.g. non-opening windows) have become the HSR industry norm, they are not currently designed for the HeliRail tube environment. Regarding species transport from tube into vehicle, the small difference in pressure and density between vehicle and tube prevents the seepage of heliox into vehicles. In the opposite direction, the atomic size of air is larger than heliox meaning that small improvements to existing train seals will prevent significant transport of air into the heliox tube, particularly during gaseous compressions. Regardless, it is recommended that an oxygen monitoring system (and regulator) is installed in the vehicle to detect and correct leakage. Finally, trains have a wide range of mechanical and electrical components (e.g. brakes and air conditioning) that are also not designed for HeliRail running. This includes electrical connections that for railway applications, typically operate at Safety Integrity Level 4. However, it is unlikely that a sustained, yet minor change in pressure will have a significant negative performance impact.

It should also be noted that rather than modifying an existing vehicle, a future alternative is to develop a new vehicle that is better optimised for HeliRail networks. This vehicle would have fast deploying carbody seals and an optimised train nose shape to maximise aerodynamic performance. This may include a reduced cross-sectional area to either minimise piston effects or allow for the construction of small diameter HeliRail tubes. Further, on dedicated HeliRail lines, a font-end compressor could even be designed to further reduce piston effects. The vehicle might also use bi-modal battery-electric power, meaning it can run with or without current collection. This would dispense with the need for overhead conductor rails in HeliRail tubes, but also allow for charging on the open network in the absence of tubes. This technology is already proven on Stadler, 'Flirt Akku' trainsets and the Japanese EV-E301 series [27], which can run on intermittently electrified lines.

3. HeliRail benefits

3.1. Energy savings

The resistance (R) to movement of a Shinkansen Series 200 high speed train is approximated in kN using the Davis equation [28]:

$$R = 8.202 + 0.10656v + 0.01193v^2 \quad (1)$$

where v=speed (m/s). This relationship is plotted in Fig. 1 and shows that at 320kmh, aerodynamics account for 84% of the total resistance.

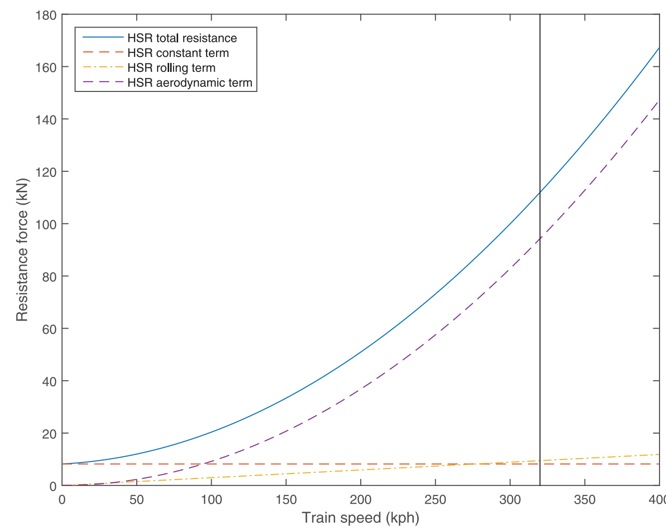

Fig. 6. Resistance force comparison between HeliRail and high-speed rail.

Heliox reduces the tube gas density to approximately 25% of atmospheric, however, to determine the effect of a lower density gas on total resistance, factors including the piston effect and Mach number need to be considered. Firstly, the opposing piston effect resistance is limited because the choice of a single large diameter tube structure, rather than twin tubes, ensures the tube cross-sectional area is much greater than that of the train [29]. This can also be improved by optimising vehicle aerodynamics. Also the Mach number for a train running in Heliox is not a huge concern. Therefore, for the purposes of illustrating the concept, the piston effect is considered negligible and the flow considered as incompressible.

There will be small yet inevitable leakage of the marginally higher pressure air from vehicles into the tube, however a ducting system will maintain heliox purity at a threshold level. Assuming this level results in the true heliox mix having a density of 28% compared to air, then the aerodynamic resistance reduction is 72%. This equates to a total resistance saving of 60% (Fig. 6). To maintain the marginal pressure differential, low-cost and low-energy consumer fans are used, powered by solar panels attached to the outer tube shell (Fig. 2). Air-locks at stations maintain the low density/pressure environment when trains enter/exit the system, meaning minimal energy is required for regaining pressure.

Finally, the power requirement for a typical train at 320 km/h is approximately 10MW (Fig. 1), meaning HeliRail will save 6MW. Considering a 280 km rail journey at 320kph, with 20 km of both acceleration and deceleration, the journey time will be approximately 1 h In this scenario, HeliRail will offer an energy saving of 6 MWh. Considering a typical home uses 4 MWh of electricity per year, then each train journey will save the equivalent of electricity for 1.5 homes per year. For a high capacity line with 8 trains per hour, running 16 h per day in both directions, HeliRail will save enough energy to provide electricity for 140,000 homes every year.

3.2. Safety

In the event of tube or vehicle seal rupture, HeliRail is significantly safer than an evacuated tube system. Firstly, the difference between HeliRail tube pressure and atmospheric pressure is <5%, which is well within the tolerance of the human body. In contrast, the very low pressures employed by vacuum transportation are instantly fatal in the case of human exposure. Secondly, the heliox mix is ≈10–15% oxygen, which although can cause impaired coordination, is above the threshold for human survival (≈6%). Therefore, although air-masks are kept on-board HeliRail vehicles, if the car-body ruptures, the negative effects of passenger exposure to heliox will be limited. Similarly, if there was a rupture in the tube, the only effect would be increased drag on the train caused by air ingress, due to the increased density of the running environment.

Further, HeliRail tubes have a large diameter compared to Hyperloop, thus making evacuation procedures more straightforward. It is also safer than HSR tunnels from a fire perspective because helium is inert and oxygen content will be below the threshold for burning (≈16%). Therefore HeliRail offers elevated fire protection. To protect against the gradual seepage of air into the tube (e.g. via vehicle or tube cracks) and increasing oxygen levels above the threshold level, the duct system will maintain a threshold level of heliox purity.

HeliRail's enclosed environment also increases safety. It prevents undesirable modifications to the wheel-rail contact patch from tree leaves, ice and other related contaminates. Further, regarding train strikes, HeliRail's enclosed nature prevents public/animal trespass on the line, therefore reducing accidents.

3.3. Economics

HeliRail capital costs vary depending upon whether the line is a ballast upgrade, slab upgrade, or a new line. Regardless, some of the larger physical item costs are: the tube structure, helium gas, pumps/fans and duct system, seals, photovoltaic cells and conductor rail. Additional costs may include concrete slab track if upgrading a ballasted line or planning a new line. For cases where existing rolling stock technology is used, additional vehicle costs are low, however for cases where new train technology requires development, extra cost is likely.

HSR lines are constructed to offer a step-change in the transport links between strategic locations, compared to existing infrastructure (e.g. traditional rail). They are typically deployed to either connect locations where there is no existing rail link, or as an additional route connecting locations. Where an older/slower rail line currently exists, it is uncommon to upgrade this for significantly higher speeds. This is because engineering (e.g. alignment curvature) and passenger experience (e.g. delays) factors make this option challenging. Therefore additional land purchase is required. Hyperloop has been mooted as a successor to HSR, and therefore the possibility of constructing Hyperloop as an additional route connecting cities which are already served by HSR, has been considered. For similar reasoning to HSR deployment, such Hyperloop lines are likely to require land purchase.

Alternatively, for cases where HeliRail is used to upgrade existing HSR lines, the large costs associated with land acquisition needed for an alternative vacuum tube route are not required. Instead, HeliRail is retrofitted to the existing infrastructure. This is also attractive from a construction timeline viewpoint, because large-scale land purchase often involves protracted legal negotiations, which can take years to navigate depending upon national legislation.

Further, minimal ground works costs are required during upgrade because the tube structure provides additional bending stiffness to the concrete slab track. Further, for new lines, this elevated track stiffness will also reduce ground works costs because less remedial works are required to address poor ground conditions. Also, Hyperloop operates using magnetic levitation which at very high speed, is at risk of dynamic instability if there are small changes in the distance between vehicle and track. In comparison, HeliRail is steel-wheel and operates at the track design speed (i.e. lower than Hyperloop), meaning it is more tolerant to lateral/vertical curves and temperature expansion. Therefore guideway geometry is relaxed, meaning construction and maintenance costs are reduced.

Table 1
Approximate capital costs for HeliRail dual-track system ($USD).

HeliRail solution type	Cost per km ($M)	280 km route ($M)
Ballast upgrade	7.1	1997
Slab retrofit	4.9	1364

HeliRail tubes are preformed/preassembled units thus maximising construction quality and precision. For ballasted upgrades and new lines, HeliRail tubes and the concrete slab track are designed and constructred together, resulting in combined track-tube units that are assembled on-site in a straightforward manner. Where possible, ancillary equipment (e.g. conductor rail) is installed inside the HeliRail units prior to arriving on-site, meaning on-site construction times are minimised, quality is maximised and working-at-height risks are eliminated. Further, the less onerous pressures inside HeliRail tubes means that the seals, expansion joints, air-locks and pumping hardware are less expensive to design and construct.

Helium is not traded on global markets and its price has been volatile in recent years. Its price varies around the world, depending upon proximity to source, supply chains and whether it is supplied as a liquid or gas. Therefore the initial filling of HeliRail tubes is an important HeliRail construction cost, and subject to fluctuation. Although the price for wholesale purchase suggested by [19] is ≈$2/m^3 USD, to account for this uncertainty, the price assumed here is $20/m^3.

Assuming design costs of 10%, considering the cost items and implications outlined above, and a slab track cost of $2.2 M/km, the total HeliRail capital costs are approximated in Table 1. Note that the cost for new-build lines has not been shown because these lines vary vastly depending upon a range of case-specific factors, including land purchase costs. Comparing the typical construction cost of a high speed rail line (≈$40 M/km [30]), HeliRail offers significant benefits for a modest additional cost (18% for ballast and 12% for slab).

Compared to existing evacuated tube solutions (e.g. [18]), the operational costs of maintaining the running environment are reduced because only minimal losses of heliox occur during operation, meaning the cost of replacing helium is low. Regarding passenger ridership, Hyperloop pods are designed to transport small numbers of people at high speed (≈30 passengers according to [23]). In contrast, because HeliRail uses existing train technology, rolling-stock is significantly larger and longer than Hyperloop pods, with the capacity for many hundreds of people. Therefore HeliRail transports greater volumes of passengers compared to Hyperloop. However, considering HeliRail uses existing HSR corridors, it is anticipated that ridership will be broadly similar to HSR, so the influence of increased fare generation on economics is disregarded for the purposes of this concept paper.

It should also be noted that HeliRail tubes are installed using a phased construction approach without pressurisation prior to commissioning. This means it is possible to install HeliRail tubes on existing lines with minimal disruption to current services. Therefore punctuality metrics and passenger revenue are less impacted compared to replacing the track with an evacuated tube. This reduces operational costs incurred by the existing railway administration during construction.

Finally, ignoring all other operational benefits and costs, and assuming an average energy price of $0.14 per kWh [31], the annual energy saving for the previous 280 km line is $78 M. This equates to a break-even period for a HeliRail investment of 25 years for ballasted lines and 18 years for slab lines. These periods compare favourably with other forms of renewables, particularly considering the potential longevity of

HeliRail tube structures, and non-monetised (and thus not accounted for) secondary benefits.

3.4. Interoperability

A key feature of HeliRail is that it allows trains to pass through the tube system and onto existing ballast/slab rail networks without passengers disembarking. To achieve this level of interoperability, HeliRail operates using steel-wheel vehicles at similar speeds to existing lines and current collection is achieved via existing overhead rigid catenary technology commonly used in rail tunnels. Therefore the mechanical running of the vehicle is identical inside and outside HeliRail tubes. Further, the combination of a pressure and density differential between tube and vehicle, coupled with standard airtight train carbody technology, will allow trains to operate safely at both HeliRail and atmospheric pressures.

3.5. Journey times

The energy savings provided by HeliRail are primarily captured as an environmental benefit, however, a fraction can be used to increase the initial vehicle acceleration phase of each journey. Compared to alternative forms of transport (e.g. airplanes), high-speed trains are slow to reach top speed and the rate of acceleration is significantly below the limits of passenger comfort. Therefore HeliRail uses a small fraction of the energy saving to increase the rate of acceleration. This reduces journey times without negatively impacting passenger comfort.

As shown in Fig. 1, aerodynamics start to affect train power at speeds above ≈90 km/h. Therefore train acceleration reduces as train speed increases. Assuming an average acceleration rate of 0.17 m/s^2 [32], then for the route scenario outlined above, the time required to reach 320 km/h from 100 km/h is 6 min. Assuming HeliRail improves the acceleration rate to 0.34 m/s^2 then 3 min are saved per journey. For the 280 km route case considered above, including deceleration time, journey times are reduced by 4%. It should be noted that journey time improvements are intended solely as a secondary HeliRail benefit and the primary focus is energy saving.

Regarding embarking/disembarking times, these are only marginally longer than current HSR durations. This is because HeliRail operates at ≈95–99% of atmospheric pressure, meaning airlocks can be designed to be lightweight, and to meet safety requirements without relying on complex mechanical safety systems. This makes them faster to operate in comparison to a vacuum system, which needs to protect against the high pressure differential between the tube environment and atmospheric.

Regarding maximum cruising speed, railway alignments are designed for a range of variables, including the expected train type (e.g. tilting or not tilting), and the highest possible expected operational train speed. If faster trains are required, then the route alignment needs modification, for example to increase the radius of vertical and horizontal curves. Therefore, to maximise sustainability and to reduce the cost of new routes, HeliRail aims to run on existing lines, and provide only a minimal train speed increase with respect to HSR. This approach maximises interoperability and energy efficiency.

3.6. Additional advantages

3.6.1. Line availability

HeliRail tubes ensure the track is held within a more highly regulated environment compared to HSR. This protects against leaves on the line, blown sand (i.e. important for lines near deserts) and other weather related delays. Therefore delays and cancellations are reduced, creating value for existing users and creating a demand uplift (including from modal shift), as well as leading to operational cost savings.

3.6.2. Maintenance

HeliRail tubes provide an environment suitable for extensive remote condition monitoring (e.g. lasers and cameras). Although the physical maintenance of tracks will be more challenging due to access restrictions, the rail industry is actively moving away from this form of inspection. Further, it is required less frequently in comparison to HSR because of the shielding provided by the tube structure. However, when required, small sections of the tubes will be de-pressurised using airlocks and a localised ducting system. This minimises the loss of heliox gas.

3.6.3. Reduced time to market for vacuum transportation

Vacuum transportation solutions such as Hyperloop are subject to ongoing research effort, with a range of technical, financial and human factors currently being investigated. HeliRail is a hybrid railway system which builds upon existing infrastructure, meaning there are potentially fewer research challenges to solve compared to a vacuum-based solution. Therefore realising HeliRail in the short-term will benefit the future of Hyperloop by providing valuable insights for Hyperloop designers. These insights are numerous and include the practical operation of tube-based transport, public perception, physical test samples to perform full-scale testing…etc. These advantages may serve to minimise the time-to-market for vacuum transport.

4. Practical application

4.1. Line types

HeliRail is predominantly intended for steel wheel high-speed rail lines and has 3 main applications. All three use a standard concrete slab-track with steel rails at the gauge relevant to the relevant local/national network, meaning track acceptance procedures are minimised:

1. *Existing HSR ballasted lines:* HeliRail tubes cannot be retrofitted directly to ballasted tracks due to the porous nature of ballast. Instead, the ballast track structure is removed and replaced by a combined HeliRail tube and concrete slab-track system. The HeliRail system has a higher stiffness than a ballasted track meaning remedial groundworks are minimal.

2. *Existing HSR slab lines:* HeliRail tubes are retrofitted to pre-cast concrete slab tracks. There are a wide range of commercial slab systems, some with better suitability than others (e.g. permeability considerations due to drainage channels and shear key arrangements). Therefore fixation systems may need to be bespoke for different slab types to minimise permeability. Cast in-situ slabs, such as Rheda 2000, present greater challenges due to the lower construction precision used during their original installation.

3. *New HSR lines:* New lines are constructed using a combined HeliRail pre-cast tube-slab system, resulting in a higher overall track stiffness compared to HSR tracks. Vehicle speeds are lower than Hyperloop meaning the line alignment and earthworks requirements are more relaxed compared to building a new vacuum-tube line, thus reducing route-related costs.

4.2. Interfacing with existing infrastructure

When retrofitting HeliRail technology to existing lines, current infrastructure may need to be considered during design. For example:

- HeliRail will use air-locks to enter/exit the existing rail network while trains are stationary. When applied on existing lines, air-locks may be located either inside stations or on the approach spur, depending upon station turnout complexity. This is because switches and crossings are likely to pose a challenge to HeliRail, however on high speed lines these are most commonly found in close proximity to stations.
- HeliRail tubes will block access across at-grade level crossings. However, this scenario is unlikely to occur in practise because level crossings are rarely used on high speed lines. Further, the rail industry is

actively moving away from these types of crossing, typically opting for grade separation.
- Under certain circumstances such as low-height bridges, rail corridors may require the diameter of HeliRail tubes to be locally reduced from their optimal dimensions. This would increase piston related resistances due to changes in the train-tube area ratio. These types of route are not ideal for HeliRail, however are less likely to occur on high speed lines, compared to traditional lines. Regardless, it can be overcome by modifying the local civil infrastructure, or using dedicated HeliRail vehicles, perhaps with front-end compressors (as proposed in [33]) that automatically commence operation on track sections with reduced diameter tubes. This approach would likely only be considered on a route with many existing HeliRail branches, after HeliRail technology had significantly matured.

5. Risks

Some of the risks to realising HeliRail include:

- *System integration:* Railway systems commonly comprise a large number of components which have complex interactions. Further, they can consist of a mix of new and legacy infrastructure. This needs to be considered when designing HeliRail for both existing and new lines. It would be a particular concern if HeliRail was intended for deployment on slower commuter lines, however its benefits arise from operating at higher speeds, meaning lower speed lines are unlikely to be considered for HeliRail deployment. Higher speed lines tend to be more modern and thus are less likely to rely on legacy systems.
- *Helium availability:* The price of helium is volatile due to global supply chain challenges, and is dependant upon the required location of deployment. Regardless, price fluctuations might affect both capital and operational costs. Ensuring sustainable usage will help manage risk.

6. Conclusions

This paper presents a concept transportation system, known as HeliRail. It is an energy efficient mass transit transport system, which combines new developments in vacuum transport with existing railway infrastructure. It improves the energy efficiency of high speed rail by 60%, and on a single route, can save enough energy to power 140,000 homes every year. Train cruising speeds don't increase, however a secondary benefit is the reduction of journey times, achieved using a small part of the energy saving for improved train acceleration. Unlike current evacuated tube transport systems, it is interoperable with traditional railways meaning rolling stock can pass through HeliRail sections and onto almost any other steel-rail part of the network. This also means that additional land-purchase is not required. Further benefits include improved safety compared to vacuum transport and fewer service disruptions compared to high speed rail. Capital expenditure is low compared to a new rail or evacuated-tube line, and is recovered after a period competitive with current renewable energy technologies. It should be noted that the present embodiment of HeliRail is not presented as a finalised system, but instead as a concept to be built upon and refined by others.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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