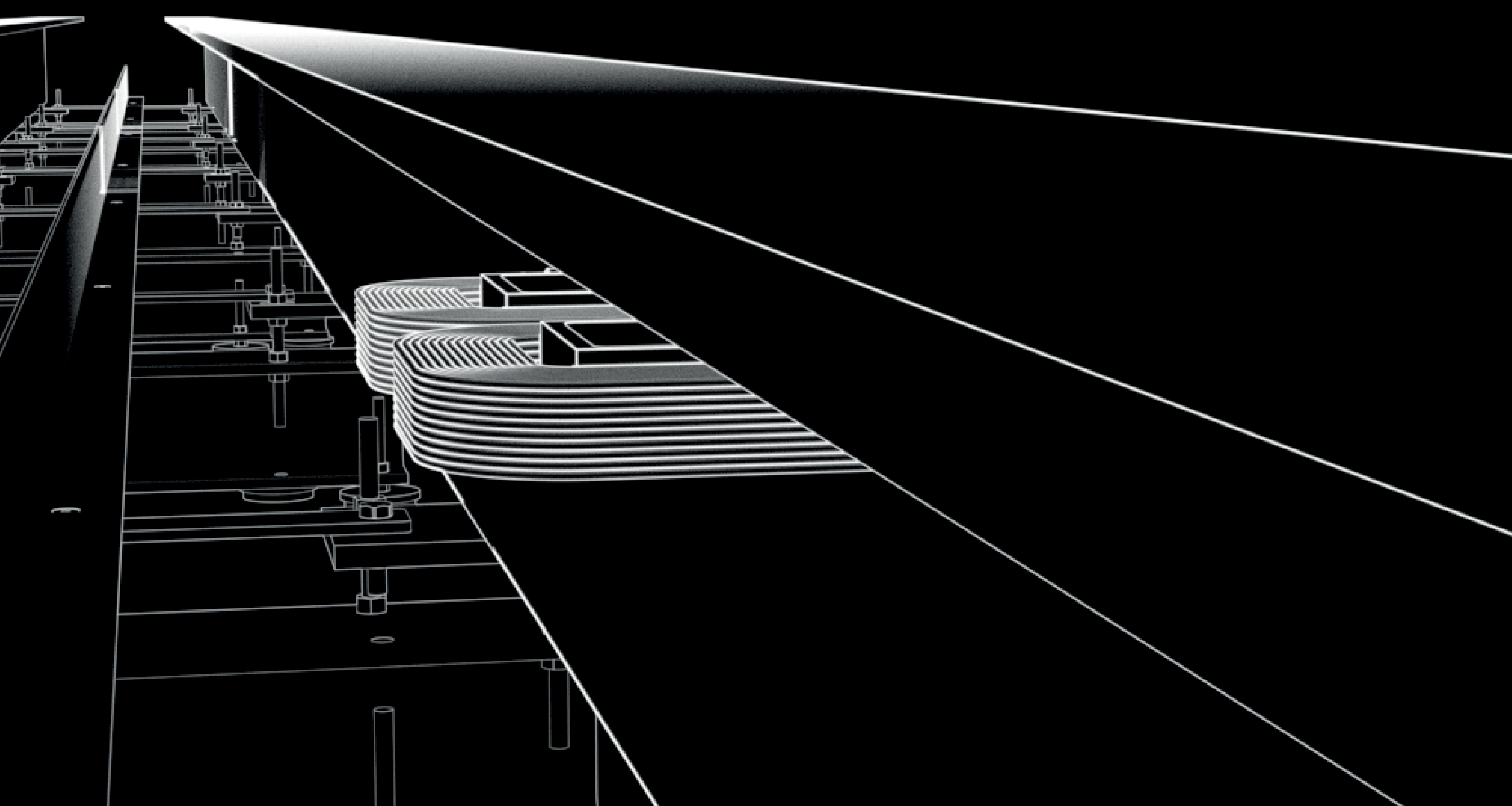
Final Research Submission

Vehicle - infrastucture synergy optimization to minimize electromagnetic drag forces

HYPERLOOP **UPV**



Contents

List of Figures

List of Tables

Acknowledgements

Thanks ArcelorMittal for their expertise and knowledge in the steel sector and for their collaboration with their experimental materials.

Also thanks to Hyperloop UPV for making this document visible to all the hyperloop enviro-ment.

Chapter 1

General

1.1 Description of the Team & Development Environment

Hyperloop UPV is a student team born and raised in Valencia, Spain, and headquartered at the Universitat Politècnica de València (UPV). The team has consistently demonstrated a steady commitment over its nine-year trajectory, focusing on intensive research and innovation within the realm of hyperloop technology.

As a diverse team consisting of 48 members from all the faculties of the university, it adopts a multidisciplinary and collaborative approach to problem-solving. The team is organized into specialised working groups, referred to as subsystems, each dedicated to addressing specific facets of hyperloop development. This approach allows the team to efficiently confront the current challenges by leveraging diverse areas of expertise. The team boasts a comprehensive skill set spanning multiple disciplines, including engineering and operations management, ensuring a holistic and well-rounded approach to finding solutions.

The primary objectives of Hyperloop UPV are to develop a scalable and functional vehicle capable of levitating within a vacuum-sealed tube, always focusing on three main aspects: safety, scalability, and sustainability.

Hyperloop UPV benefits from the support of over 90 entities, both private and public. This support enables the team to translate the project into reality year after year through invaluable in-kind and/or monetary contributions.

With this research titled "Vehicle-infrastructure synergy optimization to minimize electromagnetic drag forces", developed by Miquel Montañana, Mariano Andújar, Álvaro Pérez, Hugo Albert, and Stefan Costea, Hyperloop UPV is applying for the Full-Scale Award: Technical Aspects of Hyperloop Systems.

The total word count is XXX words.

Chapter 2

Abstract

The reduction of drag forces generated by parasitic currents induced on the infrastructure by a time-varying magnetic field is a fundamental objective for the proper development of a complete hyperloop proposal. Failure to do so can endanger any chance of achieving velocities higher than several hundred kilometers per hour.

Therefore, there is a need for high synergy between the vehicle and the infrastructure, from which arises the idea of creating this document and the research carried out. The proposed study is intended to give guidelines to be followed when designing a levitation system for a hyperloop vehicle optimised for high velocities.

Firstly, the levitation unit will be studied. This section includes topics like the shape of the unit or the orientation in order to minimise the eddy currents generated in the infrastructure.

In the other hand, an optimal infrastructure will be analysed. This includes the effect different types of steel may have on the induction of drag. With the collaboration of **ArcelorMittal**, an experimental section with custom properties has been designed and built to experimentally test the simulations.

Chapter 3

Introduction

3.1 Motivation

Electromagnetic drag, caused by eddy currents, is a physical phenomenon that directly impacts the hyperloop proposal. This friction is one of the main obstacles to the viability of the fifth mode of transport, making it a critical topic that needs to be studied.

The concept of ”zero friction” is associated with the name hyperloop because its technology is recognised for having low aerodynamic drag due to the substantially reduced pressure in the environment it travels through and its dynamic interaction with the infrastructure thanks to magnetic levitation. However, this phenomenon completely eradicates this idea, putting at risk the sustainability of this mode of transport.

Understanding the causes that worsen the effects of this phenomenon reveals a serious problem. As the speed of the vehicle increases, the losses will also increase, posing a challenge to a vehicle intended to travel at 900 km/h.

Despite these clear disadvantages, which could render the existence of hyperloop impossible, there is little documentation addressing this problem. Therefore, it has been decided to present a new perspective on the issue by conducting studies and simulations with electromagnetic levitation systems.

Therefore, this document aims to present different solutions to improve the synergy between the vehicle and its infrastructure, resulting in a considerable reduction in the electromagnetic drag. Furthermore, exorbitant manufacturing costs or complex integration into the tube will be avoided. This is crucial, considering the extension a future hyperloop network may have.

3.2 Related Work

Hyperloop technology represents a turning point for modern transportation. As the fifth mode of transport, it offers innovative features for the industry, making it a potential competitor to other transportation systems by providing the speeds of airplanes and the comfort of trains.

Its operation is particularly impressive for two reasons: it functions within a tube with pressure levels, orders of magnitude lower than atmospheric pressure, extending thousands of kilometers, and it uses electromagnetic suspension systems, allowing the vehicle to travel while levitating. Thanks to these characteristics, hyperloop can move at ultra-high speeds with almost no friction.

However, this ideal operation is interrupted by a phenomenon arising from the interaction between the levitation units and the infrastructure, causing a decelerating force that opposes the thrust produced by the motor.

This phenomenon will be investigated and documented in this report. The report will address the issue caused by the induction of time-varying magnetic fields on the steel infrastructure due to the generation of eddy currents. It will discuss the main aggravating factors, how they hinder the development of a hyperloop vehicle, and possible solutions to achieve the greatest scalability for a complete proposal.

This section will provide a brief overview of the theory behind eddy currents as a physical phenomenon, including their causes, aggravating factors, and the parameters that could be adjusted to reduce their drag force.

The origin of eddy currents is defined by Equation 3.1, based on Faraday-Lenz's law, where E represents the electric field and B represents the magnetic field.

$$\oint_C \vec{E} \cdot d\vec{l} = -\int_S \frac{d\vec{B}}{dt} \cdot d\vec{S} \tag{3.1}$$

Extrapolating this equation to the case of electromagnetic drag, it is known that the reason these opposing forces are generated is due to the electromotive force produced by the time-varying magnetic field over a limited surface. This generates a vector electric field that circulates in a closed path opposite to the magnetic field that created it.

These currents also create a magnetic field that opposes the original one, compensating for its variation. This fundamental reason explains why eddy currents cause a deceleration of the movement of an object as it interacts with an electrical conductor, according to Lenz's Law.

This law explains how currents are generated on the conductor. However, the magnitude of these currents, that is, the degree of influence they can have when interacting with the magnetic field that creates them, is determined by the current density on the surface where the magnetic field acts.

This second characteristic is defined by Ohm's Law, which shows the relationship between current density and the electric field in a conductor. In this case, the electric field is generated by the variation of a magnetic field, and this law is governed by Equation 3.2.

$$\vec{J} = \sigma \vec{E} \tag{3.2}$$

Where J defines the current density, E defines the electric field, and σ is an electrical property that defines the electrical conductivity of the material where the currents are generated.

From this equation, it is concluded that electrical conductivity is an important factor to consider for the reduction of eddy currents. For this type of application, it is necessary for the conductivity value to be minimal. In this way, the current density in a given volume of the conductor will decrease proportionally.

However, this equation is generalized for continuous conductors and linear intensity variations. To have a more accurate understanding of how current density changes over time during non-uniform motion, Equation 3.3, derived from the Lorentz force density formula, is employed.

$$j = \sigma(-\nabla\Phi + \vec{u} \times \vec{B}) \tag{3.3}$$

In this equation, equivalent to Equation 3.2 in a steady-state regime, new terms appear that help define the variation of current density over time more accurately.

The term ϕ, known as the scalar potential, defines the intensity of the vector field at various points on a surface -heat map-. However, in this case, vector values are required as they better define the behavior of the magnetic flux. Therefore, Equation 3.4, which relates the scalar potential to the vector potential A, is employed.

$$\nabla\phi = -\vec{E} - \frac{d\vec{A}}{dt} \tag{3.4}$$

Thanks to this equality, current density can be defined using vector values. The potential vector A is used as a directing vector of a vector field, which, although it does not have a real physical meaning, is employed to study the behavior of a vector field.

This relationship simply shows that the divergence of the scalar potential in a region of a conductor is equivalent to an electric field plus the time variation of the vector field, opposite to the divergence that generates them.

The cross product of u, the particle's relative velocity, and the magnetic field results in an electric field on the conductor.

Therefore, the new electric field depends on any pre-existing electric field in the steel, the rate of change of the vector potential of the vector field on the surface, and the product of the particle's velocity and the amount of magnetic field that comes into contact with the surface, generating a new magnetic field.

From these parameters, it is possible to understand which aspects directly affect whether there is an increase or decrease in electromagnetic drag, in order to later provide potential solutions to reduce this phenomenon.

These losses produced by eddy currents can also be expressed as energy losses in the form of heat, known as Joule losses. When current is induced in a conductive profile, electron flow occurs, and part of their kinetic energy is converted into heat.

This energy transformation is given by Equation 3.5.

$$P = \left(\frac{\pi^2}{6}\right) \sigma \cdot e^2 \cdot B_{\text{máx}}^2 \cdot \omega^2 \tag{3.5}$$

Where e represents the thickness penetrated by the magnetic field in the conductor, B_{max} denotes the maximum magnetic field facing perpendicularly with the steel of the conductor, and f defines the frequency, in this case, by the number of pole steps advanced per second.

In addition to using losses as a reference parameter to assess the degree of decrease in current density in the infrastructure, the drag coefficient has also been used as a reference. This coefficient shows the relationship between the vertical force produced by the unit and the electromagnetic drag generated by the variation of magnetic field over time, as shown in Equation 3.6.

$$C_d = \frac{F_{vertical}}{F_{drag}} \tag{3.6}$$

With all this information gathered from various documents throughout the research, the following studies will explore various cases in which the aforementioned parameters will be varied. These studies aim to aid in reducing electromagnetic drag within economic parameters and real manufacturing processes.

3.3 Research Objectives

Together with this proposal, different questions have been raised, which will be dealt with in the different sections of the document. Since for the scalability of the concept it is necessary to look for the resolution of problems that could appear in a real vehicle.

- Accomplish a synergy configuration between levitation unit and infrastructure capable of achieving a vertical force equivalent to twice the produced drag force at a speed of 900 km/h.
- Identify and analyze the key parameters for minimizing electromagnetic drag, and formulate technical guidelines for future hyperloop system design.
- Assess the scalability and feasibility of the proposed solution for implementation in a full-scale hyperloop system.

Chapter 4

Methodology

4.1 Overview

This research aims to address a complex problem arising from the generation of eddy currents in the infrastructure of a hyperloop vehicle, caused by the variation of the magnetic flux from the vehicle's own electromagnetic suspensions when they are in a transient state.

The research process and methodology will be supported by scientific documentation presented in the Bibliography regarding the topic under consideration, and finite element software such as ®JMAG, specialized in the study of electromagnetic elements and the multiple parameters and boundary conditions that may affect the variation of magnetic flux in transient studies.

The research will follow a brief outline with the various stages of our design process, beginning with the variation of parameters and elements comprising the levitation unit, followed by studies on new materials and shapes in the infrastructure on which the unit will interact. This will reference the distribution used in **Vèsper** but aims to apply the results to a large-scale system.

The main proposal will be divided into two parts. The first part will address different configurations of the levitation unit, explaining how they improve electromagnetic drag and the reasons behind these improvements. Various factors will be studied, including different distributions relative to the infrastructure, the value of parameters such as pole pitch or tooth length, and the number of magnets the unit should have.

Similarly, various infrastructure geometries will be presented in a more generalised manner, aiming to make these new designs applicable to any hyperloop vehicle configuration. Additionally, materials parameters that directly influence the appearance of this phenomenon will be discussed.

Furthermore, simulations have been conducted using a new steel with properties that help reduce electromagnetic drag. This experimental steel provided by **ArcelorMittal** will be studied by implementing its characteristics in the finite element software ®JMAG. This will provide accurate references for future experimental studies. The common goal is to significantly reduce the Foucault currents generated in the infrastructure without significantly increasing the economic cost of the architecture.

The manufacturing process employed will also be discussed, including the elements used in its chemical composition and forming line, as well as the economic cost compared to other solutions employed for the same purpose.

Finally, the final design proposal will be presented, discussing why it is a potential solution to the electromagnetic drag problem. Subsequently, the achieved objectives, those not met, and the reasons for these conclusions will be listed, along with the scalability of these designs for a capsule of certain characteristics.

First, various configurations will be proposed, from which later the results that have met the pre-established specifications, as well as those that do not meet them and the reasons why, will be shown, along with the degree of scalability that these designs have for a wagon with certain characteristics.

4.2 Levitation unit optimisation

In this section, a proposal will be outlined to improve both the drag generated by the units and the force they generate. To compare different proposals, reference parameters will be established to easily demonstrate the differences between various models. Therefore, different orientations of the levitation unit with respect to the plate and various changes in its geometry will be studied. Additionally, the number of magnets needed to meet the proposed objectives will be considered. This will lead to a conclusion with a unit that combines the best results to achieve a minimal amount of drag.

Initially, various configurations will be proposed, and later the results obtained from simulations applying these compositions will be presented. These results will identify which data positively affect the objectives depending on the position of the unit. Subsequently, a comparison will be made to justify why these changes improve upon the initial proposal or, if applicable, worsen it.

Later, new results will be extracted by varying the suspension design, and the impact of increasing or decreasing permanent magnets on the drag coefficient will be assessed.

Finally, all the best-performing points identified will be combined to define the final design of the unit.

4.2.1 Orientation

In the studies where we will investigate how the arrangement of our unit applying a time-varying magnetic field on an infinitely long plate infrastructure can affect, two possible arrangements will be proposed to discuss which of these should be distributed with respect to the plate. The first of these will demonstrate the results obtained with a suspension having a pole arrangement perpendicular to the movement, while the second will show poles with the same direction.

For these studies, it will employ the suspension shown in Figure 0.2.1, designed in this way to reduce simulation times. Additionally, its structure is the minimum required to use it as a comparative design.

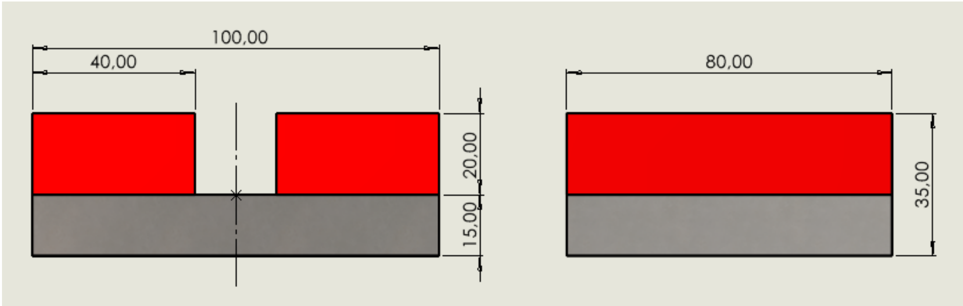


Figure 0.2.1: Units's Dimensions

Given that eddy currents are created by the time-varying flux, there is not differences in the currents generated between permanent magnets and those induced by coil-generated magnetic fields. Therefore, it has been decided to omit the assembly of coils in the teeth. This condition will be applied throughout the document. However, the spaces they could occupy will be considered in case of practical application, as they are required to enhance or reduce the flux generated by the permanent magnets.

This design will serve as a reference in all forthcoming studies, both in the section where changes to suspensions will be shown and in those displaying different designs and materials in the infrastructure. This excludes studies conducted in Section 5.1, where designs with the best results will be chosen based on the conclusions drawn from both the unit and infrastructure sections.

Next, we will present the various configurations that an electromagnetic suspension, such as the one shown in Figure 0.2.2 and Figure 0.2.3, can have concerning an infinitely long steel plate.

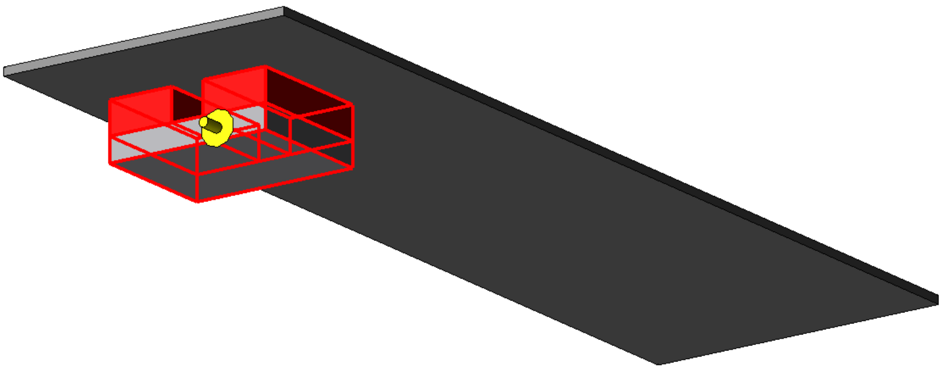


Figure 0.2.2: Unit's Position Parallel to Movement

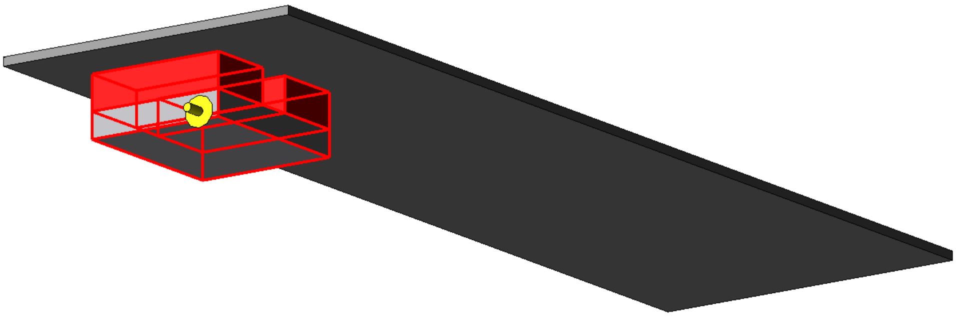


Figure 0.2.3: Unit's Position Perpendicular to Movement

For a proper comparative analysis between both cases, the study analysis will focus on three concepts: the vertical force exerted on the plate, the electromagnetic drag force, and, as previously mentioned in Section 3.2, the losses due to Joule effect on the rail.

As a comparative method, Equation 3.6 -drag coefficient- will also be utilized as it will more clearly demonstrate the difference between both results.

The information extracted from the studies can be summarized in Table 0.2.1, where reference values of 10 mm of air gap and a speed of 50 km/h have been used.

Study	Vertical Force [N]	Drag [N]	Coefficient [-]
Perpendicular	627	193	3.25
Parallel	720	73	9.86

Table 0.2.1: Orientation analysis results

The conclusion drawn from these results indicates a clear difference between which of the two orientations is a better option when assembling the levitation units to the vehicle. Not only does the parallel tooth distribution reduce the electromagnetic drag by almost three times, but it also significantly increases the vertical force.

The reason justifying this outcome can be traced back to Equation 4.1, from which we can infer that the surface over which a time-varying magnetic field is induced generates an electric vector field opposite to the axis of displacement. The greater the perpendicularity of this field to the surface, the higher its absolute value. From this, we can conclude that the application of a magnetic field parallel to the surface will result in a lower density of induced electric currents.

$$\epsilon = -\frac{d\phi}{dt} \tag{4.1}$$

Taking into account these results, we will proceed to delve deeper into the study of the geometry of the unit, where we will employ this new configuration. This will make our study more efficient, allowing us to potentially arrive at a solution for designing a unit that significantly reduces electromagnetic drag.

4.2.2 Shape

Applying the results from the previous section, various studies will be proposed for the investigation of the geometry of our unit, aiming to change the most determining characteristic parameters such as the pole pitch or the length of the teeth.

The following studies will demonstrate how varying these factors also changes the electromagnetic interaction between the unit and the infrastructure. After completing these studies, we will extract the obtained results, and the most significant conclusions will be discussed and reasoned as to why they are applicable in upcoming sections.

Firstly, sweep studies will be conducted where the distance between the centers of the teeth, known as the pole pitch, will be varied. For the following studies, the orientation parallel to the movement has been employed as it is the arrangement that yields results closest to the set objectives, achieving the best possible outcomes.

The procedure carried out to examine the results that may arise from varying the pole pitch concerning an orientation of teeth parallel to the movement involved the use of a wide width in the plate to adequately characterize the unit with a large number of pole pitches.

Next, with the same dimensions shown in Figure 0.2.4, a sweep of various cases was conducted where only the distance between the teeth was varied. This was done to understand the trend that this increase in width could follow and to determine which results could be more scalable to reality.

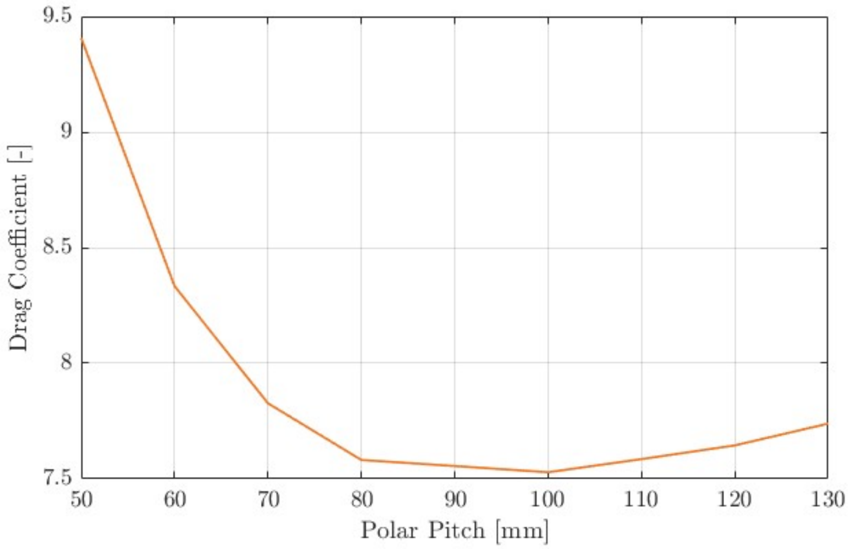


Figure 0.2.4: Polar Pitch Variation

Observing previous Figure, it is evident that with lower pole pitches, the drag coefficient is higher than with greater distances, always using the same plate properties.

As mentioned earlier, following Equation 3.5, it is evident that the increase in pole pitch, i.e., a larger area exposed to the magnetic field, also leads to an increase in the dissipated power due to the minimal resistance sought by the electric field generated by the magnetic field. These electric fields combine with the opposing currents generated by the variation of the field at the exit of the unit, hindering the magnetic flux and worsening the losses, in addition to increasing the surface on which the field acts, generating broader parasitic currents.

The second parameter studied during the investigation in the structure of the unit will be defined by different lengths of teeth to see how the increase in length, complemented with permanent magnets, varies the drag force, as the vertical force will increase considerably when adding the magnets.

It might result in conclusions similar to the pole pitch since in both studies, opposite sides in the unit are separated, thereby increasing the volume where currents are induced and consequently increasing electromagnetic drag.

However, this occurred because the flux variation occurred closely with magnets in the same direction, as the currents from the other group of magnets with opposite direction did not interact with them. But when the flux variation occurs only at the ends of the magnets, by separating the magnet from the exit with the one from the entrance, the parasitic currents that "feed back" between them reduce their effect. Still, by keeping the south pole tooth with the tooth acting as the north pole, these currents following "complementary" directions will drastically reduce electromagnetic drag. Additionally, this is compounded by the decrease in the variation of magnetic flux with respect to time, which minimizes the creation of Foucault currents in the steel.

Applying these hypotheses in a finite element analysis study, the results shown in Table 0.2.2 have been obtained:

Magnets Qty / Tooth	Force [N]	Drag [N]	Drag Coefficient [-]
2	720	73	9.863013699
3	1015	81	12.5308642
4	1212	72	16.83333333
5	1382	64	21.59375

Table 0.2.2: Results on tooth length variation

As shown in the table, there is a clear improvement in the drag coefficient because the ends where the induced currents act only interact with those of opposite direction, and the rotation generated by the ends of the teeth has opposite directions, favoring the interaction of currents between them.

However, this characteristic requires a particular study in the design of a specific hyperloop proposal. This is because the increase in tooth length maintains a trend of increasing the drag coefficient, which decreases slightly as more magnets are added along the unit.

Therefore, magnets could be added almost indefinitely along the length of the unit without noticing detrimental effects or negligible variations in drag. Thus, to define the length of the unit, as well as the number of magnets in it, a study must consider parameters such as the weight of the pod, the available surface to place the units, the space occupied by the coils that will wrap around the teeth, and the minimum space that will be maintained between these suspensions.

4.2.3 Final geometry

Once the results are developed and justified, the final geometry of the levitation unit to be used for the final proposal will be defined.

For this composition, the orientation where the arrangement of the teeth is parallel to the movement will be used. As seen in Section 4.2.1, this configuration shows an improvement in reducing drag by 62.17% compared to the perpendicular orientation. Additionally, it has been observed that the lower the pole pitch of the unit, the better the results obtained for the drag coefficient. However, the use of windings that wrap around the teeth is required for the proper functioning of the suspensions. Therefore, a minimum pole pitch should always be employed to allow positioning the necessary coil size in the unit. Finally, for the tooth length, five neodymium magnets - 40x40x20 - per tooth have been used, resulting in a length of 200 mm.

Finally, in Figure 0.2.5, the dimensions of the unit used in the final results are shown, as well as the results it provides on the infrastructure taken as the standard, as shown in Table 0.2.3.

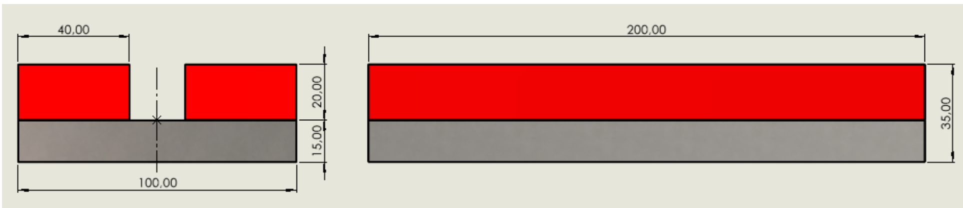


Figure 0.2.5: Final Unit Dimensions

Nº Magnets/Tooth	Vertical Force [N]	Drag [N]	Drag Coefficient [-]
5	1382	64	21.59

Table 0.2.3: Final Unit Results

The studies conducted to optimize both distributions and dimensions of the unit in a hypothetical position within the vehicle have shown results that have helped approximate the established objectives, leading to a reduction in electromagnetic drag by 66.8% compared to the initial proposal.

Furthermore, a notable increase of 664.6% in the coefficient of drag of the final design of the unit has been observed, an improvement largely defined by the increase in vertical force, whose magnitude is affected by the increase in speed, decreasing significantly at higher speeds.

All of this has been achieved without deviating from the main objective of this document, which is to identify trends for a levitation unit that can be applied in large-scale vehicles.

4.3 Infrastructure Optimization

This second part of the study will focus on the theoretical application extracted and explained in the previous point with the current vertical levitation model used in **Vèsper**, where an evolution of this vehicle-infrastructure relationship will be seen throughout the different points dealt with in the theoretical study.

In this section, we will first discuss the dimensions that best adapt to the conclusions drawn in the previous section, which is why a sweep will be made of the dimensions of the steel, considering an infinite track length.

Continuing with the study of the infrastructure, the next step will concentrate on the analysis of the magnetic properties of the material, in order to compare different values and be able to reach a conclusion on the necessary characteristics that a material would have to have in order to correspond to the objective of the vehicle. Additionally, these studies are not merely theoretical but have been experimentally validated by the leading multinational in the metallurgy sector, **ArcelorMittal**.

4.3.1 Infrastructure's Dimensions

In this section, the model of the vertical levitation unit used as a reference in the previous section has been used and nominal parameters such as air gap and unit materials have been used for all the studies, in order to obtain a reliable comparison between the different geometries of the plate and results closer to the final result. Figure 0.3.1 shows the dimensions of the unit used in these studies.

In order to standardise structural dimensions in accordance with the unit used as a reference, sweeps have been carried out with the dimensional parameters of the plate on which we will carry out future studies. Between these, studies will be carried out by varying the thickness and width of the steel, considering at all times an infinite rail length, and in all cases using a speed of 50 km/h.

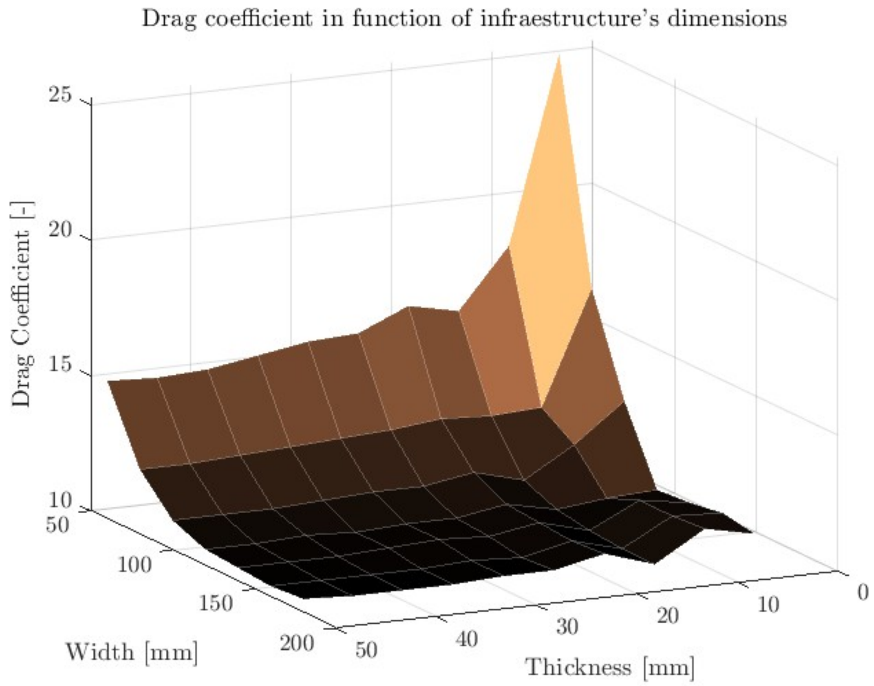


Figure 0.3.1: Dimensions Variation

The conclusions drawn from the data in Figure 0.3.1 inform us that the drag coefficient reaches a constant trend with both increasing thickness and width of the steel plate used in the studies. This is due to the fact that the cases with infrastructure widths smaller than the width of the unit produce much lower current densities due to the reduction of the surface on which the unit acts, thus reducing the energy loss, but at the same time reducing the levitation force it can provide by up to 32.9%, which means that any width smaller than the width of the unit cannot be used at high speeds, which is why those widths with values greater than 100 mm will be studied and compared.

Furthermore, it can be seen that the growth of the thickness value, like the width, tends to constant coefficients, except for those below 15 mm, which show higher values compared to those above.

Of all the remaining options, the coefficients show very similar values, this is due to the maximum hysterisation that the material undergoes, since the volume where the flow is induced is very similar in all cases, improving the levitation force slightly in the larger widths, and also worsening the electromagnetic drag in those with a larger surface area, Therefore, the criterion that will be used to choose the thickness of the steel is to use the lowest thickness, as the Hyperloop track network is intended to extend over hundreds of kilometres, so economising on the amount of material used in the guideways that the vehicle follows will reduce infrastructure costs considerably.

With the remaining steel widths, the highest coefficient value has been chosen for a thickness of 5 mm, since the difference in vertical force is greater with the lower widths and very similar with the higher ones, and in the case of dragging, even with these, so we will use a width of 160 mm.

Dimensions	Vertical Force [N]	Drag [N]	Coefficient [-]
Thickness: 5 mm Width: 160 mm	714	63	11.24

Table 0.3.1: Force Coefficient Results

Table 0.3.1 shows the results obtained with the new infrastructure dimensions, which again show a reduction of 13.7% in electromagnetic drag compared to the studies used as a reference in Section 4.2.1.

4.3.2 Infrastructure's Materials

In order to analyse and define the studies to be carried out, it is necessary to know the concepts that define the magnetic properties of materials.

To understand these differences, it is essential to start with the basic and fundamental concepts.

Magnetic flux: This is a measure of the magnetic field that crosses a surface, depending on its angle of incidence. Following the Equation 4.2 where B is the magnetic field density and A is the area that is traversed by the magnetic field.

$$\Phi = B \cdot A \tag{4.2}$$

Magnetic field density: Following Ampere's law which states that the magnetic field along a closed circuit is directly proportional to the current passing through the circuit. In other words, it is the amount of magnetic flux per unit area perpendicular to the field.

Magnetic field strength: A measure of the strength and direction of magnetic field vectors at a given point. It allows to relate the magnetic field and the permeability of the material as can be seen in the equation 4.3.

$$B = \mu \cdot H \tag{4.3}$$

All these concepts are directly reflected in what is known as the B-H or hysteresis curve of the material, shown in Figure 0.3.2.

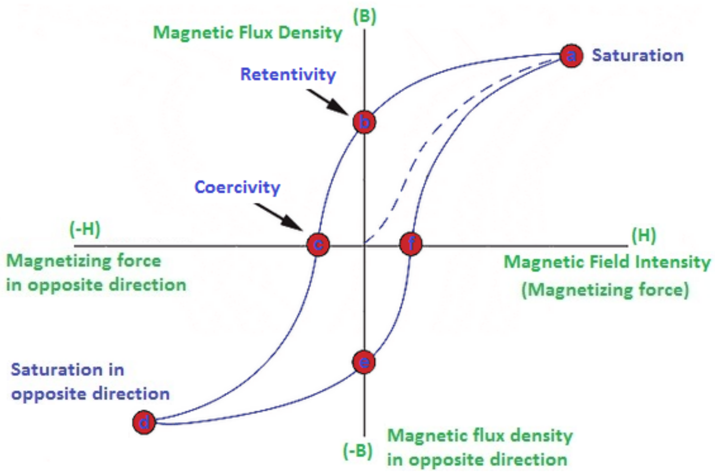


Figure 0.3.2: Hysteresis Curve

Relating the magnetic flux density B and the magnetic field strength H in a material. This curve provides crucial information about its magnetic properties such as:

- Magnetic permeability: This is a constant that indicates how much a material can be magnetised. It is therefore a differentiating aspect in the analysis of materials for the choice of their use for infrastructure.
- Magnetic saturation: Indicates that the material has been completely magnetised and cannot increase its magnetic flux density significantly, despite increasing the field strength.
- Coercivity: Represents the magnetic field required to reduce the flux density to zero after the material has been magnetised to its saturation point.
- Remanence: The magnetic flux density when the magnetic field is zero after reaching its saturation point. Representing the amount of magnetisation retained by the material.

Once the previous concepts are known, it is necessary to know how to differentiate between the properties and categories in which the materials are defined according to these characteristics.

- Diamagnetic: These are all materials whose spins are oriented in the opposite direction to that of the external field - zero magnetic momentum - thus creating a magnetic field that opposes - repels - the source of the magnetic field. These materials have a magnetic susceptibility of less than zero.
- Paramagnetic: Materials whose spins are oriented in the direction of the magnetic field - non-zero magnetic momentum. These materials are capable of being magnetised when exposed to an external magnetic field, which is why their magnetic susceptibility is greater than zero but very slightly. Due to their low magnetic susceptibility, a very high field strength is necessary to generate a small field variation inside the material.
- Ferromagnetic: Like paramagnetic materials, these have a non-zero magnetic moment. They also have a magnetic susceptibility much greater than zero, which makes them ideal for channelling magnetic field lines.

Analysing the different characteristics above, it stands out that for the requirements of a Hyperloop infrastructure, the use of ferromagnetic materials is essential. This is due to the operation of the levitation system itself, as it is simply characterised by the influence of magnetic field lines from the levitation unit unit on the infrastructure itself, thus demanding the need to use materials with high permeability and magnetic susceptibility, in order to obtain the greatest force of attraction between the two components.

Once the magnetic properties of steel have been defined, another important aspect in the study of magnetic drag reduction is electrical resistivity.

This property is closely related to the creation of currents on the surface of the steel, this relationship is defined by Equation 3.2 which is also influenced by the Faraday-Lenz Law where the variation of the magnetic field of the unit with respect to the steel sheet generates the electric field from which the currents originate in the infrastructure.

Table 0.3.2 shows the drag values obtained in steel plates with different electrical resistivity. All three studies were carried out in the @JMAG software at a speed of 50 km/h. The resistivity values are theoretical with the exception of 1.64x10-7 corresponding to a structural S10C steel, which was used as a reference.

Resistivity [Ωm]	**Drag [N]**
5×10^{-8}	150
1.64×10^{-7}	69
4×10^{-7}	29

Table 0.3.2: Resistivity vs. Drag

As can be seen in the table above, the resistivity of the material largely determines the drag generated by the unit. Clearly following a trend in its decrease thanks to the increase of this property in the material.

The conclusion of this study allows to determine a big step in the decrease of the drag with the application of different methods in the own structure of the material to increase this electrical resistivity. An example of methods for varying the composition is the addition of alloys in its structure - much higher than a normal one - in order to increase the total resistivity of the steel.

4.4 Experimental Steel

So far, results have been shown using numerical methods employed with finite element software, as this is the most widely available study method that can provide us with more reliable results than theoretical calculation. However, it is intended to carry out experimental tests during the testing phase of **Vèsper**, so that the results obtained during the previous section can be confirmed.

However, this proposal has been complemented by ArcelorMittal's research and development department, which is committed to finding a solution to the eddy current problem, by supplying two categories of steels with high electrical resistivity. In contrast to the materials proposed during the first instance of the document, the results obtained with two experimental steels that will soon be evaluated will be shown below.

4.4.1 Manufacturing

Steel is one of the materials used in many industrial applications due to its versatility. In particular, it is a very attractive material for implementation in Hyperloop infrastructures due to its combination of mechanical strength, ductility and magnetic properties. However, among the wide range of existing alloys, it is crucial to make the right choice in order to meet the objective of optimising magnetic properties and thus reducing drag. Not only this, but another essential factor to take into account is the manufacturing method to be used, as this has a direct effect on the microstructure, and therefore on the properties of the material. This section focuses on showing the manufacturing method used for the prototype, and analysing the properties obtained after the process.

This part of the development has been carried out by the company **ArcelorMittal**, which has extensive experience working with all varieties of steel, as well as facilities with the most advanced technologies for the manufacture and treatment of the material. The work with which **ArcelorMittal** has collaborated in the manufacturing research has been carried out in 'the Apple of Steel', a pilot plant that allows the reproduction of the entire steelmaking process - from the melting of the raw materials to the final rolling - as well as the complete life cycle of the steel. This allows for greater process adaptability and broadens the range of products to be developed depending on the final conditions required.

The first step in the manufacture of the material is casting. Continuous casting is a metal melting process in which the transformation of the liquid metal into a solid state is continuously controlled at high temperatures so that the material solidifies uniformly. This step requires a lot of energy and time. Not only that, but it is complex to simulate at scale. In the pilot plant it is possible to obtain ingots with a chemical composition very close to the industrial one by using a Vacuum Induction Melting -VIM- furnace with a maximum capacity of 100 kg. Figure 0.4.1 shows the induction melting furnace with which the metal casting has been carried out.

Figure 0.4.1: Vacuum Induction Melting

Once the cast steel ingot is obtained, it is transferred to the annealing furnace shown in Figure 0.4.2, where the temperature is increased up to 1200 ºC. This heat treatment mainly consists of raising the temperature of the material to alter to some extent some of its physical and chemical properties. The most notable effects are an increase in ductility and a reduction in hardness.

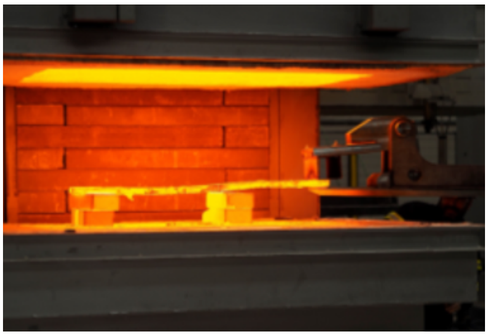


Figure 0.4.2: Annealing furnace

The last stage of the process is hot rolling. This consists of passing the steel through rollers at very high temperatures - above 1000 ºC - which exceeds the recrystallisation temperature. This facilitates the shaping of the material, and the final dimensions of the sheets are formed, which are the ones used in the infrastructure that Hyperloop UPV is presenting to EHW 2024.

This is the process commonly followed in the manufacture of steels, however it is complex to manufacture it for this prototype on a customised chemical composition scale in order to optimise the magnetic properties. It is complex because the conditions to which the steels are subjected during mass production, inside furnaces and large volume machinery, are not the same as the conditions experienced by this scale prototype. It is for this reason that ArcelorMittal's pilot plant specialises in recreating these conditions so that, by subsequently characterising the material and understanding its properties, they are as similar as possible to those that would be obtained if the material were mass-produced for application to Hyperloop infrastructures in the future.

4.4.2 Simulations

Following the procedures carried out so far, we will now proceed to carry out various studies with the experimental steels described above to see how the distributions of the reference units used so far interact with these proposals, and in this way find out how much the results obtained with the studies carried out by FEA of the experimental tests vary.

The aim of this proposal is to show the consequent improvements of the new materials at different speeds. Table 0.4.1 and Figure 0.4.3 and Figure 0.4.4 will show together the most important characteristics that will determine the differences between the study:

	Resistivity $(\times 10^7\ Ohm \times m)$	**B(T)**	**H(A/m)**
S10C	1.639	1.97	15300
Arcelor 1	3.3	1.884	103800
Arcelor 2	4.6		

Table 0.4.1: Materials Comparison

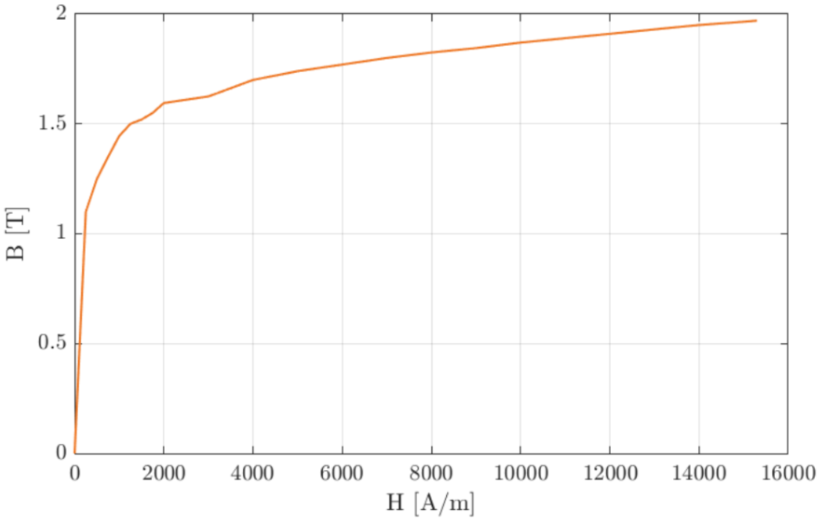


Figure 0.4.3: FEA's Structural Steel B-H curve

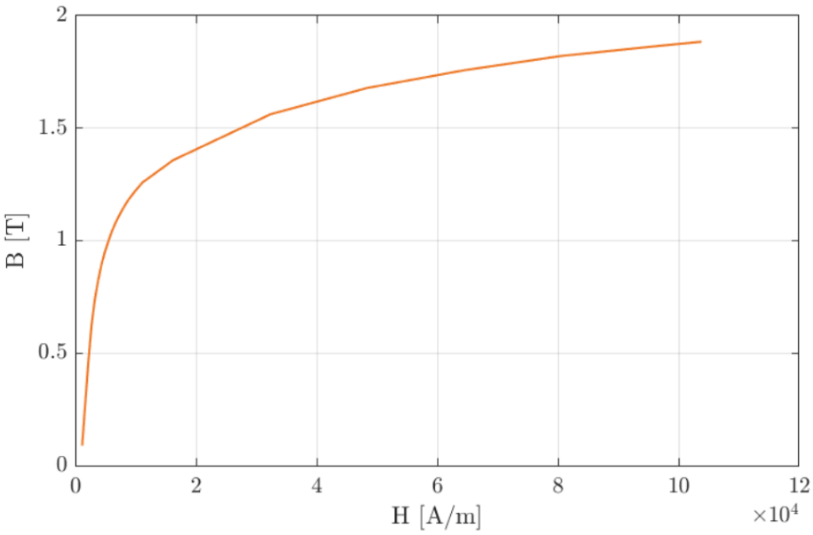


Figure 0.4.4: Arcelor's Structural Steel B-H curve

Thanks to these data and the information extracted from Section 4.3.2, a significant decrease in electromagnetic drag and an increase in the drag coefficient can be predicted, following Equation 3.2.

In order to carry out these studies, different conditions have been established prior to their calculation, which realistically represent what conditions the steels will be confronted with during the phase of higher speed that the vehicle will reach during the process of extracting the results:

- Orientation perpendicular to the movement
- Maximum speed (50 km/h)
- Width and thickness of the actual infrastructure

With these points already established, we will now show the studies carried out on the three steels shown in Table 0.4.1 together with their results, and a well-argued comparison between them.

As a first study, we will present a study similar to the one carried out in Figure 0.2.3 but with the points previously established. In this way it will be possible to take a reference to see to what degree the two experimental steels have better performance in comparison with the structural steel used.

The data obtained with Steel 1 is shown in Table 0.4.2 in comparison with the same study but with the Structural Steel in the first section:

	Force [N]	Drag [N]	Coefficient [-]	Loses [W]
S10C	628	196	3.20	2520
Arcelor 1	607	95	6.39	1270

Table 0.4.2: Structural Steel and Arcelor Steel Comparison

The conclusions that can be drawn from Table 0.4.2 are very similar to those drawn in Section 4.3.2, so it can be reaffirmed that electrical conductivity is an essential parameter for the reduction of electromagnetic drag.

However, it is visible with the new material a reduction in the vertical force with respect to the structural steel used in the simulations, this is due to the manufacturing process used for this new steel.

In this process, priority has been given to reducing the electrical conductivity by adding elements that generate internal defects, which also reduces magnetic properties, as in this case, saturation.

Although the saturation point decreases with respect to that of the structural steel, the loss of vertical force is of a lower order than the resulting force, so these losses can be considered negligible. However, this change in the micro-structure of the steel considerably improves the results of electromagnetic drag, increasing the drag coefficient proportionally with respect to the increase in the resistivity of the steel.

Following the same methodology of the studies used with the previous steels, for Steel 2, studies have been carried out with the same conditions mentioned above, from which the drag of the three steels can be seen in Figure 0.4.5.

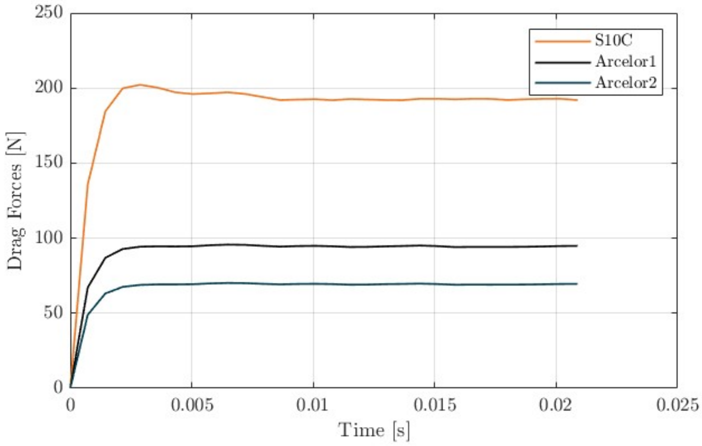


Figure 0.4.5: Electromagnetic drag comparative

With these results it can be justified that these new materials show performances in line with the objective of this paper, decreasing to a great extent the electromagnetic drag in the way followed by Equation 3.2, where it is definitely seen that the reduction of the electrical conductivity of the steels is an essential factor for the minimisation of the electromagnetic drag.

4.4.3 Economical aspects

The infrastructure involved in developing the hyperloop technology represents a significant economic challenge for this project. The need for a completely vacuumed space over thousands of kilometers poses considerable difficulties in terms of fabrication and assembly. This is a critical factor in the scalability and viability of this means of transport, making it essential to research and develop new technologies to address these challenges.

Therefore the design for the infrastructure should bear in mind that the price should remain low when produced in large quantities. In addition, it needs to be compatible with current industry fabrication processes.

As detailed and explained in Section 4.4.1, there are no substantial differences in the manufacturing processes of these new experimental steels developed together with **ArcelorMittal** compared to those used on a larger scale and in a standardized manner, such as S10C steel, which is widely used in construction.

The other major option for reducing the drag induced in the infrastructure is the use of electrical steel. It is composed of thin sheets of steel isolated from each other. This leads to a considerable increase in performance as fewer eddy currents are generated. Nevertheless, the production process consists in laser cutting each sheet and then gluing them together. This is a slow and costly process. Based on the Linear Synchronous Motor designed by Hyperloop UPV for the EHW 2024, electrical steel can be up to 50 times more expensive per kilogram than structural steel.

To conclude, new alloys that allow for a reduction in the drag forces generated while keeping costs low is the path to follow in order to achieve a hyperloop network extended over thousands of kilometres. Structural steel does not meet the requirements needed for ultra-high speed transportation while electrical steel makes it too expensive.

Chapter 5

Conclusions

5.1 Results & Discussion

Once discussed the different aspects directly affecting electromagnetic drag, the results of the combination of all studied parameters will be presented. The conclusions drawn from each are summarized below:

- **Orientation:** A position of the teeth parallel to the movement reduces the severity in flux variation compared to a perpendicular tooth orientation.
- **Pole Pitch:** The minimum pole pitch possible is preferred - as far as coils fit - as the current densities generated by the unit are reduced by the complementary fields generated by both teeth.
- **Unit Length:** Increasing the distance between the incoming and outgoing zones in a transient study positively affects a less aggressive flux variation, potentially improving its values the greater this distance is, adapting to substantial changes in vehicle dimensions and parameters.
- **Infrastructure Dimensions:** Infrastructure dimensions have been optimized in pursuit of improved unit efficiency.
- **Infrastructure Materials:** The influence of different electrical and magnetic properties of steels has been proved to modify the Eddy currents generated. The results show that higher resistivity is favored.

With this overview of the research conducted so far, all conclusions drawn from each of these points will be used, and an open study will be conducted to demonstrate the potential solution extracted for the maximum reduction of Eddy currents for proper scalability.

The final proposal is ultimately defined by a tooth orientation parallel to the movement, with a minimum pole pitch necessary to assemble coils around the teeth, a length of 200 mm defined by five neodymium permanent magnets placed on each tooth, with this number being subject to variation depending on the criteria mentioned in Section 4.2.2. For the infrastructure, various sweeps of its dimensions have been carried out, concluding with a steel thickness of 5 mm and a width of 160 mm, and along with a material of high electrical resistivity such as experimental steel 2, we obtain a configuration shown in Figure 0.1.1, with final results shown in Table 0.1.1.

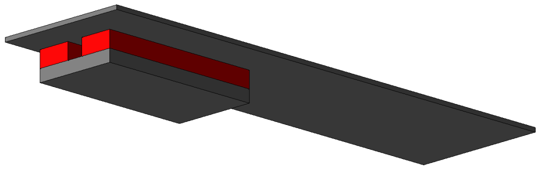


Figure 0.1.1: Final Design

Type of Steel	Vertical Force [N]	Drag [N]	Coefficient [-]
Arcelor 2	1200	19	63.16

Table 0.1.1: Final Results Table

The culmination of all conducted studies has been aligned with the sought objective, achieving a reduction in electromagnetic drag of 90.2% compared to the initially employed reference.

Throughout this entire research, progress has been seen towards achieving optimal synergy between vehicle and infrastructure, allowing for the possibility that this sequence of studies can be adapted to any situation of a hyperloop vehicle employing attraction-based levitation.

Next, the proposed objectives will be discussed, and the obtained results justified, along with an explanation of how such conclusions were reached.

The aim was to achieve a drag coefficient greater than two for ultra-high speeds, as this value would ensure that the vertical force exerted by the unit would not become inferior to the force of the opposing magnetic field generated by Eddy currents. Studies conducted to achieve this goal have been carried out using the final proposal shown in Figure 0.1.1, with the parameter used for speed changed to 900 km/h. From this variation, the results shown in Table 0.1.2 have been obtained.

Type of Steel	Vertical Force [N]	Drag [N]	Coefficient [-]
Arcelor 2	825	220	3.75

Table 0.1.2: Final Proposal Results for High Velocities

Concluding that it is indeed possible to achieve a drag coefficient greater than two, which prevents the aforementioned inflection point where the force of the induced magnetic field from the steel does not surpass that created by the levitation unit.

This conclusion demonstrates that the data derived from the studied elements bring us closer to the future of the fifth mode of transportation, leaving an open avenue for further investigation into various geometries of electromagnetic suspensions and infrastructure design with new materials to aid in solving this problem in future studies.

5.2 Scalability

Magnetic levitation poses as a great ally in order to achieve huge speeds that make hyperloop an alternative to aviation in certain routes. Nevertheless, magnetic levitation as has been discussed presents its own challenges. Being able to create a design where electromagnetic drag is minimised while maintaining it easy to fabricate and cost-effective is of crucial importance.

Bearing in mind that hyperloop is an electric vehicle and therefore all the energy must be stored in batteries that considerably outweigh fossil fuels, the cruise conditions must be really efficient. If a large amount of drag needs to be compensated, a lot of energy will be needed by the on-board propulsion system.

In the one hand, all of the characteristics of the levitation units described along this paper can be applied to a real vehicle, offering important guidelines when designing a levitation system intended to work at high speeds.

In the other hand, infrastructure has been proven to play a pivotal role. Specifically, developing new levitation-optimised steels appears as one of the main paths that hyperloop researchers should follow for addressing the electromagnetic drag issue.

There are many doubts regarding the scalability of a vehicle with such innovative characteristics, leading to problems in many areas of its development because of these same characteristics. Especially in reaching speeds of 900 km/h, being at the point where the same phenomenon studied in the document - Electromagnetic Drag - prevents this from happening.

Hence the reason for this document, to mitigate as much as possible the interaction of this force in every Hyperloop vehicle and to pave the way for further steps in its study and development.

In a scaled Hyperloop vehicle, it is crucial for its proper functioning because the need to use either larger levitation units or a greater number of them would aggravate the problem substantially, endangering the development and benefits involved in its creation. Calculating theoretical numbers, taking as an example a passenger car of a current Maglev train weighing around 30,000 kg, it would take about 700 levitation units with the reference arrangement to make it move at 50 km/h. The electromagnetic drag created by each of these units becomes a crucial factor, completely preventing the attainment of these ultra speeds of 900 km/h, and even showing a phenomenon of repulsion of the levitation units from the infrastructure.

Once the changes established in this document have been made, and reducing the forces of electromagnetic drag and repulsion on the steel plates, the possibilities of reaching such speeds increase exponentially. Furthermore, taking the same previous example of the weight of a commercial car, the need for levitation units is drastically reduced to 400 units.

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