Feasibility Study of Suspension and Levitation Systems for a Hyperloop System

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Contents

1 Abstract

Hyperloop is made of different subsystems, each playing a pivotal role in making the system function as intended. One important subsystem is the suspension or levitation subsystem, which addresses the issue of wheel-on-track friction in most existing vehicles. This paper investigates the feasibility of four suspension/levitation systems that have been considered to be integrated into hyperloop. These systems are wheel-on-rail suspension (WRS), electrodynamic suspension (EDS), electromagnetic suspension (EMS), and electrodynamic wheels (EDW). It will investigate the different technologies and mechanisms, costs, and commercialisation of the four chosen systems and aim to compare them using the information presented.

EDW is estimated to be the cheapest magnetic levitation (maglev) technology, but this has not been proven as it has not been implemented yet and there has not been any comparison between WRS cost and EDW cost. EMS has a dynamic, unstable electromagnetic force, but EDS is naturally stable. However, EDS requires a minimum speed to produce a lift force, while EMS does not. EDW can produce lift forces at all speeds and produce simultaneous lift and thrust forces, but it has a highly complex configuration. Although WRS does not eliminate wheel-on-track friction, it is highly commercialised compared to systems using maglev technology. The most feasible system among the considered suspension/levitation systems was inconclusive with the information and assumptions presented in this paper. The most highlighted aspect of the comparison was that the limitations of some systems were overcome in other systems in terms of technology, cost, and commercialisation. This is because of a lack of information on some systems, making it impractical to compare. There is room for more research needed in order to reach a more concrete conclusion.

2 Introduction

This is a study of the feasibility of different hyperloop levitation and suspension technologies. The four suspension/levitation systems chosen as the primary focus of this study are Electrodynamic wheels (EDW), Electromagnetic suspension (EMS), Electrodynamic suspension (EDS), and Wheel-on-rail suspension (WRS). The paper will consist of a technical overview, cost and system commercialisation analysis for each of the levitation/suspension systems. A comparison of the four systems using three comparison metrics: technology, cost, and commercialisation-will be made to highlight the challenges and strengths of each system relative to the others. The information in this paper will be based on existing literature with assumptions, which will be clearly stated and justified in each section. It will focus mainly on the levitation/suspension system and how it might perform in a hyperloop environment without necessarily factoring in the interaction between the levitation/suspension subsystem and the other subsystems present in hyperloop.

It will be assumed that the sustainability to produce these systems at scale are considered comparable with respect to materials, emissions during construction, etc, apart from where stated. The objective of this project is not to provide a definite answer to what the best levitation/suspension system is, because we recognise the fact that we may not have all the information to make such a conclusion or certain non-trivial aspects of reaching a definite conclusion may be out of the scope of this research project. Nevertheless, this study will take an academic approach in analysing the chosen levitation and suspension systems using the same criteria and highlighting the benefits and drawbacks of each of them.

The underlying concept of hyperloop — pods in a nearly perfect vacuum tube — has been around for centuries. The Crystal Palace atmospheric railway, which ran through a park, was built in the mid-1860s in South London. The train was propelled by a fan measuring 22 feet in diameter. The fan's blades reversed on the return journey, sucking the carriage backwards. The hyperloop concept garnered more attention and gained traction because of many research groups and companies, following the introduction of a more modernised and innovative form of the concept of pods in vacuum tubes by Elon Musk. Over the years, research has been aimed at understanding and building the technology necessitated by this novel concept and how to make it work. Hyperloop consists of many subsystems, each playing a pivotal role in the design of the vehicle and its overall functionality. The levitation or suspension subsystem is one of the most important hyperloop systems because it addresses wheel on track friction, the main drawback in most existing transportation systems.

Suspension systems consist of tyres, tyre air, springs, shock absorbers, and linkages that connect a vehicle to its wheels and allow relative motion between the two. The tuning of suspension systems involves finding the right compromise. It is important for the suspension to keep the road wheel in contact with the road surface as much as possible, because all the road or ground forces acting on the vehicle do so through the contact patches of the tyres [10]. Unlike most traditional suspension systems that involve wheel-on-track contact, maglev technology does not. To overcome the major friction present in existing vehicles and modes of transportation, maglev was proposed for hyperloop as a solution to wheel-on-track friction and for hyperloop to be successful and attain its estimated theoretical speeds. This paper will study the feasibility and implementation of both wheel-on-track contact suspension systems and suspension systems that make use of maglev technology.

3 Wheel-on-Rail Suspension System

3.1 Introduction

The wheel-on-rail suspension (WRS) is an active suspension consisting of a combination of sensors, controllers and actuators, which acts as a measurement system. As depicted in Figure 1, the workflow of the suspension starts by acquiring an input such as the vehicle's acceleration, displacements, and vibrations using the various sensors. This information is analysed by the control unit, which will then decide the best course of action to maintain the dynamic performance of the vehicle and send the command to the actuation system, which consists of actuators and motors. The actuation system will then generate the necessary force to carry out the command [1]. The system provides adaptability for the vehicle when running on a track with irregularities, allowing for a smooth ride for the passengers. These irregularities could be in the form of discontinuities in the railway track, such as slight misalignment and small gaps at crossings, or are an effect of wear and tear. However, there has not been much research and development to integrate WRS into a hyperloop system due to its limitations. One of the main disadvantages is its wheel-on-track friction, which minimises the potential to attain the theoretical speed for a hyperloop system making it less promising. There are a few suggestions covered in this section on how to overcome these challenges for easier implementation. This section will also present a technical overview, commercialisation of the wheel-on-rail rail suspension system and the costs involved with the system.

3.2 Technical Overview

Active suspension can be classified according to the location of the suspension, the degree of control and the objective of the active control. In terms of the location of the suspension, there are two types: active primary and active secondary suspension, which are mainly covered in this paper. The primary suspension prioritises stabilising, gliding and controlling the curve-negotiation behaviour of wheels. The secondary suspension focuses on the quality of the ride and control of the quasi-static motion of the body of the vehicle by isolating the it from the vibrations produced from the flawed track [32]. The main focus in this section will be primary active suspension systems. For this study, the type of primary suspension wheels covered in this paper are solid-axle wheelsets (SW) and independently rotating wheels (IRW) because they both provide different kinds of stability in terms of wheel kinematics, while still preserving the wheels.

3.2.1 Primary Active Suspension

The primary suspension allows the vertical movement of the wheel set relative to the frame. It mainly consists of springs and dampers, connecting the wheel set and the bogie frame. This set of springs and dampers allow vertical movement of the wheel set, acting as a 'cushion' system, damping the vibrations coming from the contact of the wheels along the track [32]. In principle, the springs are

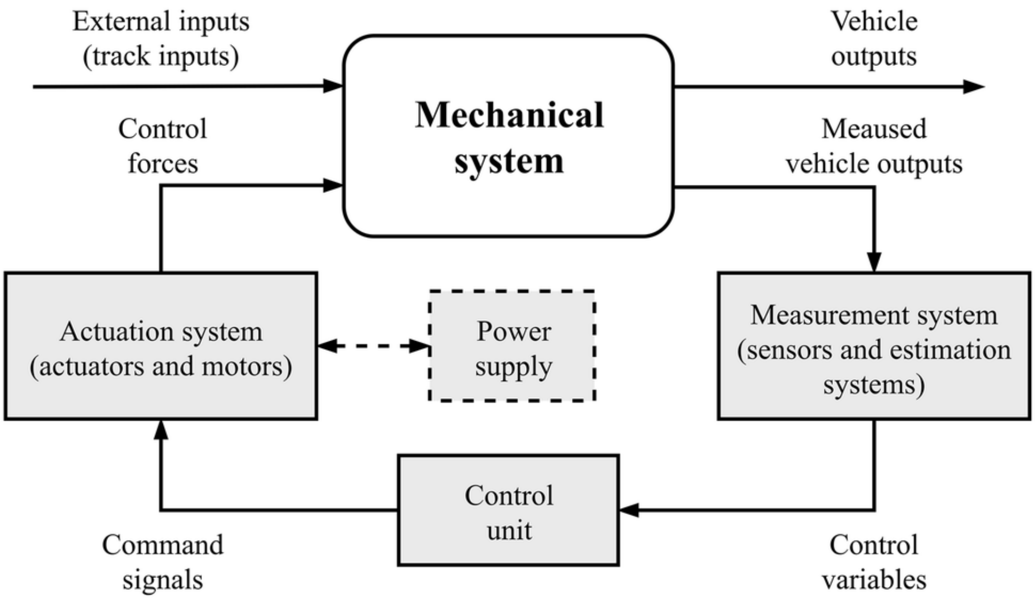

Figure 1: Workflow of an active suspension [1]

made up of steel plates of various lengths and are arranged as layers, secured at the centre with a steel strap and mounted onto the axles. The springs are often called ‘steel leaf springs’ due to the layers, or ‘leaves’, of the steel plates. The top layer is kept in place to the vehicle’s underframe using steel pins while the axle carries the weight of the vehicle body and connects it to the wheel set. When the wheel set moves up and down, these layers flex and slide over each other, which provides damping of the vertical movement. The ‘horns’ of the axlebox ensure that the wheel set only moves vertically, however this can cause some issues over time. For instance, when braking, the axlebox will hit the horns and over time this pressure from hitting the horns will wear out the surface of the components and may cause the spring to be immobilised. This also produces tensile stresses, which lead to cracking at the horn’s base as it continuously carries load over time [32].

In recent years, there have been modifications to the concept of the primary suspension such as using a rubber shear block instead of the usual steel leaf springs. The rubber shear block is more laterally flexible. and able to give a more comfortable ride which is difficult to achieve using leaf springs due to their design for vertical movement and their fixed position [32]. Trailing arm suspension, otherwise also known as crank axle suspension, is also another modification and is usually used with hydraulic dampers for passenger cars. One end of the control arm links the wheel with a spring coil and the other is attached to a pivot point, which is the frame of the vehicle’s body. Similar to the leaf springs, it only allows vertical movement. This type of suspension takes up less space, allowing for more space for other components and is generally lighter [32].

As stated previously, the primary suspension wheels covered in this paper are Solid-axle Wheelsets (SW) and Independently Rotating Wheels (IRW).

Wheel Sets

The wheel sets connected to the primary suspension can be divided to two types based on their mechanical configuration; solid-axle and independently rotating wheels [1]. For the solid axle wheelset, a pair of wheels are mounted onto the same axle, and as a result, both wheels will have the same velocity. This configuration will also produces longitudinal creepage, which in turn gives guidance to the vehicle and provides the vehicle the ability to self-centre itself. However, it also makes the vehicle body unstable in terms of hunting and increases the rate of wear of the wheels when it comes to curve negotiation [32]. Hunting is the event whereby when the vehicle reaches a certain speed, it will start to lurch sideways, which lowers the ride quality. Additionally, this limits the vehicle’s speed at which it can move safely, and this limitation is not ideal for hyperloop speeds.

The independently rotating wheels differ as the individual wheels have different velocities, which means that they do not have the advantage of longitudinal creepage. Instead, due to their configuration, they are able to give more space allowance which is useful for low-floor carriages where the height of the floor is lowered above the position of the bogie. Furthermore, since the wheels independently rotate, the instability due to hunting is reduced, allowing the vehicle to achieve higher speeds while maintaining stability [30]. However, they pose an issue in providing guidance to the wheels as the constraint between the wheels is removed. Besides this, the presence of longitudinal creepage still remains and may further worsen the wheel set's stability. Instability in guiding the wheels at hyperloop speed can pose a huge threat to the vehicle and the passengers, hence extra steps need to be taken to provide the necessary stability and steering control.

- **Solid Axle Wheel set**

  For this type of wheel set, there are three types of principles: actuated solid-axle wheel set (ASW), secondary yaw control (SYC), and actuated yaw force steered bogie (AY-FS)

  1. **Actuated solid-axle wheel set (ASW)**
     In this configuration, in order to provide stability and improve the vehicle's curve negotiation behaviour, lateral forces are applied to the wheel set to control the vehicle's vertical motion. This is implemented using a few methods. One of the methods uses a yaw actuator, which is situated between the bogie and wheelset to directly apply the lateral forces. Other than that, a pair of actuators are used and attached to the ends of the wheelset. However, this method is less effective than the yaw actuator method as it does not provide sufficient force and, hence, reduces the ride quality. Additionally, the method uses a lot of actuators, posing an issue with the space allowance [1].

     Instead, each wheelset could be attached with a longitudinal actuator. This allows the actuation force to be transmitted equally to each wheel set and, therefore, reduces the quantity of actuators used, which in turn saves space and costs. However, precaution must be taken to ensure that each actuator has high performance and is able to provide great force, for this mechanism to be efficient [3]. In addition to actuators, 'yaw relaxation' is also implemented whereby a spring and a longitudinal actuator are connected in series, linking the axle to the bogie. The spring's stiffness and the actuation system reinforce the stability of the vehicle using low bandwidth frequency. A parallel arrangement is not suited as it will require a higher actuation force to counter the stiffness of the springs when it comes to curving tracks. Instead, connecting the actuator parallel to a passive suspension is better in ensuring the active suspension remains efficient.
  2. **Secondary yaw control (SYC)**
     The secondary yaw control utilises the concept of an "active yaw damper" whereby two longitudinal electro-mechanical actuators are attached where the passive yaw damper would be. This generates yaw torque and enhances the vehicle's critical speed but reduces the control of the wheel set's motion. Even though it does not have effective steering, it allows for improved stability during turns. Further development has been made using the secondary yaw control to create an active control for a bogie [35]. In this research, actuators were used and positioned on the front and back beams of the bogie frame, which resulted in an improvement of the vehicle's stability by decreasing the bogie's displacement in the lateral direction.
  3. **Actuated yaw force steered bogie (AY-FS)**
     The actuated yaw force steered bogie is based on SYC, combining it with passive steering linkages. This mechanism was simulated and was observed to be successful in controlling the steering angle but not the yaw angle, which is influenced by creep forces from the wheel. By reducing the creep force, the bogie's yaw and steering control can be manipulated in order to provide better traction steering alignment [36]. Moreover, this will be able to assist heavy hauling locomotives in maintaining their stability during curving.

- **Independent Rotating Wheels**

  For this type of wheel set, there are three types of principles: actuated independently rotating wheel (AIRW), driven independently rotating wheel (DIRW), and directly steered wheels (DSW).

1. **Actuated independently rotating wheel (AIRW)**
   For actuated independently rotating wheels, the main concept is to modulate the yaw and vertical displacement of the common axle [1]. This concept is carried out either by directly applying torque onto the axle or by utilising a linear actuator. There has also been research into the potential of using semi-active, or more specifically, magnetorheological (MR) dampers, which have been proven to have similar performance to a full active approach [42].
2. **Driven independently rotating wheel (DIRW)**
   The driven independently rotating wheels use the notion of autonomously manipulating the velocity of a pair of wheels on an axle. This is done so by coupling motors to the two wheels to generate torque, and with recent advancements, usually alternating current (AC) motors are used. The motors do not necessarily need to be attached internally and can also be linked to the wheel set through a gearbox. The applied torque provides steering control and wheel guidance with traction. Unlike the other concepts covered, there is no usage of actuators, which saves installation space and costs and also reduces the likelihood of faults, improving the system's reliability [1].
3. **Directly steered wheels (DSW)**
   Unlike the other types of wheel sets, there is an absence of a common axle between the wheels of the directly steered wheels. Instead, the two wheels are linked by a track rod mounted on a frame. By this method, direct steering of the wheels is achieved, and by controlling the displacement of the steering rod, actuation forces can be applied [1]. It has been observed that through this mechanism, the stability of the system is not as influenced by friction and traction [48].

3.2.2 Wheel Sets for Hyperloop

Choosing the right wheel set is important as wheel sets play a key part in achieving the desired speed for hyperloop. The wheel itself must be strong enough to be able to handle the speed while still being able to sustain the weight of the vehicle and its cargo load. Other than speed, stability and steering control are also characteristics that can be manipulated with the right wheel set in order to ensure a safe and comfortable ride. By integrating different devices such as motors and actuators, these aspects can be controlled, but also come at the risk of failure. The best option for integration into a hyperloop system would be to combine both the steering capability of the solid-axle wheels and the rotation advantage of the independently rotating wheels.

3.2.3 Secondary Active Suspension

The secondary suspension connects the body of the vehicle and the bogie, which bears the weight of the body. It has an additional set of springs and dampers which are meant to distance the vehicle body and further dampen the vibrations from the wheel sets due to the irregular tracks. Unlike the primary suspension, the secondary suspension allows vertical and sideways movement. Hence, if the sides of the tracks have flaws or kinks, the vehicle body will then move side to side in order to decrease the impact of the flaws or kinks. Instead of springs, actuators can be used to link the bogie and the vehicle's body to control the vibrations and the vertical motion of the vehicle. However, the best and most practical solution for controlling the dynamics of the vehicle's motion is to use a combination of springs and actuators, either in a series or parallel arrangement [1].

When the actuators and springs are arranged parallel to each other, smaller actuators can be used as static and quasi loads in both lateral and vertical directions and will be borne by the springs, reducing the costs. On the other hand, when they are connected in series, the springs will be able to dampen the vibrations at higher frequencies that cannot be countered by the actuators. To obtain the benefits of both series and parallel arrangements, it is recommended to use a combination of the arrangements—the number of actuators used can be decreased and will be able to last longer as the vibrations are further reduced by the passive suspension, making this method more reliable and cost-effective [1]. Ideally, the springs used should be non-linear, but this is not possible due to their uniform stiffness. Over time, the spring system is no longer preferred because of this and is replaced by the air suspension system, which uses air springs, also known as air bags.

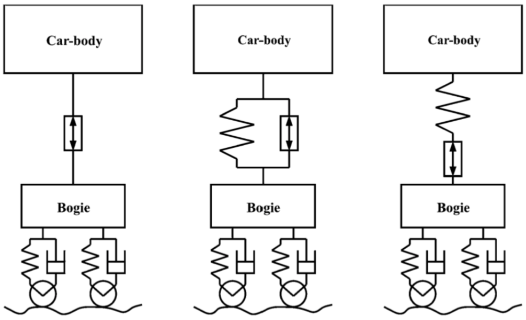

Figure 2: Secondary Suspension [1]

Bogie

A bogie is the mechanical structure, located at the underside of a vehicle's body, that attaches the axles and wheels together with bearings [40]. The bogie is meant to provide steering flexibility and ensure the wheels are able to stay in line with the track, especially when the vehicle is making a turn.

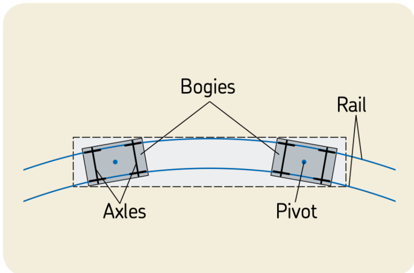

Figure 3: Bogie [40]

One of the common bogie designs to connect multiple units for vehicle bodies is the *Jacob bogie*. As shown in Figure 3, only one bogie supports the two ends of two separate units. This concept reduces the number of bogies installed, which also reduces the net weight of the vehicle, resulting in greater ride quality. Hence, it would be useful to integrate this concept for hyperloop as reducing the number of bogies also means reducing the number of wheel sets, allowing there to be less friction and increasing the potential to achieve hyperloop speeds. In recent times, transportation, such as high-speed trains, is

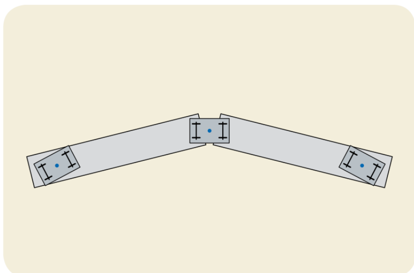

Figure 4: Jacob Bogie [40]

now equipped with powered bogies. The propulsion system of this bogie consists of the usual wheelset, a gearbox, a traction motor, and often additional complicated designs made to assist with the guidance of wheels [40]. This idea also has the potential to be implemented for hyperloop, as to overcome the drag friction from the wheels, more propulsion is required, and hence, it will need more power, which can pose an issue in installation space and net weight of the vehicle.

3.2.4 Combined Primary and Secondary Active Suspension

Even though its configuration is far more complicated than the regular spring system used, it is able to provide a more comfortable ride and maintain the height of the vehicle and the neighbouring carriages at a constant level, making it easier when docking at stations [32].

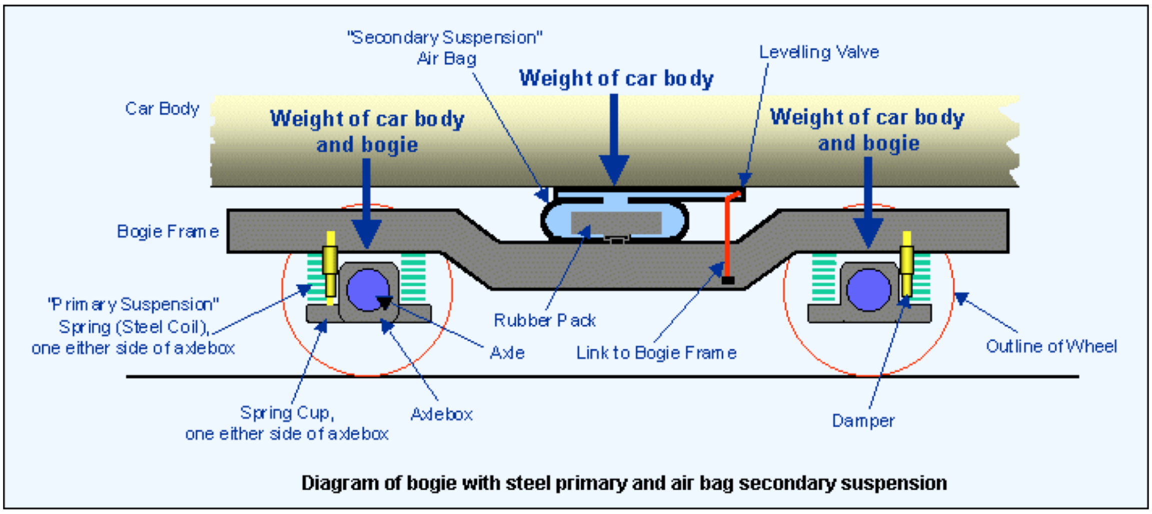

Figure 5: Arrangement of an air sprung bogie [31]

The airbag in the system is pumped with compressed air, allowing the air pressure in the air bag to easily be controlled by a valve. The sensors in the system detect the vertical motion of the vehicle, which triggers a mechanism to adjust the air pressure within the air bag accordingly using the valve. Compressed air is fed into the air bag through a valve attached to the underside of the carriage's body. By adjusting the air pressure of the air bag, the height of the vehicle can be kept constant even as more load is added to the vehicle, causing the weight of the vehicle's body to increase. If the load is taken off the carriage, some of the air pressure in the airbag is released by the valve, which is why occasionally hissing can be heard as passengers get off a coach at a station [31].

3.3 Cost

This section provides an estimate of the costs involved in manufacturing and maintaining a wheel-on-rail suspension system. It should be noted that infrastructure costs generally differ by country and the lack of fixed costs for multiple currencies has caused difficulty in fully being able to provide a more accurate discussion on the costs involved in a wheel-on-rail suspension system. Additionally, the section does not cover the cost of operating a wheel on rail suspension system.

Using the Costing for Designer (CFD) tool for a simulation, the production cost for a single suspension has been estimated to be about £3700 (45800 SEK) and about 73% of this cost is for the materials needed for the production [26].

3.3.1 Manufacturing Cost

The cost variables for the simulation, as shown in the Table 1, are gathered from multiple sources such as the CAD-model, previous work, different material suppliers and international metal prices. Both outer and inner shells used in the simulation have the properties and cost of a hollow section beam and the costs do not include gross processing. The costs of the remaining parts are based on the international steel price. The total cost for each part of the system and the types of costs are covered in the table, note that these figures were originally stated in SEK (Swedish krona) and have been converted to GBP.

Table 1: Cost parameters taken into account [26]

Variable	Meaning	Value
V_{cut}	Machine speed per machine type	500 m/h
A	Cross sectional area of machining tool	0.00005m^2
$C_m p$	Hourly manpower cost	600
K_{raw}	Process difficulty index	1
K_{setup}	Setup complexity	1.4
$K_{process}$	Manufacturing complexity	0.4
$K_{precision}$	Required precision	0.4
$K_{material}$	Compensation for material handling	1.2
T_{access}	Time to start and complete machining process	2 min
M_w	Weight of weld per meter	0.4
I	Amount of weld weight deposed per hour	5
B_F	Arc time factor	0.3

Table 2: Cost of each part and cost type in GBP

Part	Cost, GBP				
	Material	**Process**	**Addition**	**Weld**	**Total**
Outer shell	281.68	7.96	34.74	38.15	362.53
Framework	1365.37	41.99	245.48	234.20	1887.04
Inner shell	190.75	2.30	26.97	0	220.01
Foundation	809.56	52.14	166.79	105.84	1134.33
Stop plate	51.15	1.75	10.34	0	63.24
Assembly	-	-	-	42.47	42.47
Total	2698.51	106.14	484.32	420.67	3709.63

For the cost of gearboxes, according to London Underground, a supplier company and a gearbox manufacturer in 2013 stated that a single-stage gearbox costs about £3,550. About £1,500 was for the materials, and the rest was spent on the manual labour required, which was around 20 hours [47].

3.3.2 Maintenance Cost

The maintenance of the system is also taken into account for costs, and its main drivers are the wear of the system and the ageing of the materials and components of the system. Maintenance can be classified into three types of measures: preventive, corrective, and improvement measures. For a wheel-on-rail system integrated as a hyperloop system, all of these measures have to be equally considered. For instance, the maintenance of a wheel set cover requires constant inspection for cracks and fractures, including condition checking and ensuring the tolerance of the wheels is still acceptable [47].
Information on the cost for each maintenance service varies in each country, for this section, however, the main country of focus is the United Kingdom. Coney and Yule, who used the Midland Mainline high speed train as reference, states that for 4 wheelsets, replacement for flat wheels cost up to £1000. For an entire wheelset change on the other hand, the price can go up to an equivalent of £4000. Siemens Desiro UK mainland trains, on the other hand, have been charged about £3040 by their overhaul supplier, for a power wheelset overhaul, which does not include new wheels [47]. However, for a Hyperloop system, these costs may be higher, as typically wheel on rail suspension systems used steel wheels, which are not suitable for hyperloop speeds. According to Holmes and Dymott, it was found in 1997, the total maintenance costs for 560 trains, which consisted of 3880 individual carts, was estimated to be £60 million per year. This indirectly means that every year, the maintenance cost of a single cart is around £15 thousand. However, as aforementioned, this estimation was made in 1997, and with the current economy today, the maintenance cost has surely increased, and should be taken as a rough minimum [47].

Level	Light maintenance	Interval	Occurrence in 40 years
M1	Visual inspection of wheelset	25k km / 2months	240x
M2	Wheelset measurement	50k km / 4months	120x
M3	Gearbox oil change	150k km / 1year	40x
M4	Ultrasonic testing	400k km / 32months	15x
	Heavy maintenance (Overhaul)	**Interval**	**Occurrence in 40 years**
M5	Wheel exchange	1500k km / 10years	3x
M5	Axle bearing exchange	1500k km / 10 years	3x
M5	Gearbox overhaul	1500k km / 10years	3x

Table 3: Preventative maintenance tasks and their intervals [47]

3.3.3 Overall Cost

Overall, these costs should be considered as rough estimates when calculating the costs to implement a wheel on rail suspension system for hyperloop, as there is expected to be various modifications to systems, such as suggested in the previous section. The costs of these modifications are not covered in this section as they are only at an initial stage and, therefore, are not available entirely in the railway market. For instance, airless tyres by Michelin have been priced at around £600 ($750), but currently, these tyres are only available for cars and have yet to be tested for locomotives [11]. Hence, progress in market research for wheel on rail suspension can only be completed when these modifications are fully tested and available commercially.

3.4 System Commercialization

3.4.1 Energy Sources

Power regenerating dampers (PRDs) in railway vehicle primary suspension systems have been popularised. This is because in a typical passenger rail vehicle, much of the motive energy is wasted by the resistance from track irregularity, friction of moving parts and thermal losses. The kinetic energy loss of the primary and secondary dampers is one of the notable causes of energy losses in rail vehicle, with a total dissipated power between 3.5 and 3.8kW per vehicle [28]. Theoretical modelling research is used to evaluate potential energy regeneration in various applications such as passenger cars, trucks, military vehicles, and rail cars, and found that dampers on railway vehicles travelling on typical American track can recover 5 kW - 6 kW. Although much of the research into regenerative approaches has focused on potential and regenerated power in road vehicles, the goal of this work is to recover a significant amount of power from a vertical primary damper in a rail car.

According to their functioning principles, regenerative approaches in car suspension systems can be divided into three categories: mechanical, electromagnetic, and hydraulic regenerative suspension. Hydraulic or pneumatic power is typically used in mechanical regenerative suspension to transform kinetic energy into potentially recoverable mechanical energy that can be stored for subsequent use. Using electric generators to provide recoverable electricity, electromagnetic regenerative suspension turns relative vibration isolation into linear or rotary motion. Through a planned hydraulic circuit, hydraulic regenerative suspension turns reciprocating linear motion into unidirectional rotating motion and thereby produces power via a generator.

Table 4: Cost of each part and cost type in GBP

Damper Power	Potential Power	Regenerated Power	Regenerated Power Efficiency
Primary Vertical Damper	39.07 W	1.47 W	3.75%
Secondary Lateral Damper	4790 W	1247 W	0.67%
Secondary Vertical Damper	25.83 W	0.32 W	1.25%
Secondary Yaw Damper	3700 W	3.03 W	0.08%

Power Regenerating Dampers (PRD)

With the constantly expanding need for huge amounts of energy in rail transportation, the development of recoverable energy in rail vehicle suspension systems is an effective way to accomplish the goal of energy

conservation in the future regenerative dampers in rail vehicles. Due to its intrinsic design benefits of unidirectional flow with low inertia loss, dependable hydraulic transmission, and high regeneration efficiency, the *regenerative electro-hydraulic damper* has the most potential among them. A schematic design of a PRD is provided, which includes a double acting hydraulic cylinder, a hydraulic rectifier (four check valve arrangement), a hydraulic motor and a generator.
The hydraulic cylinder is constructed with four ports placed on both sides of the cylinder body, as well as four check valves that operate as a hydraulic rectifier. During bounce and rebound motions, the hydraulic fluid passes through the hydraulic motor in one direction due to rectification. The pressurised flow drives the hydraulic motor, which is directly attached to the generator. The hydraulic motor translates the primary suspension system's linear motion into rotary motion via fluid transfer, and the hydraulic motor's subsequent rotation drives the generator to generate electricity.

3.4.2 Advantages of Wheel-on-Rail Suspension

- **Passenger Comfort**
  Continuous traction from the wheels will be able to provide comfort to the passengers, which is a priority in making hyperloop successful. This also comes in handy as an emergency breakdown recovery method. In a situation where a pod breaks down, the rest of the pods behind will be forced to halt and wait for it to be moved before continuing their journeys. Using the continuous traction and wheels, the pod can be moved forward by having another pod push it to the nearest station[21].

- **Design and Construction**
  The design and construction of the wheel-on-rail suspension system is simple, and unlike the other systems, there are only a few unknowns that are still in the research stage. Even if it were to not be used as the main suspension for the pod, it could be implemented as a low-speed suspension system during take-off or when arriving at the next station.

- **Comparison to Conventional Trains**
  The advantage of suspended trains over normal trains is simple: centrifugal force. Train cars are not completely rigid; they include a suspension mechanism that allows for some bending of the bogies and the car body. The body leans a few degrees to the outside of each curve as a result of centrifugal force. The only difference is that the train's floor now leans toward the inside of the curve rather than the outside. As a result, the suspension system minimises rather than increases the lateral acceleration experienced by the passengers. It is feasible to give an infinitely large degree of tilt by softening the suspension system, which is limited only by the maximum track safety value of lateral acceleration, which is not the limiting factor in urban trains.

3.4.3 Disadvantages of Wheel-on-Rail Suspension

- **Friction**
  The maximum speed produced by a wheels-on-rail suspension system is far from reaching the speed of sonic range, which is expected for hyperloop. This is due to the fact that the wheels may not be scalable and still require bearings due to friction. More research on the manufacturing and design of the wheels is needed to reduce wear and ensure the wheels are shock-absorbing enough to be able to handle rail imperfections. Even if the wheels are able to achieve the required velocity, the system would require very high propulsive power, which adds to the need for power supply in the pod. This need may increase the cost of the pod and/or the tube, depending on how the extra power is supplied.

- **Complication in Route Planning**
  Additionally, to ensure the wheels are able to provide sufficient traction, the route needs to be simple with multiple slow sections and stations. This may be difficult to plan, depending on the geography of the location. As aforementioned, high propulsive power will be required by the system to achieve and maintain hyperloop speeds. Hence, the pod might need to be installed with a power supply. Not only does this increase the cost of the system, it may limit the journey time of the pod, which will be dependent on how long the power supply lasts. This may be avoided by supplying power through the tracks instead. However, this still brings complications in designing the track and indirectly affects the route planning of the pod.

- **Higher Maintenance and Manufacturing Cost**
  Even though the wheel on rail suspension system is very simple, in order to implement it as a hyperloop system, the system will need to be modified, mainly due to the drag friction of the wheels and the continuous propulsive power requirement of the wheels. Hence, there is more complexity in the design of the wheels and pod to fulfil these requirements and overcome the friction, and more complex designs will cost more to manufacture and maintain. Other than the wheels and the pod, the tracks will also need to be taken into account, especially if the wheel on rail suspension system is implemented. This is because over time, other than the wheels, the tracks too will face wear and tear at a fast rate with hyperloop speeds. Therefore, the tracks will also be required to be maintained constantly to ensure smooth rides, which can cost a fortune for long journeys.

3.4.4 Integration into Hyperloop

For a number of reasons, typical railway style rims (steel ones specifically) with steel wheels are not reliable in achieving high velocity. Steel wheels will not be able to provide sufficient traction as they have a low friction coefficient. The tracks also need to be perfect to ensure no bumps because even the smallest flaw in the track can cause shock loads, which leads to an uncomfortable ride for passengers. This is unrealistic as, over time, the track will experience wear and tear, and constantly replacing the track would cost a lot. In addition, the low strength-to-weight ratio of steel causes it to not be able to handle the large rotational forces at hyperloop speeds [21].

Moreover, the propulsive power requirement for the system is very high as it is a result of frictional drag of the wheel. The propulsive force can be found using Eqn.1:

$$P_{friction} = Dv_{friction} + \nu_{friction} mgv \tag{1}$$

Whereby v is the capsule's service velocity, $D_{friction}$ is the rolling friction drag, m is the mass of the vehicle, g is the gravitational acceleration.

As seen from the equation, the propulsive power scales linearly with both vehicle weight and velocity [29]. Hence, the propulsive power would be very high since the vehicle needs to achieve hyperloop speeds. This would make the system extremely energy intensive, which leads to the issue of how to provide the pod with enough energy for operation. This is especially since there is a significant energy loss with acceleration and regenerative braking. There have been a few proposals on how to provide sufficient power to the system and the pod itself, such as lithium ion batteries and supercapacitors. 'Power pickups' are also a potential suggestion whereby the tube will have power tracks allowing the pod to 'pick up' power, which can allow for an input of power of up to 320kW [21].

3.4.5 System Modification

Pneumatic tyres are preferred over the usual steel wheels in a wheel-on-rail suspension system. These types of tyres are able to provide good shock absorption, even if the tube is flawed, and can still have good continuous traction for acceleration and braking. Additionally, they are readily available on the market and do not have a high manufacturing cost, which increases savings. Typically, pneumatic wheels are designed with a metal hub mounted with rubber tyres that are filled with air or foam. However, solid rubber wheels increase the chance of overheating due to friction per unit volume [21]. On an ideally smooth tube surface, these tyres will not wear out as fast as they would on a regular track, but may be required to be manufactured with materials such as polyurethane, to ensure the tyres are still reliable in wet conditions, although this might not necessarily be an issue in the case of a hyperloop vacuum tube [21]. On the other hand, there is no evidence that these tyres will be durable and reliable enough at hyperloop speeds, even though there are records of pneumatic tyres reaching speeds of over 1000km/h.

Airless tyres, otherwise known as non-pneumatic tyres, are also proposed. Unlike pneumatic tyres, they do not go flat and, hence, do not require constant replacement, which saves costs. Other advantages include being more environmentally friendly as less natural and synthetic rubber will be needed for manufacturing and there is a possibility of manufacturing using 3D printing. Seeing as no air is pumped for this type of tyre, it provides potential space for additional brakes as some designs have more space allowance on the inside of the tyre [38]. On the other hand, they have a higher rolling resistance and are not as shock-absorbent compared to pneumatic tyres. These tyres are still being researched, so there is no guarantee of their durability at high speeds, let alone hyperloop speeds, which may limit the maximum operating speed of a pod.

In addition to these types of tyres, smaller wheels are recommended for multiple reasons. To begin with, smaller wheels take up less space, allowing more space to be used for passenger comfort and necessitating a lighter bogie.This will also lower the centre of gravity of the vehicle body, and as a result, there will be fewer forces acting on the wheels when curving, decreasing the wear rate of the wheels. Smaller wheels also mean smaller mass, reducing the power needed for propulsion and energy consumption of the suspension system [47].

3.5 Conclusion

The wheel-on-rail suspension system has been analysed and classified as either active primary suspension or active secondary suspension. By examining the advantages and disadvantages of each classification, it has been deduced that, for wheel-on-rail suspension to be integrated into a hyperloop system, a combination of both types of suspensions should be utilised. Multiple power regeneration methods have also been discussed as energy is constantly lost due track irregularities, wheel friction, heat loss and vibrations from the contact between wheels and the track. While this type of suspension has been proven advantageous in terms of its design and construction's simplicity, and being able to provide a comfortable ride for passengers, it is still a long way from being able to reach hyperloop theoretical speeds. This is mainly due to the friction from the wheels, and to even overcome this issue, the system will require a continuous power source, which will only add onto the costs to design and build the system and even maintenance costs. This counters the entire purpose of hyperloop, which was proposed to be a cheaper and faster alternative.

A few suggestions for modifications of the system have been made, such as replacing the usual steel wheels with pneumatic or airless wheels. Smaller wheels have also been recommended as they will take up less space, allowing room for passengers' comfort and reducing costs in general. In conclusion, while the wheel on rail suspension system is the most simplistic solution, which consists of the fewest unknowns compared to other suspension systems due to its long history in the transportation industry, it is still not ready to be implemented as a hyperloop system. More research is needed to configure suitable modifications and to confirm current suggestions for it to be able to reach hyperloop speeds.

4 Electrodynamic Suspension System

4.1 Introduction

In an electrodynamic suspension (EDS) system, the track and vehicle exert a magnetic field. The repulsive forces produced as a result of the two magnetic fields levitate the vehicle. The magnetic field in the train can be produced by either superconducting electromagnets (e.g. JR-Maglev) or by an array of permanent magnets (e.g. Inductrack), while the repulsive force in the track is created by an induced magnetic field in wires or other conducting strips in the track. However, the EDS train can not be levitated at zero translational velocity—suspension occurs at certain speeds. When the train is in motion, the moving magnetic field of the onboard magnet will excite the induced current in suspension coils (always low-temperature superconducting coils or permanent magnets) installed in the line. The moving field interacts with the induced current and produces a lift force to draw the vehicle above the track surface by a certain height, approximately 10–15 cm in general [41].

An example of an EDS system is a linear induction motor (LIM), an alternating current asynchronous motor designed to directly produce motion in a straight line. It is most easily understood as a rotary motor, which has been cut and rolled to generate linear motion instead of rotary motion [43]. This section will focus on linear induction motors to evaluate an EDS system. It will provide a technical overview, cost analysis, and also the commercialisation of an EDS system.

4.1.1 Introduction to Linear Induction Motors (LIMs)

In general, linear motors frequently run on a three-phase power supply and can support very high speeds. They are often used in maglev propulsion, but they have also been used independently of magnetic levitation, for example in Tokyo's Toei Ōedo Line [27]. Linear induction motors can produce a levitation effect, and can have two basic designs: single-sided or double-sided. They consist of a primary, also called a stator, and a secondary, called a rotor. In a double-sided linear induction motor, the stator is on both sides of the rotor, while in a single-sided linear induction motor, it is only on one side of the rotor [37].

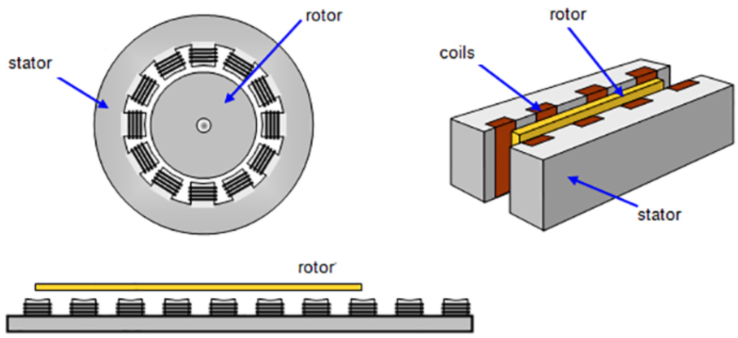

Figure 6: Construction of a Linear Induction Motor (LIM)

Specifically, linear induction motor technology has been deployed in numerous transit systems and in driver-less, elevated guideway systems, while also being used in some launched roller coasters, as well as for launching aircraft. Additionally, the Bombardier Innovia Metro is an automated system that also utilises linear induction motor propulsion, and the system is also used in cranes for material handling, for pumping of liquid metal, as actuators for door movement or in high-voltage circuit breakers [37].

The first work involving linear induction motors can be traced back to the 1840s, when Professor Sir Charles Wheatstone went on to patent a pioneering early design of a linear induction motor [12]. However, the model was in reality too inefficient to be practical. A more reasonable linear induction motor is described in US patent 782312 and is for driving trains or lifts [27]. The first working model was built in 1935 by a German engineer, Hermann Kemper, and the full-size working model was developed in the late 1940s by professor Eric Laithwaite from Imperial College in London. Laithwaite called the later versions a magnetic river, since these versions of linear induction motor use a principle called transverse flux, where two opposite poles are placed side by side, which permits very long poles to be used and thus permits high speeds and increases efficiency [27].

4.2 Technical Overview

4.2.1 System Components

A linear induction motor can be obtained from its rotary counterpart, the induction motor, by the imaginary process of cutting the rotary's stator and rotor in a radial plane and unrolling it at the same time as replacing a cage or a winding with a conducting sheet [33]. A linear induction motor is made of a primary (stator) and a secondary (rotor), and based on construction, is classified as single-sided or double-sided. As previously mentioned, in a single-sided linear induction motor, the primary is on one side of the secondary, while in a double-sided induction motor, the primary is placed on both sides of the secondary. The primary consists of a three-phase winding assembled on a steel lamination stack and is encapsulated in epoxy. For the single-sided linear induction motor, the secondary consists of a reaction plate—a flat aluminium or copper conducting sheet with a ferromagnetic core, usually with a steel backing, while in the double-sided linear induction motor, only a conductive sheet is used [13]. The magnetic steel primary core, distributed three-phase copper winding with a three-phase excitation terminal, an aluminium top cap, and the back iron are the main components of linear induction motors [33].

A linear induction motor can either be a short-primary or a short-secondary. In the short-primary, the coils are truncated shorter than the secondary, and in the short-secondary, the conductive plate is smaller. In transportation systems, rotary motors can be thought of as "infinite," in that their primary winding generated magnetic field is continuous and has no beginning or end around their circumference. However, the short-primary linear induction motor has a finite length—only the part of the secondary side that is immediately below the primary is subjected to a primary generated magnetic field. During motion, the new unexcited parts of the secondary side equivalent "rotor" continually enter under the linear induction motor's primary magnetic field generated by a distributed magnetomotive force. This generates a continuous electromagnetic response in the new incoming segments of the secondary, the reaction rail, in the form of induced magnetic potential. Hence, it resists the immediate establishment of the magnetic flux under the front end of the primary. The reaction rail consists of a series of aluminium top cap segments and underlying iron bars, the back iron [33].

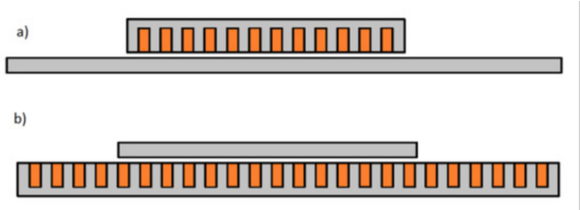

Figure 7: Short primary linear induction motor (a) vs short secondary linear induction motor (b)

When a three-phase alternating current power is applied to the primary, a travelling electromagnetic flux wave is induced which moves relative to the primary and travels along its entire length. The electric current is induced into the aluminium plate due to the relative motion between the travelling flux and the conductors. This induced current interacts with the travelling flux wave to produce a linear force or thrust F, with the equation:

$$F = \frac{P_2}{v_s} \tag{2}$$

Where P_2 is rotor input power and v_s is linear synchronous speed. [44] The linear synchronous speed v_s of the travelling flux wave produced by the primary of the linear induction motor is given by:

$$v_s = 2wf, \tag{3}$$

Where w is the width of one-pole pitch and f is the frequency of a supply voltage in hertz [37].

For a linear induction motor, the speed of the secondary is less than the synchronous speed, and the difference between them is known as slip, which is calculated using:

$$s = (v_s - v_r)/v_s \tag{4}$$

Where v_r is the speed of the secondary. Therefore, the speed of the secondary v_r in a linear induction motor is [37]:

$$v_r = (1 - s)v_s \tag{5}$$

If the secondary of the linear induction motor is fixed and the primary is free to move, then the force F will move the primary in the direction of the travelling flux wave [37]. Linear induction motors can achieve speeds in excess of 1800 inches per second (45 m/s) and accelerations in the range of 3 to 4 g's. Standard linear induction motors can produce forces in the range of 720 lbs (3200 N) at a 3% duty cycle. Multiple motors can be used in conjunction with each other to generate larger forces [43].

4.2.2 Non-symmetric double-sided linear induction motor system

WooYoung Ji et al. proposed a paper about an all-in-one system for hyperloop that conducts propulsion, levitation, and guidance. Hyperloop needs all of these functions for its service, and many devices are necessary for them. Such a large number of devices makes the entire system complicated, and it increases the size of the vehicle as well as the hyperloop tube. Therefore, the overall cost of the system and its maintenance is increased, and it becomes difficult to control each one of the devices. In the aforementioned paper, the concept of a non-symmetric double-sided linear induction motor is introduced, which is an all-in-one system that could conduct all functions. A non-symmetric double-sided linear induction motor (NSDLIM) has a structure similar to that of a single-sided linear induction motor. A double-sided primary is installed on the bottom of the tube, and a secondary plate is attached under the bottom of the vehicle. The simple structure and fulfilment of all functions make the entire system simple and reduce devices, so there are many advantages for cost, operation, and control. NSDLIM could perform propulsion, levitation, and guidance at once [2].

4.2.3 Levitation System Design and LIMs

For a linear induction motor to function properly, the levitation system design is an important part of the functionality of the whole system. In order to achieve levitation, it is necessary to use eddy currents. Eddy currents are loops of electrical current induced within conductors by a changing magnetic field in the conductor according to Faraday's law of induction. By Lenz's law, eddy currents always oppose the changing magnetic field. Hence, magnetic levitation always opposes motion [5]. In other words, the conductor, be it a loop, a coil, or simply a piece of plate metal, that is placed in this field will have eddy currents induced in it, thus creating an opposing magnetic field in accordance with Lenz's law. The two opposing fields will repel each other, creating motion as the magnetic field sweeps through the metal [27].

4.3 Cost

4.3.1 Infrastructure Cost

Since in linear induction motors there is no need for a gearbox, they occupy less vertical space, which results in lower tunnel construction costs. However, building an active, multiphase primary along a multi-kilometre guideway would be expensive. Therefore, for economic reasons, only the single-sided, short-primary linear induction motor is currently being used. In spite of that, a non-symmetric double-sided linear induction motor has an advantage over the single-sided motor, which is that it reduces the need for many devices and hence reduces the cost of the whole system.

What is more, linear induction motors run on steeper grades, which provides more flexibility in the elevated guideway structure design, resulting in reduced civil and land release costs. Also, this system is the least expensive for maintenance and has low operating costs [33]. The overall cost highly depends on the country and the particular type of linear induction motor system used.

4.4 Commercialisation

4.4.1 Advantages of Electrodynamic Suspension

As mentioned before, linear induction motors do not use mechanical gearboxes, they do not have moving parts, and the propelling force is directly applied to the vehicle in the direction of motion, thus the losses introduced by the gearbox are avoided. The linear induction motor system's tractive effort is developed as a direct electrodynamic force between the primary and the reaction rail, and therefore, linear induction motors are extremely reliable and can perform well under wet or otherwise contaminated rail conditions. This also means that linear induction motors can accelerate at any rate and achieve their nominal speeds sooner than rotary-motor-based transportation systems [33]. Furthermore, they have better system-level performance compared to rotary induction motors. They are also naturally stable and do not require complex control algorithms to ensure the stability of the vehicle on track.

Linear induction motors require very little energy as compared to other transport systems; they have low operating costs and are the least expensive in terms of operation and maintenance. Since they have a flat form, they occupy less vertical space, which helps to decrease the tunnel construction costs and energy consumption resulting from air resistance. Furthermore, linear induction motor-based vehicles can run on steeper grades due to direct forces and negotiate sharper curves, providing more flexibility in the elevated guideway structure design [33]. Linear induction motor systems have a simple structure while fulfilling all functions, which means that the systems have a reduced number of needed devices. Additionally, since these motors make no use of fossil fuels and there are no harmful gases released, they are eco-friendly [5].

4.4.2 Disadvantages of Electrodynamic Suspension

Linear induction motors are advantageous in many ways, but they also have their disadvantages. Linear induction motor systems have complicated construction and controls since they require sophisticated control algorithms [25]. Even while occupying a smaller vertical space, they have a large physical size and require a larger air-gap as compared to a conventional rotary induction motor, which means they are less efficient in this motor-to-motor comparison. Linear induction motors also draw a larger magnetising current than rotary induction motors of the same rating. Moreover, the efficiency and the power factor of linear induction motors are lower than those of conventional induction motors of the same rating [25]. Although there are no magnetic attraction forces during system assembly due to the fact that linear induction motors do not contain permanent magnets, they produce large attractive forces during operation, which must be supported by bearings and structure, and this affects the life of the system. Furthermore, unless an alternating current vector drive is utilised, linear induction motors do not produce a force at standstill and a minimums speed of 30 km/h is needed for a lift force to be produced [41]. Since linear induction motors are less efficient than permanent magnet linear motors, they produce more heat [25].

4.4.3 Operation Reliability

The main advantage pertaining to the reliability of linear induction motors is that they can work efficiently even while facing an excessive threat from weather or any natural calamity. They also produce good thrust and lift at high speeds, so they are the most suited for high-speed systems [33]. The successful implementation of the linear induction motor system heavily depends on the levitation system design, so the incorrect choices in the levitation system may lead to an inefficient or faulty implementation of the linear induction motor system [5]. The reaction rail is usually offset from the longitudinal symmetry line of the primary side of the linear induction motor, leading to decentralised transverse forces and potential lateral instability. Therefore, the asymmetrical construction of the reaction rail necessitated by the vicinity of switches needs to be used to aggravate this effect [33].

4.4.4 Integration of EDS into Hyperloop and Readiness of EDS

As previously mentioned, for a linear induction system to work properly, the levitation system design must be done appropriately. Due to the dynamics of the vehicle as well as the reaction rail's limited construction accuracy, the reaction rail is usually offset from the longitudinal symmetry line of the primary side of the linear induction motor, leading to decentralised transverse forces and potential lateral instability. Hence, the asymmetrical construction of the reaction rail is needed [33]. There are also unbalanced normal forces, attractive and repulsive, that add complexity in the analysis of an optimal air gap and the construction of the motor, since they affect the distance between the lowest point of the primary and the top of the reaction rail top cap [33]. Several studies have been done on the topic of linear induction motors, with an analysis of their use in different high-speed systems. For example, linear induction motors have been used for high-speed urban transportation, elevators, roller coasters, or in launching aircraft [27]. However, there has not yet been a double-sided linear induction motor system implemented due to economic reasons. Although EDS is a good fit for a hyperloop subsystem, there are gaps in our knowledge of its implementation, making it more challenging to currently integrate it efficiently into a hyperloop system. This is made more difficult by the fact that EDS has yet to be implemented and commercially used.

4.5 Conclusion

Electrodynamic suspension is a promising maglev technology. It is advantageous in many ways when compared to other maglev technologies, but it also has its limitations. There is on-going research into this technology, and this research is needed if EDS is to be integrated into the hyperloop. There must be more research to address the limitations of the system and its implementation on a higher scale.

5 Electromagnetic Suspension System

5.1 Introduction

In order to achieve a tangible reality of the hyperloop concept, there is a need to research and consider alternative or non-conventional suspension systems. There have been other means of suspension systems proposed to levitate the hyperloop capsule, one of which is the electromagnetic suspension system. The electromagnetic suspension system is a passive maglev system and hence does not require on-board power to levitate the hyperloop capsule. The traditional method works well for numerous maglev train systems around the globe. However, they do possess a fatal flaw as 3/4 of the entire energy being put into powering the vehicle is used to counter the significant air friction experienced at high speeds [51]. This problem could ideally be resolved with the new innovative hyperloop system concept: putting the hyperloop capsule within a low air pressure environment would potentially lower the energy wasted to overcome air friction significantly.

The electromagnetic suspension system's theory is to provide the moving capsule with a levitation force derived from its own kinetic motion. There are numerous models implementing the basic mechanism of the passive maglev system. Some were flawed during the early years, while the modern system utilises advantageous features from other mechanisms [34].

5.2 Technical Overview

To study the mechanism of an electromagnetic suspension, the Inductrack model, which was introduced in 1996, will be analysed. This model used the electromagnetic suspension mechanism but was also modified to address some of the challenges of this suspension system. This suspension model contains arrays of permanent magnets on the moving capsule and a track embedded with circuits [34]. A levitation force is produced as the array of magnets on the capsule induces current in the conductor embedded within the track when the capsule is moving, even at relatively low speeds. This is because, while in motion, the induced current by the array of permanent magnets within the conductor causes the conductors to act as magnets, hence providing a levitating force to the capsule.

5.2.1 Levitation and Resistance

The mechanism utilized to achieve the levitation of the capsule is by placing arranged sets of permanent magnets in a configuration called the Linear Halbach Array and above a track with implemented circuits known as the Inductrack [19]. A Linear Halbach Array contains a set of permanent magnets that are arranged specific directions to achieve the "one-sided flux," which produces a magnetic field that is intensified on one side and cancelled on the other side [20].

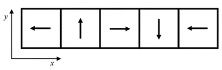

Figure 8: A simplified illustration of a Halbach Array [20]

To understand how the capsule move above the track, we need to calculate the levitation force when the capsule is in motion, and the corresponding drag force which acts as one of the resistance forces. First, we map out the magnetic field around the linear Halbach array. Let h be the distance between the linear Halbach array and the track h_0, M be the number of magnets per period of the Array, let λ be the length of each set of linear Halbach array and $\frac{2\pi}{\lambda}$ while the x axis is pointing at the direction where the capsule is moving and y axis is pointing from the track to the linear Halbach array. The magnetic field of the magnet arrangement can be expressed as [34]:

$$B(x+iy) = i2B_r cos[k(x+iy)] \times e^{-kh}(1-e^{-kh_0})\frac{sin(\epsilon\pi/M)}{\pi/M} \tag{6}$$

Let B_0 be the maximum value of magnetic field when $y = h$

$$B_0 = 2B_r(1-e^{-kh_0})\frac{sin(\epsilon\pi/M)}{\pi/M} \tag{7}$$

This gives the horizontal (x) and vertical (y) components of the magnetic field:

$$B_x = B_0 sin(kx)e^{-k(h-y)} \tag{8}$$

$$B_y = B_0 cos(kx)e^{-k(h-y)} \tag{9}$$

As shown above, the magnetic field changes when the Halbach array move along the x axis, thereby changing the total amount of magnetic flux within the conducting circuit. The *corresponding magnetic flux* Φ can be expressed as below after integrating Eqn(4) from the top to the bottom of the wire embedded in the circuit; let d_w be the width of the circuit and d_h the height of the circuit [34]:

$$\Phi = B_0\frac{d_w}{k}e^{-kh_0}sin(kx)(1-e^{-kd_h}) \tag{10}$$

Secondly, the circuit induction process is analysed. Let v be the speed of the capsule, $I(t)$ be the induced current, Φ_0 be the maximum flux going through the circuit, and define $\omega = \frac{2\pi}{\lambda}v$

$$V = L\frac{dI(t)}{dt} + RI(t) = \Phi_0 \omega cos(\omega t) \tag{11}$$

Solving Eqn(6) at steady state gives:

$$I(t) = \frac{\Phi_0}{L}\frac{\omega^2 L^2}{\omega^2 L^2 + R^2}[sin(\omega t) + \frac{R}{\omega L}cos(\omega t)] \tag{12}$$

The above equation is only suitable when the capsule is moving at the speed where $\omega >> \frac{R}{L}$. When this condition is met, the magnitude of $\frac{R}{L}$ will correspond to a speed above 2km/s. Given that the system being analysed - hyperloop - is a high speed transportation system with its theoretical speed higher than 2km/s, the condition of $\omega >> \frac{R}{L}$ can be assumed to be met. Hence Eqn(7) can be simplified as [34]:

$$I(t) = \frac{\Phi_0}{L}sin(\omega t) \tag{13}$$

Eqn(8) can be rewritten usign Eqn(5) and Eqn(7) to give:

$$I(x) = B_0\frac{d_w}{k}\frac{\omega^2 L}{\omega^2 L^2 + R^2}e^{-kh_0}[sin(kx) + \frac{R}{\omega L}cos(kx)] \tag{14}$$

Using Lorentz's force law:

$$F = qv \times B = IL \times B \tag{15}$$

Substitute Eqn(3), Eqn(4), Eqn(7) and $L = dw$ into Eqn(10) to obtain the average force acting on each circuit in the different directions [34]:

$$\langle F_x \rangle = \langle I(t) d_w \times B_y \rangle = B_0^2 \frac{d_w^2}{2k}\frac{\omega^2 L}{\omega^2 L^2 + R^2}e^{-kh_0} \tag{16}$$

$$\langle F_y \rangle = \langle I(t) d_w \times B_x \rangle = B_0^2 \frac{d_w^2}{2k}\frac{\omega^2 L}{\omega^2 L^2 + R^2}e^{-kh_0} \tag{17}$$

Eqn(11) gives the x axis component which is the drag force and Eqn(12) gives the y axis component which is the levitation force. For a better analysis and understanding of the result above, a ratio between the levitation force and the rag force is derived [34]:

$$\frac{F_{levitation}}{F_{drag}} = \frac{F_y}{F_x} = \frac{L}{R}kv \tag{18}$$

Eqn(13) suggests that the ratio increases as the speed of the capsule increases. This is an ideal model and hence does not take into account certain factors that occur in practice. These factors include interference due to skin depth effect and eddy currents which will deviate the practical performance of the concept from the above ideal model. The 1996 passive maglev system was an improvement on early day designs which had a number of flaws. The most primitive maglev systems which was built two decades ago used only electromagnets to levitate the vehicle -the underlying principle was the Earnshaw's theorem which made the vehicle vertically unstable. By using linear Halbach array, the capsules do not need any on-board power source to drive the electromagnets. The passive maglev system provides a safer, easier, and more energy-efficient levitation system which does appear ideal for the hyperloop system.

EMS is characterised by dynamic unstable electromagnetic attraction as explained by Earnshaw's law. Samuel Earnshaw showed that it is not possible to place a collection of bodies, subject only to electrostatic forces, in such a way that they remain in a stable equilibrium configuration and this applicable to magnetic forces as well [41]. Due to this, EMS systems rely on active electronic stabilization; such systems constantly measure the bearing distance and adjust the electromagnet current as required. An advantage of EMS is that lift forces can be produced at any translational speed unlike some other maglev systems [41].

5.2.2 Propulsion

The passive maglev system is not only used to levitate the capsule. A non-contact propulsion system is needed for the capsule to move at an extremely high speed. There are numerous means to power the levitated capsule. We are going to look into two main methods that have already been put into practical use in the past: the Linear Induction Motor and the Linear Synchronous Motor.

Linear Induction Motor (LIM)

The mechanism of linear induction motors can be compared to that of an unrolled-rotating induction motor. It includes the primary part and the secondary part: the stator and the rotor. They interact with each other when connected to the power. One of them will stay fixed while its counterpart moves. When an alternating current is connected to the primary part, often a laminated flat magnetic core, it will induce an electromagnetic flux which behaves like a wave. According to Lenz's Law, as the amount of flux changes, it would then produce an electric field and generate an electric current in the secondary part, often a sheet of aluminium with an iron backing plate. The interaction between the induced flux and induced current causes a linear force that propels the capsule. The propulsion force has a positive correlation with the frequency of the alternating current; as the frequency of the AC increases, the produced forces become larger, thereby pushing the capsule faster [33].

The first maglev system put into practical public use was the Birmingham maglev back in 1984. It was propelled by a simple Linear Induction Motor. However, improvements have been made to the basic form of the linear induction motor over the years. The primary and secondary parts of the motor were altered to produce a more ideal version. Many counterparts, such as the Double-Sided Short Primary Sheet Rotor Motor and the Single-Sided Linear Induction Motor (SLIM), have been introduced over the years. Linear Induction Motor is advantageous in many respects: the power system and construction are similar to conventional electric railway systems. Since the system is already well-established, it is more feasible than its counterpart. Secondly, LIM's simple mechanism makes it safer and more reliable than traditional railway track, and the installing process is more adaptable to different designs. Additionally, LIMs are quite flexible to uncertainties during practical use: the size of vehicles is not limited and relatively easier to upgrade [33].

However, there are also disadvantages. To begin with, LIMs have a low energy efficiency compared to the traditional rotary induction motor. Hence, limiting its operational speed capacity as the increase in weight of the motor is impractical during high speed travelling. The maximum speed of a practical LIM is around 225 km/h, which is not quite ideal for hyperloop implementation. Besides, the coupling between the thrust and the attraction/repulsion force between the stator and rotor generates forces in directions other than the moving direction of the vehicle.

Linear Synchronous Motor (LSM)

A Linear Synchronous Motor (LSM), similar to a linear induction motor, can be compared to an unrolled rotating synchronous motor. It also has a primary part and a secondary moving part: the stator and the rotor. The LSM's secondary part contains permanent magnets, electromagnets, or electromagnets with direct current (DC) supply to create a constant magnetic field. As the propulsion/attraction force propels the vehicle toward the next set of magnets with the opposite force, the primary part changes the current direction and creates an opposite magnetic field to continue the cycle. linear synchronous motor also changes the frequency and amount of current to change the speed of the vehicle [17].

The advantages of LSM compensate for some of the disadvantages of LIMs. Since the propulsion force is supplied by the stator, which is embedded within the track, the vehicle is lighter without the added weight of the on-board power supply. Practical implementations such as the Transrapid Maglev System can operate at a relatively high speed with a maximum of approximately 500 km/h. Moreover, the LSM system can also be combined with the levitation system as they both require permanent magnets. The Halbach array within the capsule can also be used for the LSM propulsion, which would make the capsule even lighter and allow faster acceleration and deceleration. However, considering the comfort of passengers, this does not stand out as a crucial advantage compared to LIM [17].

LSM has some disadvantages: it is less reliable compared to LIMs. Given the nature of LSM, a precise vehicle position and velocity sensor is required to have the exact corresponding frequency and magnitude of the alternating current. The magnets used for LSM also need reliable on-board power as they need to operate continuously. Secondly, the structure of LSM is also very complicated, so maintenance is considerably more difficult. It also lacks adaptability and is less scalable since the length of the vehicle cannot be changed easily given the precise configuration needed.

5.2.3 Alternatives

In the several decades since the maglev system was first introduced, numerous innovations have been introduced. The fastest superconducting maglev in Japan can travel up to 603 km/h. The system uses LSM as propulsion while superconducting electromagnets and null flux coils are used for levitation and guidance. However, there are also ideas such as the non-symmetric double-sided linear induction motor that could potentially combine propulsion, levitation, and guidance. Such alternatives become crucial to the implementation of hyperloop as it needs to be fast while being cheap to build.

5.3 Cost

In this section, we will conduct a study of the existing implementation of EMS maglev systems and apply it to the Edinburgh-London line to estimate and compare their costs of construction, maintenance, and operation. The purpose of this section is to provide an estimate of the total cost of a new maglev line in Shanghai and to apply it in the case study of the United Kingdom for the Edinburgh-London corridor.

5.3.1 Construction

The Shanghai transrapid system started operations in 2004 with trains manufactured in Germany. The system connects a distance of 30 kilometres going at speeds of up to 431 km/h with mostly elevated track with a track gauge of 2.8 m [18]. In the case of the Edinburgh-London track, the track distance is about 633 kilometres. The Shanghai transrapid system consists of four primary components: the vehicle, the guideway, operation control, and power supply.

Electromagnets are used in the vehicle to elevate and propel the system including on-board batteries, levitation control systems, and an emergency braking system. Auxiliary infrastructure includes substations, switch stations, other power supply equipment, and trackside feeder cables [18]. Assuming current auxiliary infrastructure is sufficient or will need to be modified at a nominal cost, including the start and end points of the stations and the track being a modified version of the East Coast main line, the cost of construction will be looked at through the cost of the four main parts of the maglev system itself and labour costs.

The Shanghai maglev system cost £38.7 million per kilometre to construct [8]. Extrapolating this data to the Edinburgh-London line gives a total construction cost of about £24.5 billion assuming there is no existing infrastructure. Current labour costs in the UK average around £22.80 per hour [49]. The Shanghai Transrapid System took nearly 2.5 years to build Assuming that a similar timeline is used for the Edinburgh-London line, given that tracks will be repurposed and the tube will be overlaid instead of constructed from the start, and the technological advances made in the field, gives the amount of man hours to be approximately 4500 man hours using the Organisation for Economic Cooperation and Development (OECD) average of 1800 man hours per year [15]. Assuming about 350 labourers working on this project gives an estimate of £36 million just for labour costs.

Using another estimate for a EMS maglev line in Turkey from Ankara to Sivas [18]. breaks down the cost as follows:

Table 5: Construction Cost Breakdown [18]

Materials	Unit Price (million £)	Distance/Quantity	Total (million £)
Rail cost per km	15	633 km	9495
Vehicle Cost	18	10	180
Electrification cost per km	1	633 km	633
Communication Control per km	1	633 km	633
Tube covering per km	1	633 km	633
Total initial construction cost	-	-	11574

The vehicle's cost includes electromagnets, batteries, levitation control system, and braking system. The planned size of pods in line with the demand was set at an average of 5 pods per system, with two systems being ordered with each pod carrying 20 people, making it a total of 100 passengers per system with potential room for more. Including labour costs gives the total cost of construction to £11610 million, or £11.6 billion, an average of £18.34 million per kilometre.

5.3.2 Maintenance Cost

The ratio of operation costs for the Shanghai Transrapid system were given as: 64% energy, 19% maintenance, and 17% operations/support services. Guideways on average last about 50 years with minimal maintenance required due to the lack of mechanical contact and wear. [6] This also makes it quieter when compared to other systems. The only components that will need to be maintained are the vehicles, which will need to be constantly tested for safety purposes, as well as the systemwide electrical and communication systems. Based on this data, we assume maintenance to be approximately 19% of the operation costs of a hyperloop system.

5.3.3 Operation Cost

To estimate the cost of an electromagnetic suspension based train, a comparison of the track's cost per kilometre can be made between rail-based transport. This does not necessarily give the operation cost of the EMS system since the operation cost takes into consideration the other subsystems in the train but nevertheless provides a broad estimate of the operation cost of trains with different suspension systems including EMS.

Table 6: Operation Cost Comparison [18]

Method of Transport	Track cost per km (million GBP)
Traditional train	12.5
Shanghai Transrapid	38.7
Shanghai Metro Line 3	35.5

Recalling that the traditional train is UK's London North Eastern Railway (LNER), note that the cost per kilometre is considerably larger for the Chinese Transrapid – this will be heavily influenced by the terrain the tracks are built on, along with the different prices of labour and materials (among other factors) for the two different countries. A more informative value to compare the Transrapid is another Shanghai railway such as the city's Metro Line 3, which shows that the cost of implementation of both traditional and EMS tracks is similar.

Another relevant comparison would be the energy consumption of the different railway vehicles. The trains used in LNER are British Rail Class 801 (Traditional train). Since energy consumption won't change significantly compared to the effect of terrains depending on the country, a simple one-to-one comparison can be made.

Table 7: Energy consumed by different railway systems, per railroad car, per kilometre, at a speed of 125mph (201km/h). [46] [8] [45]

Method of Transport	Energy per railroad car, per 100 seats, at 201km/h [kWh]
Traditional train	2.48
Shanghai Transrapid	2.2
Shanghai Metro Line 3	2.9

These values show that the Transrapid is slightly more energy-efficient than the other two systems which implies cheaper energy costs. This will be due to the fact that magnetic propulsion motors are highly efficient and also because the Transrapid train has less mass than the other two, since most of the propulsion system is in the tracks and not it the train; an additional benefit of this is that more passengers can fit inside the train since the space is not needed for motors.

5.4 System Commercialisation

The technology for passive EMS exists and has been in commercial use for more than 20 years. The most notable application of the suspension system is in the German-developed Transrapid train. Although Germany had test tracks, the first fully commercial Transrapid was inaugurated in 2002 in Shanghai, China, and is used to this day. In comparison to Transrapid trains, the difficulties in implementing passive or active EMS in a hyperloop would be limited to ensuring the safe and efficient construction of the tube around the tracks, which will keep the pods in a partial vacuum. To get a better idea of how practical implementing an EMS based train is, a particular look at the time taken to travel between London and Edinburgh for traditional transport systems versus the Shanghai Transrapid can be made:

Table 8: Time taken for different methods of transport between London and Edinburgh [8].

Method of Transport	Time taken
Plane	1h 15min
Car	7h 42min
Traditional Train	4h 16min
Shanghai Transrapid	1h 59min

The table above shows how an EMS-based train would make the inter-city trip in much less time. If the suspension system were implemented in a hyperloop, where air drag would be incredibly minimised compared to the Transrapid, the journey time would be even shorter. The time for the Transrapid was calculated assuming it would travel the same distance that the traditional train would travel if it would go at its maximum speed (201km/h) constantly throughout its travel time. Also assuming Shanghai Transrapid moves constantly at its maximum speed, 431km/h. The two assumptions work against each other.

In the UK, the implementation of a Transrapid train could be made by heavy modification to the existing tracks. The only factor that would make re-purposing the existing railway track into EMS-supporting track difficult would be the land or space that the tracks take up; otherwise, it would be easier to build new tracks. Constructing a hyperloop with EMS would be more challenging as it would also require the tube that surrounds the magnetic tracks, supporting pylons, and modification of the route—underground or above-ground—depending on the type of terrain.

5.5 Conclusion

In conclusion, an EMS-based hyperloop system would be feasible to construct and operate on an Edinburgh-London line. However, because maintenance costs are lower and more passengers can be transported in less time, the EMS-based train system may be a more cost-effective mode of transportation than traditional railways in the long run, regardless of its high construction costs. Implementing this suspension system into a hyperloop will further increase efficiency and speed due to the lack of air resistance that current EMS maglev trains suffer from. Electromagnetic suspension has already been implemented in other vehicles, but implementing it in a hyperloop environment is not certain since research must be done to predict how it will interact with other subsystems in the pod.

6 Electrodynamic Wheels Suspension System

6.1 Introduction

Aluminium and back iron track with single-sided linear induction motor (SLIM) was promising as a means of propulsion for high-speed ground transportation, which led to the development of a high-speed way-side power collection method in the USA. However, SLIM had its limitations. SLIM has a low power factor and must be built very long to compensate for end effects. It is also unable to provide any lift force for suspension. Hence, normally a secondary electromagnetic suspension system is needed for lift and guidance on the track, and this increases the cost and drag losses of the system. An alternative was to use the concept of "electromagnetic river" with SLIM, but that still had a low power factor and lift-to-weight ratio [24].

The electrodynamic wheels (EDW) mechanism proposed in the 1970s consists of the simultaneous rotation of radially positioned magnets and their translational motion above a flat conductive non-magnetic track to create a time-varying magnetic field that can inductively create a lift and thrust force. EDW can be compared to a linear Halbach array wrapped around a circular rotor. This mechanism has a high power factor and a potential high lift-to-weight ratio, unlike the models before it. Although there are increased losses from mechanical rotation, EDW is able to produce all the necessary forces and hence has a lower overall loss compared to other maglev systems [24].

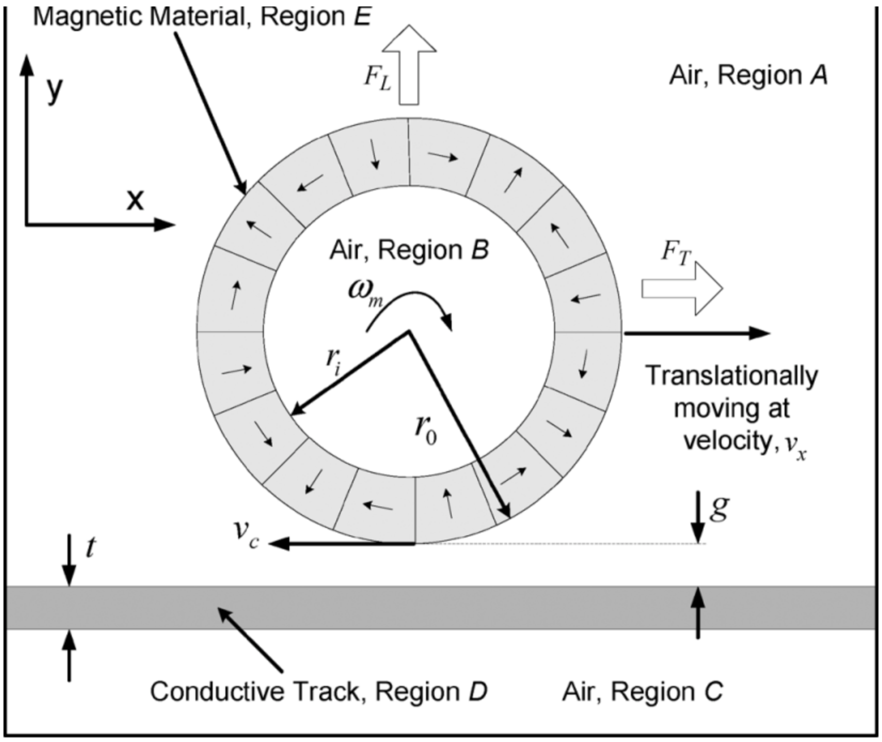

Figure 9: An Electrodynamic Wheel translationally moving and rotating above a conductive, nonmagnetic track [24]

Because EDW can provide propulsive, levitation forces, and even guidance on a track, it is considered a viable levitation/suspension system for hyperloop while functioning in other respects (e.g., propulsion) in a hyperloop environment. There has been an increase in EDW research over the years. However, more research is still needed due to the complexity of its design and the novelty of this novel concept since it has never been tested in a vehicle. Although, electro-dynamic wheels can provide both propulsive and levitation forces, the focus of this will be on their levitation force. This section will provide a technical overview of the EDW mechanism, cost, and commercialisation of the system to investigate the possible implementation of EDW in a hyperloop system.

6.2 Technical Overview

6.2.1 Mechanism

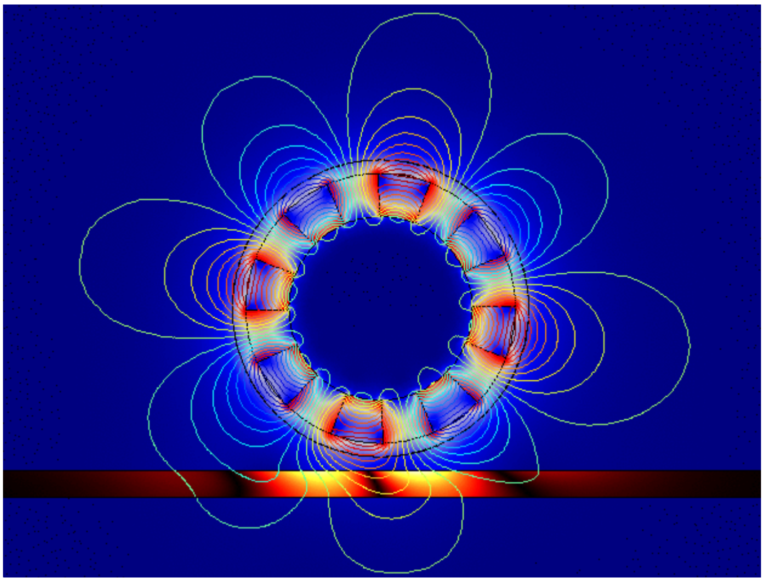

Figure 10: Simulation of an electrodynamic wheel [14]

The working mechanism of an electrodynamic wheel (EDW) magnetic levitation system is depicted in the figure below. The EDW magnetic levitation system consists of a permanent magnet Halbach rotor that rotates and/or moves translationally above a passive conducting guideway. The rotation and/or translational motion of the Halbach rotor induces eddy currents in the guideway. The induced eddy current subsequently generates an opposing magnetic field that interacts with the source magnetic field to provide both lift and thrust force. The lift and thrust forces produced by the wheels are used to levitate and also propel the vehicle [14]. Electrodynamic wheels produce a lift force similar to that of electrodynamic suspension (EDS). However, since the magnets are wrapped around a rotor, the rotors can rotate without the vehicle moving. This implies that EDW does not need any low-speed mechanical drive systems and also repurposes and eliminates the drag forces associated with a traditional EDS system. An EDW maglev vehicle needs an on-board power source or a way of providing power to the vehicle [50].

Johnathan Bird, an active researcher into the implementation and viability of EDW, used Finite-Element Analysis (FEA) to determine an optimal ratio of inner to outer radii that maximises the lift-to-weight ratio of a Halbach rotor. For a 4-pole-pair, it was calculated to be 0.68 and confirmed using a 2D steady-state current sheet model. The 2D steady-state current force sheet model reduces the complexity of an EDW system. The lift and thrust forces of an EDW are derived from a slip velocity, s, which is defined as [24]:

$$s = v_c - v_x [ms^{-1}] \tag{19}$$

Where v_c is the circumferential velocity and v_x is the translational velocity. Although the slip velocity significantly influences the lift and thrust forces, it was determined that the general relationship between the parameters often scaled almost equally with slip velocity.

The surface velocity of a radial rotor v_r is given as [24]:

$$v_r = \omega_m v_0 \tag{20}$$

where ω_m is the rotor's mechanical rotational velocity and v_0 is the rotor's outer radius.

The forces in the electrodynamic wheels could potentially be created by superconducting magnets or rare-earth magnets. An example of a rare earth magnet that has been used as the rotor material in an EDW system is the neodymium iron boron (NdFeB). The Halbach rotor is the main component in an EDW configuration. One of the most important mechanical aspects to be considered in the Halbach rotor is the manufacturing of the magnet segments with different polarisation orientations. The Halbach rotor can be manufactured by glueing trapezoidal sections together. Embedded magnet topologies in new rotor designs include V-magnet, double-V, dovetail, semi-Halbach, and full Halbach array designs [4].

Magnet Segmentation

The difference in the polarisation directions of the magnet segment from one another makes manufacturing a whole Halbach rotor challenging. According to manufacturers, magnet segments of this type can be cut from a bulk magnet block that has already been magnetised. The figure below shows how to cut the magnet segments. The magnets (orange) are sliced from a polarised bulk magnet (grey); the magnets have varying polarisation orientations as a result of the cutting positions [4].

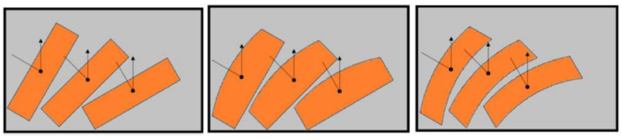

Figure 11: Cutting of magnet segments with different polarisation orientations [4]

In theory, the best Halbach rotor is made up of 11 segmented magnets per pole, but in practice, it would be easier and less expensive to make with fewer magnet segments. As previously stated, one way of manufacturing a Halbach rotor out of magnet segments with different orientations is to glue them together to form the final rotor construction. Glue, on the other hand, takes up around 0.1 mm in each layer, depriving the magnet material of space. Approximately 0.6 percent of the magnetic torque is lost due to the smaller magnet volume [4].

6.2.2 Mathematical Modelling

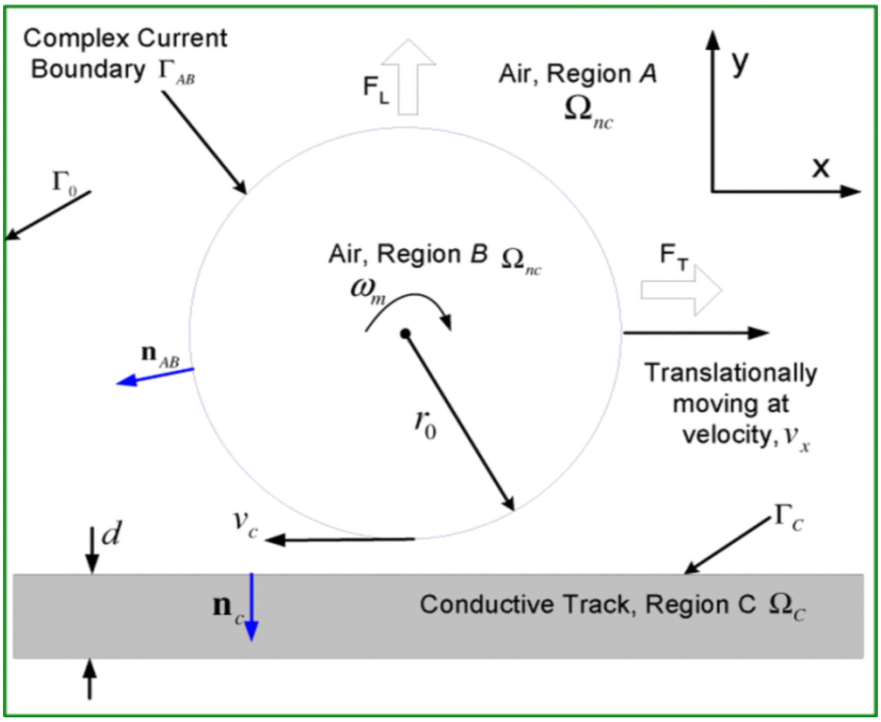

Figure 12: EDW modelled using problem regions of an "equivalent" current sheet model [7]

In the past, the thin and thick plate approximations were used to analyse moving magnet inductive devices. The thin and thick plate approximations assume that the thickness of the plate is either much less or much greater than the magnetic diffusion depth. These have been successfully used to model the general relationship between forces at limited velocities. However, the current density plot obtained using FEA shows that such approximations are not reasonable for this device. The current sheet model, which is used to approximate the mechanism of an EDW system, neglects the change in permeability within the magnet and magnetic eddy-current losses. These assumptions are made because magnet permeability is close to one and if the magnets are highly segmented, there are minimal eddy-current losses [7].

Mathematical Formulation Quasi-static Maxwell's equation can be applied [7]:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{21}$$

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{22}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{23}$$

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B} + \mathbf{J}^s) \tag{24}$$

$$\nabla \cdot \mathbf{J} = 0 \tag{25}$$

where σ is the tract conductivity, $\mathbf{v}$ is the velocity of the conducting material and $\mathbf{J}^s$ is an external excitation source.

The conductive material is assumed to move translationally instead of the magnetic rotor and the conductive material is also assumed to be isotropic and linear. Using the generalised constitutive relation [7]:

$$\mathbf{B} = \nu_0(\mathbf{H} + \mathbf{M}) \tag{26}$$

Expressing $\mathbf{E}$ as $\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla V$ and $\mathbf{B}$ as $\mathbf{B} = \nabla \times \mathbf{A}$ where $\mathbf{A}$ is the magnetic vector potential and V is the electric scalar potential. These expressions can be used to rewrite Eqn 5 and Eqn 8. [7]

$$\sigma\frac{\partial \mathbf{A}}{\partial t} + \nabla \times (\frac{\nabla \times \mathbf{A}}{\nu_0} - \mathbf{M}) - \sigma \mathbf{v} \times (\nabla \times \mathbf{A}) + \sigma \nabla V = \mathbf{J}^s \tag{27}$$

$$\nabla \cdot (\mathbf{v} \times (\nabla \times \mathbf{A}) - \frac{\partial \mathbf{A}}{\partial t} - \nabla V)\sigma = 0 \tag{28}$$

Using the identity $\nabla \times (\nabla \times \mathbf{A}) = \nabla(\nabla \cdot \cdot \mathbf{A}) - \nabla^2 \mathbf{A}$ and the Coulomb gauge $\nabla \cdot \mathbf{A} = 0$, Eqn 10 and Eqn 11 can be written as [7]:

$$-\frac{\nabla^2 \mathbf{A}}{\nu_0} + \sigma(\frac{\partial \mathbf{A}}{\partial t} + \nabla V - \mathbf{v} \times (\nabla \times \mathbf{A})) = \nabla \times \mathbf{M} + \mathbf{J}^s \tag{29}$$

$$\nabla \cdot \mathbf{v} \times (\nabla \times \mathbf{A}) - \nabla V)\sigma = 0 \tag{30}$$

Eqn 13 is simplified using various vector identities. Since the current sheet model is a simple 2-D model, the conductive track is assumed to be moving only in the $x-direction$. Using subscripts to denote scalar directions, Eqn 13 can be written as [7]:

$$\nabla^2 \mathbf{A}_z - \nu_0\sigma(\frac{\partial \mathbf{A}_z}{\partial t} + v_x\frac{\partial \mathbf{A}_z}{\partial x}) = -\nu_0 \nabla \times \mathbf{M} - \nu_0 \mathbf{J}_z^s \tag{31}$$

If the conductivity within the magnets is assumed to be zero, then the magnet region D, simplifies to:

$$\frac{\partial^2 \mathbf{A}_z}{\partial x^2} + \frac{\partial^2 \mathbf{A}_z}{\partial y^2} = -\nu_0 \nabla \times \mathbf{M} \tag{32}$$

6.2.3 Parameter Analysis

This section will consider certain design parameters of the current sheet model and, in effect, the electrodynamic wheel and how they affect the performance metrics of the device. These metrics include magnet mass, lift force, thrust force, lift-to-weight ratio, track power, watts-per-kilogram for lift, lift-to-thrust ratio, and thrust efficiency. However, this section focuses specifically on the effect on the magnitude of lift force. The simulation parameters for investigating the design parameters can be found in Table 4.

1. **Pole Pairs**
   These are equal number of North and South magnets facing outwards from the rotor, and each N and S pair is referred to as a pole pair. The figure below shows the influence of the number of pole pairs present in the rotor on the amount of lift force produced. From the graph, the magnitude of lift force reduces with an increasing number of pole pairs. This is because as the number of pole pairs increases, the flux density over the surface of the rotor decrease [24].

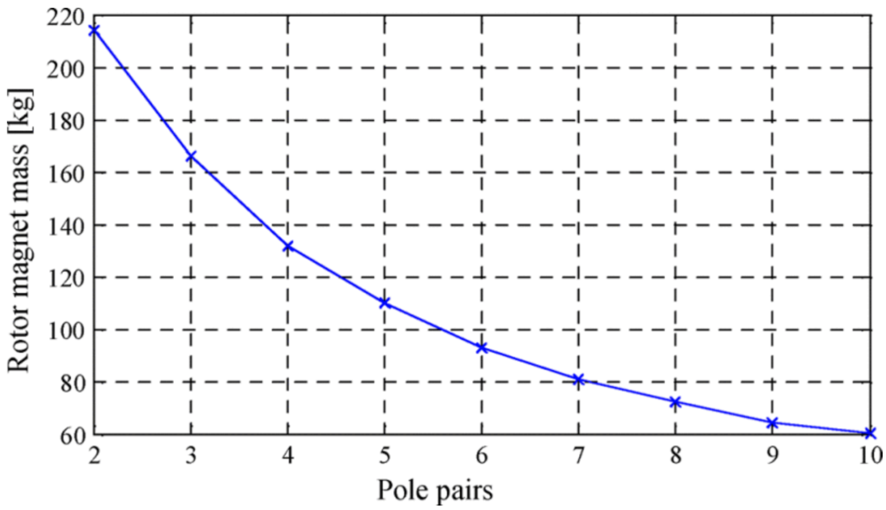

Figure 13: Relationship between pole pairs and lift force [24]

2. **Rotor Radius**
   The effects of rotor radius, specifically the rotor outer radius, can be seen in the figure below. There is a positive linear relationship between the rotor's outer radius and the magnitude of lift force produced. Hence, lift forces are basically proportional to the track surface area covered by the rotor. Additionally, the thrust force and lift-to-thrust force ratio increase with increasing rotor radius, and this relationship is an important characteristic of EDW when used to provide both propulsive and levitation forces [24].

3. **Track Conductivity**
   The lift force increases as conductivity rises, whereas the thrust force decreases. This is due to the fact that when the conductivity of the track increases, bigger currents flow within the track, preventing the vertical rotor magnet field from penetrating entirely into the track. With conductivity, the drop in thrust and rise in lift result in a reduction in thrust efficiency but an increase in the lift-to-weight ratio. To improve the lift-to-weight performance and lift force provided on the track, a more conductive track, such as copper, could be employed [24].

Table 9: Conditions and dimensions used in parameter analysis simulation [24]

Translational velocity	$135ms^{-1}$
Slip speed	$45ms^{-1}$
Track thickness	10 mm
Magnetic width	0.2 m
Air gap	10 mm

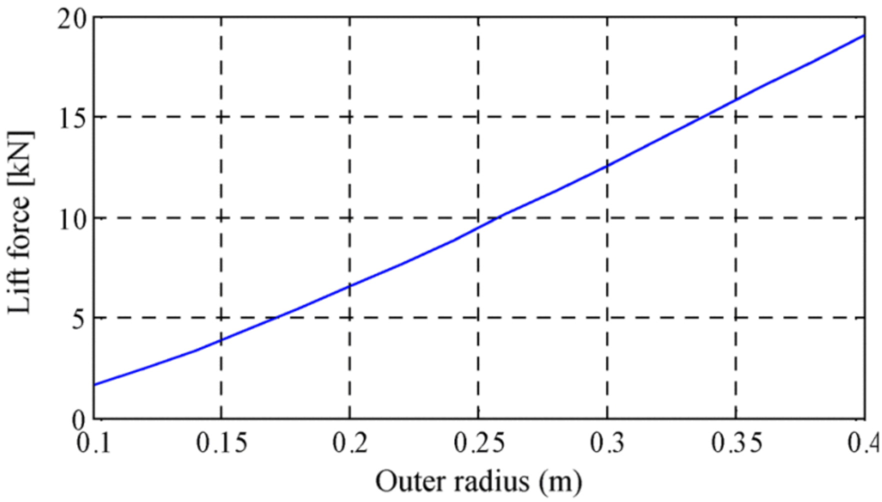

Figure 14: Relationship between rotor outer radius and lift force [24]

6.3 Cost

This section covers the cost of integrating electrodynamic wheels into a Hyperloop system. The maintenance and operation costs are not deeply discussed under this section as there has not been enough research and development, hence this section will focus on the manufacturing costs. Therefore, in terms of maintenance and operation costs, it will be compared to its predecessor, the EDS system, which has a similar mechanism as EDW.

6.3.1 Halbach Rotor Cost Estimate

According to Lindh, the main factor in the manufacturing cost of electrodynamic wheels is their neodymium iron boron (NdFeB) magnet material. The amount of NdFeB material is dependent on the configuration of the rotor design, as demonstrated by Lindh, using a 12-pole permanent magnet synchronous motor with parameters listed in the table below. Figure 13 displays the increase in cost depending on the rotor design, as well as the maximum torque and the difficulty of manufacturing the rotor [4].

As shown in the figure above, Rotor F, which is a full Halbach rotor, provides the greatest maximum torque, but also has the highest cost. The assumed grade for the NdFeB magnet is N55, as the material at this grade has a high magnetic strength-to-weight ratio, making it suitable for the device [16]. There has not been much development to estimate the material as most simulations done use different masses and numbers of NdFeB magnets. Additionally, the cost of an NdFeB magnet is also influenced by the size and shape of the magnet desired. The costs are expected to be extremely high, as the price of neodymium is approximately 239.40 per unit kg [22]. However, approximate relative costs for NdFeB magnets with 40BHmax per pound is $35.00 and $0.88 per BHmax [39].

Hence, in terms of BHmax, NdFeB magnets are less costly. Usually, when using a more powerful magnet, the size of the device using said magnet can be reduced, which also results in saving costs. But, this may not be the case for a hyperloop system, and therefore, it might still be expensive.

6.3.2 Track Cost Estimate

For the tracks, aluminium sheets are suggested to be used as a more affordable alternative, and by doing so, increases the potential for an EDW system to be cheaper than high-speed rail [24]. The cost of aluminium sheets depends on the desired grade and thickness of aluminium sheet. For instance, a single grade 1050 aluminium sheet with the dimensions of 3m x 1.5m and no special finishes, costs approximately £82 and £103 for a thickness of 1.2mm and 1.5mm, respectively [22]. It is estimated that the track's thickness does not have to be more than 10mm, as at hyperloop speeds, thicker tracks

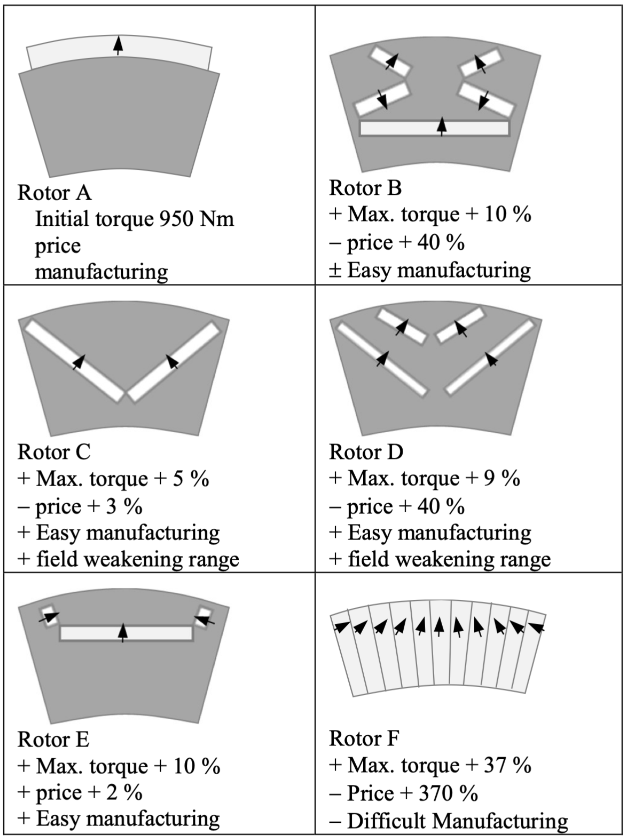

Figure 15: Rotor structures studied by the finite element method. A is the commercial rotor-surface-magnet motor, B is a dovetail rotor, C and D are embedded magnet rotors with the V-shape. E is a Halbach structure with the U-shape and F is a full Halbach rotor [4]

will result in more forces acting on the wheel [23]. However, there is still insufficient information on what exact grade of aluminium should be used to fully evaluate the cost of the tracks. Additionally, to use aluminium sheets as tracks, special finishes will be required for extra protection, and they may be required to undergo extra processing and moulding in an EDW system. More development and research are required to verify if the cost of using aluminium sheets for tracks is much lower than integrating a secondary electromagnetic suspension system.

6.3.3 Comparison of Electrodynamic wheels and Electrodynamic suspension Costs

This comparison is necessary to have a better general estimate of the cost of EDW even though not much has been done in this particular research area. The two systems are similar enough that a cost comparison seems reasonable.The electrodynamic suspension (EDS) system has a relatively lower maintenance cost, and since an EDW system does not require a driving system, it is predicted that its maintenance cost is even lower than that of an EDS system. However, there is a possibility of unbalanced magnetic pull, irregularities in the air gaps, and rotor mechanical unbalance, and hence, the system may require extra sensors for monitoring, which might increase maintenance costs.

Additionally, there would be regular reviews to ensure that the magnet segments remain attached, and in the case where a magnet segment is damaged or misaligned, it will need to be replaced, and the entire construction may be required to be re-glued. As aforementioned, to operate the EDW system requires a continuous power supply, which can either be supplied through the track or through an on-board battery. If power were to be supplied through the tracks, the idea of using aluminium sheets as tracks may not be viable, and hence, may be very costly. Integrating a battery on board the hyperloop pod will also increase its cost and will also take up some space allowance, which may reduce passengers' comfort. Either way, the operation cost of an EDW system is predicted to be much higher compared to an EDS system. To confirm these hypotheses, more research needs to be done as well as simulations to provide a more accurate result.

6.4 Commercialisation

This section provides information on some aspects of the commercialisation of electrodynamic wheels. Since it is a relatively new suspension system, there is not a lot of readily available data to completely investigate each aspect of its system commercialisation. The electrodynamic wheels technology still needs a lot of study to be undertaken in order to be implemented into a vehicle. They have never been in commercial use. However, the estimated low cost and efficiency make the technology promising. Hence, this section will cover the commercialization of EDW based on currently available information.

6.4.1 Advantages of Electrodynamic Wheels

- **Low track cost**
  The electodynamic wheel system is proposed to be relatively cheaper than existing maglev systems. This is because the track does not need to be electrified; it only needs to be conductive. Therefore, the guideway can consist only of aluminium, which is cheap and light. The low cost of the track might be able to compensate for any additional costs that might emerge during manufacturing and installation, including costs from modifications. This is very important in the implementation of hyperloop because the less costly the subsystems are, the lower the overall cost of hyperloop will be and hence more attractive to investors and the general public.

- **Simulataneous Lift and Thrust Forces**
  In contrast to other maglev systems, in electrodynamic wheels, the drag force can be converted into a thrust force. When the magnetic wheels are rotated as well as moved translationally over a conductive surface, a time-varying magnetic field is created. Hence, currents are induced, which enables the propulsion. If EDW is implemented in a hyperloop system, it has the potential to produce both propulsive and levitation forces, which makes it more efficient than traditional maglev systems.

6.4.2 Disadvantages of Electrodynamic Wheeel

- **Complexity of the System**
  When multiple EDWs are considered, the system becomes coupled and hence unstable. Highly complex simulations and calculations would need to be performed in order to properly analyse and design EDW on a track. This is probably the most significant challenge in integrating the mechanism into hyperloop. Additionally, for control purposes, real-life calculations would be necessary to update stiffness and damping, which would be very computationally intensive.

- **Power Supply** Another disadvantage of EDW is how power is supplied to rotate the Halbach rotors. One way is by providing an additional onboard power supply to rotate the magnets. An onboard power source means a heavier pod and hence an increase in the amount of power needed to levitate and translationally move the pod on the track. The alternative is to supply power through the tracks, but as previously mentioned, this makes aluminium, which is a cheap material for the track, not viable, and this change in the track material might lead to additional costs.

- **Minimising Air-gap**
  Due to poor magnetic coupling between the circular wheels and the flat guideway, the air gap needs to be kept small. Both lift and thrust forces have the same dependence on the value of the air-gap size. Lift and thrust forces increase inversely with the size of the air gap. This results in a limitation on the peak thrust efficiency necessary to keep a reasonable lift-to-thrust and lift-to-weight ratio. It might prove challenging to attain the smallest air-gap required to levitate the hyperloop pod and provide enough thrust force to operate at theoretical hyperloop speeds. However, further research will need to be done to prove this hypothesis.

6.4.3 System Modification

The system could be improved by implementing superconducting magnets. Using superconducting magnets would increase the coupling between wheels and the track, reducing the air-gap and hence the thrust and lift efficiency could be increased. Additionally, high-temperature superconducting magnets would allow the use of less energy for the cooling process, and therefore the cost of operating the vehicle would significantly decrease. However, the design of such a mechanism is complex and no further research has been conducted on it given that electrodynamic wheels have just gained traction as a potential levitation and propulsion system.

6.4.4 Integrating into Hyperloop

Even though EDW could potentially be a relatively cheaper and environmentally-friendly suspension system, integrating them into hyperloop would be a non-trivial problem to solve. Firstly, further work needs to be done to simplify the calculations and reduce the computation time of the simulations. The mechanism would first need to be tested on a smaller scale in a vehicle and then scaled to fit the hyperloop. There is currently no research on how scalable the electrodynamic wheel system is and this needs to be known if it must be implemented in a hyperloop system. Moreover, suitable control techniques have to be developed to ensure the reliability of the system.

EDW is the least sustainable system compared to the other systems due to the use of rare-earth metals like neodymium. The production and processing of rare earth elements found in hybrid/electric vehicles come with their own hefty environmental price tag. These damages include radioactive wastewater leaks and 'slash-and-burn processes' required to manufacture and separate rare earth metals [9]. This raises concern about the environmental impact of EDW because a system is only as clean as its materials.

6.5 Conclusion

The electrodynamic wheel (EDW), or magnetic rotating wheels, seems promising in its ability to not only provide levitation force but possibly convert drag forces present in traditional maglev systems into thrust force. This characteristic of EDW makes it a promising subsystem option since it provides two major forces in a hyperloop system. There is currently on-going research into this suspension system. When considered as a suspension subsystem in a hyperloop environment, not much can be said about this since more research needs to be done to verify the feasibility and implementation of EDW as a hyperloop subsystem.

7 Comparison

This section will focus on comparing the discussed suspension and levitation systems using three comparison metrics: technology, cost, and commercialisation. The comparison will be based solely on the information presented in each section and will aim to present similarities, differences, and limitations relative to the different systems in relation to their compatibility and contribution to a hyperloop system.

7.1 Technology

The reintroduction of hyperloop highlighted the limitations of friction and air resistance in traditional transportation. One solution that was a selling point in hyperloop was magnetically levitating the pod on the track to eliminate wheel-on-track friction. With this preamble, the *wheel-on-rail suspension* might not be a viable suspension subsystem considering hyperloop is estimated to run at 1000 km/h. However, the wheel-on-rail suspension system could be implemented in the hyperloop as a back-up system in case the primary maglev technology fails.

One major advantage of the electromagnetic suspension and electrodynamic wheels is that they can work at all speeds, even at zero translational velocity in the case of EDW, unlike the electrodynamic suspension, which only levitates the vehicle at a minimum speed of 30 km/h. Hence, implementing EDS in hyperloop will require an additional low-speed suspension system [41]. In contrast, the main disadvantage of the EMS technology is the unstable and dynamic nature of electromagnetic attraction, which requires constant monitoring of the levitation air gap. However, EDS is naturally stable. A minor decrease in the distance between the track and the magnets creates strong forces to repel the magnets back to their original position. Less control and monitoring is needed if EDS is implemented in hyperloop.

There has not been a vehicle tested with EDW yet, but an experiment to investigate the effect of EDW interacting in series, which will be a necessity in hyperloop implementation, showed that lift-to-thrust ratio decreases with increasing EDW in series but thrust efficiency increases.

7.2 Cost

Comparing the cost of these systems in a hyperloop environment is non-trivial because there are no quantitative estimates for some of the systems. Wheel-on-rail suspension is the most advanced and commercialized, so there is already infrastructure for this system, which should help reduce costs. The cost of WRS is highly terrain dependent and hence tends to differ significantly depending on the location. EDW is proposed to be cheaper than existing maglev technologies, and the fact that it simultaneously produces thrust and lift forces might make it cheaper than implementing EDS and EMS and a different propulsion system. Even though EDW might be cheaper to implement in the hyperloop, its cost comparison to WRS is not certain.

7.3 Commercialisation

There is not much to say about the commercialization of these systems because of a lack of information and, in some cases, no real implementation. The wheel-on-rail suspension is the most commercially used since it is used in most traditional trains. EMS has proven to be commercially viable when it was implemented in recently developed maglev trains and attained speeds of up to 500 km/h. EDS has not been commercially implemented yet, but there has been a lot of research in this area of research. EDW has the potential to provide both propulsive and levitation forces in theory. It has not been implemented commercially, and more research is needed to understand its implementation on long tracks for commercial use.

8 Conclusion

Investigating the feasibility of different suspension systems for hyperloop has highlighted some alternatives, like using WRS as a backup suspension system, and the limitations and advantages of different maglev systems. However, it also made specific areas of hyperloop that need more research, like EDW implementation and ways of overcoming the natural instability of EMS systems, more apparent. There is no definite answer to the best suspension system for hyperloop because the technological limitations of one system might be the advantages of the other and vice versa, and this becomes even more complicated when cost and implementation strategies are considered. The results are not conclusive and more research is needed to ascertain the viability, feasibility, and economic benefits of each of the proposed systems in a hyperloop system for more concrete conclusions to be made.

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