CONCURRENT AERODYNAMIC SHAPE / COST DESIGN OF MAGNETIC LEVITATION VEHICLES USING MULTIDISCIPLINARY DESIGN OPTIMIZATION TECHNIQUES

By

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(ABSTRACT)

A multidisciplinary design optimization (MDO) methodology is developed to link the aerodynamic shape design to the system costs for magnetically levitated (MAGLEV) vehicles. These railed vehicles can cruise at speeds approaching that of short haul aircraft and travel just inches from a guideway. They are slated for high speed intercity service of up to 500 miles in length and would compete with air shuttle services. The realization of this technology hinges upon economic viability which is the impetus for the design methodology presented here. This methodology involves models for the aerodynamics, structural weight, direct operating cost, acquisition cost, and life cycle cost and utilizes the DOT optimization software. Optimizations are performed using sequential quadratic programming for a 5 design variable problem. This problem is reformulated using 7 design variables to overcome problems due to non-smooth design space. The reformulation of the problem provides a smoother design space which is navigable by calculus based optimizers. The MDO methodology proves to be a useful tool for the design of MAGLEV vehicles. The optimizations show significant and sensible differences between designing for minimum life cycle cost and other figures of merit. The optimizations also show a need for a more sensitive acquisition cost model which is not based simply on weight engineering. As a part of the design methodology, a low-order aerodynamics model is developed for the prediction of 2-D, ground effect flow over bluff bodies. The model employs a continuous vortex sheet to model the solid surface, discrete vortices to model the shed wake, the Stratford Criterion to determine the location of the turbulent separation, and the vorticity conservation condition to determine the strength of the shed vorticity. The continuous vortex sheet better matches the mechanics of the flow than discrete singularities and therefore better predicts the ground effect flow. The predictions compare well with higher-order computational methods and experimental data. A 3-D extension to this model is investigated, although no 3-D design optimizations are performed.

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To bobi & zady

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Nomenclature

c chord

$\mathbf{c}$ constraints

C_p pressure coefficient

C_D drag coefficient

C_L lift coefficient

C_m pitching moment coefficient

d characteristic diameter

D drag, and
structural depth

e internal energy

$\mathbf{g}$ gradient of the objective function

h height

H Hessian matrix

k thermal conductivity

l direction along line integral

L lift, and
structural length

m pitching moment

$\mathbf{n}$ unit normal

N_Z ultimate load factor

OBJ objective function

p pressure

$\mathbf{p}$ search direction

q dynamic pressure

R region

$\mathbf{r}$ position vector

Re Reynolds number

S region boundary

S_f surface area

t time

u tangential surface velocity

u_* friction velocity

$\mathbf{V}$ velocity vector

W weight

x dimension parallel to solid surface

$\mathbf{x}$ design variables

y dimension perpendicular to solid surface

α angle of attack

γ vortex sheet strength

Γ circulation

δ boundary layer height

η Lagrange multiplier

μ distributed doublet strength, and
viscosity

ν kinematic viscosity

ρ density

σ vortex blob diameter, and
source strength

Φ velocity potential, and
dissipation function (energy equation)

ϕ disturbance potential

$\mathbf{\Omega}$ vorticity vector

Subscript

B	Boundary Layer
dg	design gross
f	fluid
h	gap height
L	lower
TE	trailing edge
S	solid
T	turbulent
U	upper
w	wake
∞	infinity

Chapter 1

Introduction

1.1 Overview

The design of advanced aerospace vehicles is inherently multidisciplinary and should therefore be reflected in a suitable design methodology. Approximately 80% of the cost associated with the product is committed during the conceptual and preliminary design phases [1]. Since very little money has actually been spent at this stage in the design process, the gravity of the design decisions and the pivotal nature of these early phases becomes evident. In the design of most aerospace vehicles, aerodynamics plays a major role in determining propulsion, structural, and control requirements. Aerodynamics also has strong ties to the overall cost. Designing for good aerodynamics while ignoring cost as a design objective will surely result in a flawed design which will incur many off-design penalties over the life of the vehicle. It is, therefore, important to develop a design methodology which will incorporate all essential disciplines. This research involves the development of such a methodology which includes cost as a figure of merit for the shape design of high speed, magnetically levitated vehicles (trains).

The technological advantage of MAGnetically LEVitated (MAGLEV) vehicles over trains is that they lack wheels which cap the maximum speed at approximately 200 mph. This technology is capable of speeds approaching that of aircraft, so the target speed for this first generation of MAGLEV vehicles is 300 mph. Market analyses have, therefore, slated MAGLEV vehicles for high speed intercity service of up to 500 miles in length. This would put MAGLEV vehicles in competition with short haul air transportation and shuttle service. It could complete this mission, with approximately two stops, in under two hours and embark and terminate in city centers. This would relieve highway and air traffic congestion and offset the need to add highway lanes and build new airports near cities to accommodate for growth. In addition to this, the MAGLEV system has low energy consumption per seat mile estimated at one quarter of that of a commercial aircraft for a similar mission [2].

The design challenges for the aerodynamic shape of MAGLEV vehicles are greatly different from that of airplanes. With magnetic suspension, aerodynamic forces are not the only source of lift and drag, so the performance parameters are not as strong a function of the aerodynamic lift to drag ratio. The inclusion of cost as a design goal is, therefore, essential in making design decisions involving magnetic vs. aerodynamic forces and moments. The absence of onboard fuel removes range from the problem. Performance is based on cruise Mach number, energy used, and payload weight. The close proximity of the track changes the aerodynamics, necessitating specific ground effect analyses for design. Cross wind sensitivity is important due to the small track clearances involved and the need for lateral directional control. The design for some service corridors will be based heavily on the issues of vehicle aerodynamics in tunnels and vehicle passing. The potential proximity to areas of human population makes noise abatement a prominent design goal. The aerodynamic shape must also be chosen with respect to manufacturing complexities and concerns. The issue of manufacturability strongly connects the aerodynamic design to the life cycle cost of the vehicle.

The study of life cycle costs is important for measuring the economic viability of the project. Use of only the acquisition cost, or only the operating cost as the primary measure, neglects the real operating environment of the system. Life cycle cost captures all relevant costs for the project, from the conceptual design phase, through the detailed design phases, production of the system, deployment of the system, operation and maintenance of the system, and the planned retirement and disposal of the system. This analysis takes account of the economic factors relevant to the life cycle, such as the cost of capital, the time value of money, tax effects on cash flows, and the costs of disposal of the system. For this work, the life cycle cost model uses capital cost elements from the work breakdown structure prepared for the Northrop Grumman MAGLEV vehicle [3]. Using projected passenger traffic loading, the profitability of the project can be calculated using discounted cash flow analysis. The realization of this technology hinges upon economic viability which is the impetus for the design approach presented here.

The concurrent handling of aerodynamic and economic performance is accomplished using multidisciplinary design optimization techniques (MDO). Multidisciplinary design optimization is the instrument by which one can consider several disciplines at once and mathematically link them to consider the interactions. This is advantageous over dealing with each discipline sequentially. Using such tools, one can deal with numerous individual disciplines and satisfy mission requirements while achieving optimum performance with respect to some predetermined figure of merit. Such an approach is very useful for conceptual and preliminary design phases where analyses are, by definition, simple and inexpensive to perform. The work here employs the sequential quadratic programming method. It is a gradient based optimization method and is considered to be the current state of the art in this "mature" area of optimization theory.

The work presented here involves the development of a design methodology for the concurrent aerodynamic and cost design of MAGLEV vehicles. The design methodology has been created to operate in an automated fashion, and it is modular to allow for the continual improvement of the individual models. This attribute is particularly important for the cost models which are low fidelity at this early stage in the development process. The design loop is set up around the sequential quadratic programming optimizer which can perform constrained optimizations. The objective functions for the optimization are provided by several modules which are shown in Fig. 1.1. The module input, output, and contents are discussed in the following chapters. A great deal of effort was put into developing the aerodynamics model which is a low-order model for the flow over bluff bodies in ground effect. "Low-order" refers to methods based upon Laplace's equation (to be discussed in Chapter 2) while "high-order" refers to models based upon the Navier-Stokes equation. One of the largest problems involved in performing multidisciplinary design optimizations of vehicles is in acquiring the aerodynamic coefficient sensitivities. The method developed here is a low-order (simple and quick) method which can predict flow phenomena normally attributed to high-order methods. This model overcomes this obstacle which stems from the prohibitive cost of high-order aerodynamic calculations for these complicated flow fields. The cost models were assembled by Eaglesham and Deisenroth from the Industrial and Systems Engineering Department at Virginia Tech [4]. A five design variable test problem (2-D, side view) is performed to evaluate the methodology and determine design optima for several figures of merit. These are drag coefficient, lift to drag ratio, empty weight, acquisition cost, operating cost, and life cycle cost. The extension to full 3-D designs is discussed in the section on the 3-D aerodynamics model (Section 2.3). Optimizations have not yet been performed using full 3-D aerodynamics.

1.2 Ground Effect

The aerodynamics problem being dealt with in this work is the incompressible, exterior flow over a bluff body in close ground proximity. The ground effect flow is different than that of an automobile or conventional train. The MAGLEV vehicle is in close proximity to a guideway, which is raised above the ground. The modeling of such flows is a difficult problem and is one which involves non-linear aerodynamics and consequently expensive solution methods. A new development associated with this work is the use of low-order aerodynamic computations to solve for these flows. The method proposed is capable of generating solutions which are comparable to higher-order methods and experiments. The "lift reversal" phenomena is captured, and quantitative aerodynamic characteristics are obtained. It is also shown that the choice of panel method singularities is crucial to the calculation of flow over bodies in strong ground effect.

1.3 System Requirements

The MAGLEV transportation system technical requirements can be found in a report put together by ENSCO, Inc. [5]. This document discusses the different operation concepts and specific factors outlined by the Intermodal Surface Transportation Efficiency Act of 1991. Requirements are outlined in the general categories of basic performance, system operations, operating environment, safety and security, environmental impacts, ride quality and passenger environment, and cost. Most of these requirements involve detailed design parameters which are not dealt with here. This report describes a balance between technical performance and capital and operating costs. This design methodology is developed to address such requirements in the conceptual design phase.

1.4 A Brief History of MAGLEV Vehicles

Magnetic levitation (MAGLEV) is finding its way into many applications ranging from space launch systems to bearings. It had initially been proposed as a means of high speed ground transportation at the beginning of the twentieth century. Interest has been intermittent throughout this century, and financial backing materialized when technological obstacles broke down and the political climate allowed. A brief history of MAGLEV Vehicles can be seen in the following subsections each pertaining to a specific country which is participating in the development of such vehicles [6].

1.4.1 United States of America

The use of magnetic levitation as a means of high speed ground transportation was first proposed by Robert Goddard in 1909. His idea involved a vehicle traveling through a tube in partial vacuum [7]. In 1912, a french engineer named Emile Bachelet built and patented a small scale prototype vehicle which achieved levitation using AC current repulsive magnets. Due to the level of technology at the time, Bachelet's ideas could not be extrapolated to a full-scale vehicle.

Superconductivity paved the way for a full-scale magnetically suspended vehicle. Powell and Danby worked in the area throughout the 1960s at Brookhaven National Laboratory. Their work which involved superconducting levitation magnets and vehicle propulsion via linear synchronous motors became well known, and they received a patent in 1969. Work continued in the US under Federal Railroad Administration funding through the High Speed Ground Transportation Act of 1965. A 1/25th scale model riding on a guideway was completed at the Stanford Research Institute in 1973. Research ended abruptly in 1975 when all funding was cut by the federal government.

After fifteen years of technological progress abroad, interest was renewed in the US. The National Maglev Initiative was founded in 1990 as a consortium consisting of the Federal Railroad Administration, the Department of Transportation, the US Army Corp of Engineers, and the Department of Energy. The Intermodal Surface Transportation Efficiency Act of 1991 stipulated the adaptation of the national intermodal transportation system to new technologies, including magnetic levitation vehicles. It also established a US MAGLEV prototype development program for the design and building of a prototype system. Senator Daniel Patrick Moynihan (D-NY) was instrumental in the inclusion of MAGLEV technology in the highway bill, which appropriated $725 million for the prototype development program. Under this program, the National MAGLEV Initiative chose four companies to propose system concept definitions; Bechtel, Magneplane, Foster Miller, and Northrop Grumman. Their respective designs can be seen in Fig. 1.2.

As part of this program Virginia Polytechnic Institute was contracted to perform wind tunnel testing on the Northrop Grumman vehicles (1993) [8]. In an effort separate from that of the NMI, American Maglev Technologies of Florida received a contract from the federal government to develop and build a prototype of their own system along with a test track. Ground was broken in 1995. Virginia Polytechnic Institute was also involved in the aerodynamic testing of the American MAGLEV Technology [9] vehicle whose shape was design by Lockheed Martin Georgia Company. Interest by the federal government has since waned.

1.4.2 Germany

German involvement in MAGLEV vehicle technology began with Kemper who performed research in the 1930's and received a patent in 1934. A consortium of German companies began a program to develop and test vehicles in 1969. Their seventh vehicle, the Transrapid 07 (TR07) was certified for operation in 1991 (Fig. 1.3). Their system is of the ElectroMagnetic Suspension (EMS) type which is characterized by their attractive magnets and their configuration which has the vehicle wrapped around a "T" shaped track. EMS systems are unstable since a perturbation upwards brings the attractive magnets closer together, increasing the attractive force. A perturbation downwards moves the attractive magnets further apart, decreasing their attractive force, and therefore their ability to return to the neutral position. Active control is required to maintain stability. A schematic diagram of an EMS system can be seen in Fig. 1.4. It shows the vehicle, "T" shaped track, and attractive magnets. The TR07 was the first MAGLEV vehicle system ready to enter commercial service. Plans to build the TR07 system for a 13 mile stretch from Orlando airport to Walt Disney World in Florida by 1996 ($98 million) was later cancelled by the US government. The author is unaware of any current plans to implement this transportation system.

1.4.3 Japan

The Japanese program is run by the Japanese National Railways. Their first vehicle was built in 1970, and the first successful levitation was achieved in 1972. The Japanese system employs ElectroDynamic Suspension (EDS) which is characterized by repulsive magnets and a "U" shaped track similar to a bobsled. A schematic diagram of an EDS system can be seen in Fig. 1.5. EDS systems are stable since perturbations are naturally corrected by the change in magnet proximity. A perturbation upwards moves the repulsive magnets apart, decreasing their repulsive force, and returning the vehicle to the neutral point. A perturbation downward also returns to the neutral point since the reduced proximity of the magnets increases its repulsive force. The Miyazaki test track, a 4.4 mile long facility was opened in 1977 for the testing of Japanese vehicle prototypes. Testing began on the MLU002 system in 1987. In 1990 the project gained the status of a nationally funded project [10], and building began on a new test facility called the Yamanashi Test line. The MLU002 was destroyed in a fire, and the MLU002N began testing in 1993. In the spring of 1997, full-scale tests began using the Yamanashi test line which could become part of the Tokyo/Osaka line after tests are completed in 1999 [11].

1.5 Literature Review

1.5.1 MAGLEV Design

The work presented here deals with the design of MAGLEV vehicles with respect to aerodynamic shape and its effect on system cost. Numerical optimization is employed to formally link the individual disciplines. Such an optimization design requires choosing a specific MAGLEV system, since each differs in the method for propulsion and levitation. A review of the existing system concepts and some past design efforts is presented here.

The Japanese design teams have been developing MAGLEV vehicle concepts for almost thirty years. A great deal of information concerning their current activities and a brief history of their designs can be seen on the Japanese Railroad homepage [10]. The aerodynamic design for their current MLU002N can be seen in reports by Mitsubishi Heavy Industries, Central Japan Railway Company, and Railway Technical Research Institute. The evaluation of their aerodynamic model is reported by Kaiden, Hosaka, and Mazda [12]. Experimental validation for these computations is described in a report by Shimbo and Hosaka [13]. The aerodynamic design of the current Japanese vehicle (MLU002N) is discussed in a report by Miyakawa and Hosaka [14]. This work involves the design of frontal shapes using both experimental and computational tools. Consideration is given towards structural and manufacturing issues although no specifics are mentioned. The resulting design is a double cusp shape which has complex curvatures. The cause for such a complicated shape is the flow of air over the vehicle in the EDS ("U" shaped) track and for the aerodynamic behavior during vehicle passing.

Aerodynamic work undertaken in Germany for the flow over MAGLEV vehicles and high speed trains is reviewed in a journal article by Peters of Krauss-Maffei [15]. In this paper, he discusses the aerodynamic issues involved with these vehicles, analysis methods (computational, track tests, wind tunnel tests, towing tank tests), drag breakdowns, and transient phenomena (cross-wind sensitivity, tunnels, and noise). Test track results for the German Transrapid system are discussed in a paper by Merklinghaus and Mnich [16].

Although the concept of MAGLEV vehicles has been known in the United States for most of the twentieth century, full-scale vehicle designs only began with the National MAGLEV Initiative in 1991. Details of the four system concept definitions can be seen in the final report of the government MAGLEV system assessment team [6]. This document compares the system concepts of Bechtel, Foster Miller, Grumman, and Magneplane. It also weighs the attributes of these designs against that of the German TRO7. The work presented here uses design specifics from the Northrop Grumman design, since this design concept went the furthest out of all the American concepts and the most information is available for it. The Grumman MAGLEV design is outlined in a summary report by the Grumman Team. This report consists of ten individual papers dealing with the system concept definition [17], the benefits of MAGLEV technology [18] [19], magnet design [20], power generation [21], the MAGLEV suspension system [22], structures and materials [23], aerodynamic design and analysis [24], cost [3], guideway cost [25], guideway design [26], and vehicle control [27].

Details of the aerodynamic design are covered in a paper by Siclari, et.al. [28]. This paper discusses the aerodynamic analysis method using the Reynolds Averaged Navier-Stokes equation (RANS), the design selection process, and the details of the final designs. The high cost of performing such computations precludes the incorporation of this type of analysis in an MDO framework. This aerodynamic analysis forms the baseline for the formal optimization work described here. The only evidence of another formal optimization design performed for the aerodynamic design of such vehicles is presented in a National MAGLEV Initiative report [29]. A minimization of the front end drag of an EDS type vehicle is performed. Such a minimization is accomplished by minimizing the strength of the vortex that comes off the channel guideway as the vehicle passes ("bow vortex"). The channel is simulated using point vortices, and the passing vehicle is modeled using a point source of varying strength. This is used to control the rate at which the cross sectional area of the passing vehicle changes (circular cross section). An analytic function is obtained for the drag coefficient and it is minimized by plotting the function over a range of the single design variable and visually determining the minimum point.

1.5.2 MDO in Vehicle Design

Multidisciplinary design optimization enables the designer to consider several disciplines at once and design a vehicle concurrently for multiple objectives. This work deals specifically with linking the aerodynamic design to the system economics. This type of formal optimization hasn't been done before for MAGLEV vehicles, although there has been work performed for subsonic aircraft. Johnson [30] looked at minimizing life cycle cost for these aircraft. She considered fuel burned, take off gross weight, direct operating cost, acquisition cost, and life cycle cost as figures of merit. The results of this study showed different designs for the different figures of merit. Jensen [31] also looked at designing subsonic aircraft for various figures of merit. This work focused on determining which figures of merit to design for. He considered gross weight, life cycle cost, acquisition cost, fly-away cost, direct operating cost and fuel as figures of merit. Optimizations were performed based upon the different figures of merit, and off-design penalties were calculated. The inclusion of cost in multidisciplinary design of aircraft is discussed in an article by Rais-Rohani [32]. He discusses the different types of cost estimation models and addresses the issues involved in implementing them in such a design methodology.

1.5.3 Lower-Order Aerodynamic Analysis

Low-order aerodynamics analyses generally deal with the solution to Laplace's equation which results from simplifying the Navier-Stokes equations for an incompressible, inviscid, irrotational flow. As part of this work, a low-order method is developed for the analysis of flow over a bluff body in ground effect. This method is a vortex panel method with continuous surface vorticity, a discrete vortex wake, separation location model, base pressure model, and ground effect model.

Vortex methods with discrete vortex shedding were first used by Rosenhead in the early 1930's. Since then, many methods have been developed which employ free vortices (vortex cloud). Leonard [33] discusses several methods along with the intricacies of vorticity transport and some insight into the theory and its capabilities. With the proper simulation of the flow mechanics, vortex methods are capable of simulating real flows including viscous layer velocity profiles, and boundary layer separation. These capabilities are usually attributed to high-order aerodynamics methods.

Katz [34] uses a discrete vortex method and sheets of free vortices to model the post-stall aerodynamics of wings. Vorticity is shed from the trailing edge and a predetermined separation location on the top surface of the airfoil at high angle of attack. Katz suggests the need to model thickness effects and to employ a separation criteria to allow for the calculation of flows at varied Reynolds numbers over bodies of arbitrary geometry. This idea forms the basis for the model used here to predict the ground effect flow, over bluff bodies.

A similar vortex method with separation criterion can be seen in work by Mendenhall [35]. This work deals with the flow around tactical missiles at angle of attack. Mendenhall uses the cross-flow analogy to determine the formation of the cross-flow separation. The cross flow planes are mapped into circles, and the bluff body flow around a circle is solved using a vortex method with sheets of shed vorticity. The location of the separation points is determined using the Stratford criteria, much the same way as it is done here.

The model used here is centered around a continuous vortex sheet method discussed in a paper by Mook and Dong [36]. That work is concerned with blade-vortex interaction and uses a continuous sheet vortex panel method for the flow over sharp trailing edge bodies. The trailing edge is treated using a flow model discussed by Giesing [37] and Basu and Hancock [38]. This model allows for an analogy to bluff body separation if one does not consider flow entrainment into the separation bubble.

The problem of an airfoil in ground effect is discussed in a paper by Coulliette and Plotkin [39]. They perform calculations on a zero thickness parabolic arc airfoil and a Joukowski airfoil in ground effect conditions. The calculations are performed using both numerical and analytic solutions. This work is mentioned here because Coulliette employs a piecewise linear vortex panel method similar to the one used in this work. They were unable to calculate lift reversal, since flow separation was not modeled. A 3-D extension to the continuous vortex sheet method was developed by Mracek and Mook [40].

1.6 Design Problem Statement

The problem is to design the aerodynamic shape of a railed MAGLEV vehicle based on several figures of merit; drag coefficient, lift to drag ratio, empty weight, acquisition cost, direct operating cost, and life cycle cost. The vehicles use the Northrop Grumman geometry definition and the Grumman propulsion and levitation system. The system mission is for a corridor with an $800km$ trip distance, passenger load of 2000 per hour, and top speed of $134m/s$. The vehicle structure is composed of aluminum and they each carry 50 passengers. The economic factors used and the design specifics are discussed in the proper chapters to follow.

1.7 Outline

This dissertation is organized in the following manner. Chapters 2 through 6 discuss the different analyses employed in this design optimization. The multidisciplinary design optimization problem statement is described in Chapter 7. The basic 5 design variable problem is posed and a replacement 7 design variable problem is proposed. Chapter 8 shows the results from the optimizations. The 7 design variable problem is used to overcome the obstacle of non-smooth design space. Optimizations are performed for the following figures of merit; drag coefficient, lift to drag ratio, empty weight, direct operating cost, acquisition cost, and life cycle cost. The resulting designs are compared. Conclusions and recommendations for future work in this area are shown in Chapter 9.

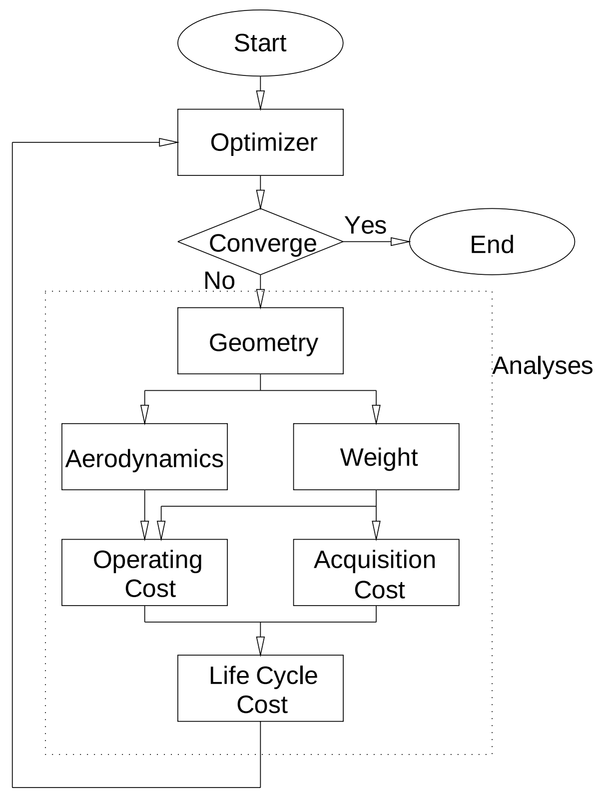

Figure 1.1: Design Methodology Flow Diagram

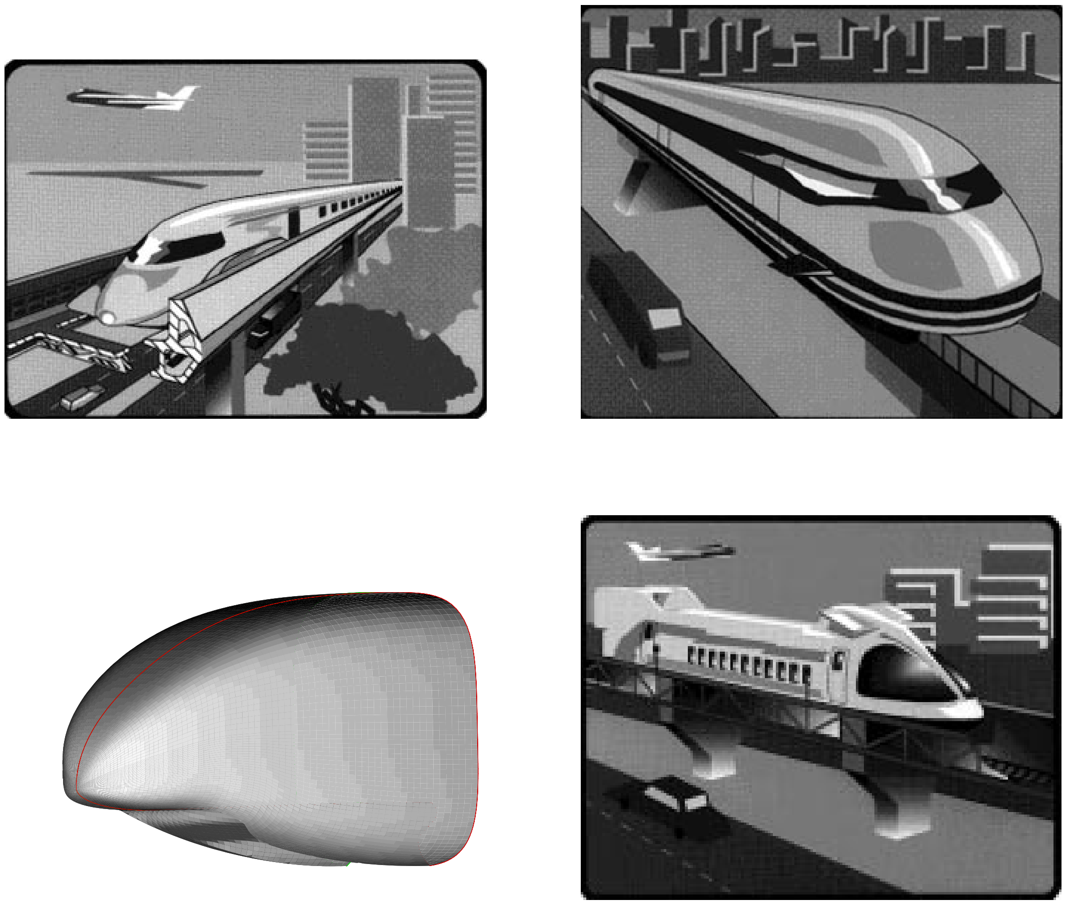

Figure 1.2: National MAGLEV Initiative System Concept Definitions [41]

Figure 1.3: Germany's Transrapid 07 [42]

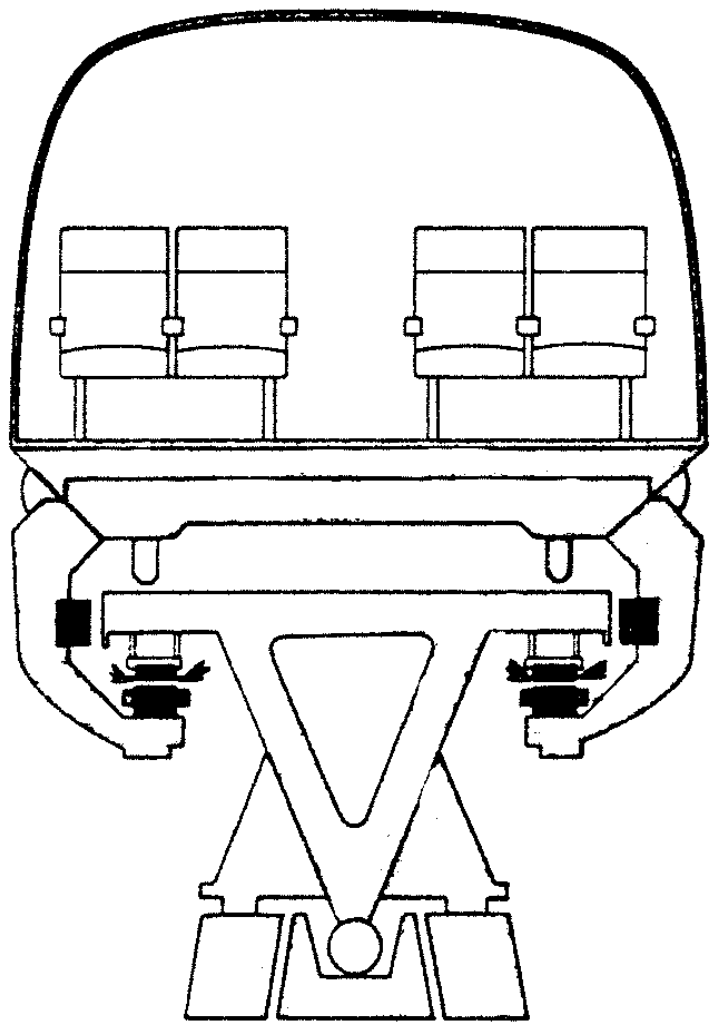

Figure 1.4: A Schematic Diagram of an ElectroMagnetic Suspension System [7]

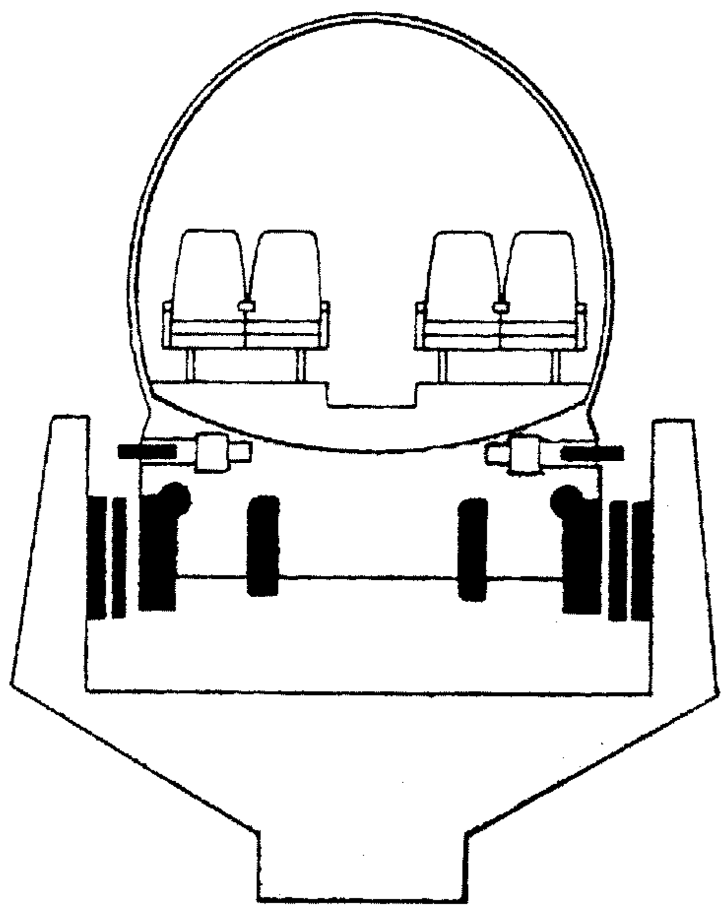

Figure 1.5: A Schematic Diagram of an ElectroDynamic Suspension System [7]