Faculty of Aerospace Engineering

Magnetic Assisted Take-Off for Commercial Aircraft

A conceptual design study

C.B.H. Eeckels

March 6, 2012

Delft University of Technology

Challenge the future

Magnetic Assisted Take-Off for Commercial Aircraft

A conceptual design study

Master of Science Thesis

For obtaining the degree of Master of Science in Aerospace Engineering at Delft University of Technology

C.B.H. Eeckels

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Faculty of Aerospace Engineering · Delft University of Technology

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The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled **"Magnetic Assisted Take-Off for Commercial Aircraft"** by **C.B.H. Eeckels** in partial fulfillment of the requirements for the degree of **Master of Science**.

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Preface

I started this assignment with great enthusiasm on the idea to develop a system utilizing magnetic assisted take-off. When I look back at what I have accomplished during one year of work, I am satisfied with the results. A vague idea on a launch system has been transformed into a conceptual design of a magnetic assisted take-off system. Hopefully, research on magnetic assisted take-off is continued at the faculty and my work can be used for further development of the launch system.

I would like to thank both my supervisors, *dr. ir. Roelof Vos* and *dr. ir. Marcel Schroijen*, my initial supervisor, for their expertise and excellent guidance during this thesis.

I also would like to thank *dr. ir. Frans Van Schaik* who assisted me developing the first ideas on the elaboration of my thesis assignment.

Many thanks goes out to my fellow students, *Bart, Ming Ming, Mariana, Bert* and *Jeremy*. I really appreciate that you always had some time left with giving your thoughts on my design ideas/problems. Special thanks goes out to *Jan*, who was always there for me during the past six years.

Catherine

Delft,
March 6, 2012

Summary

In this report, research is performed in the design of a magnetic assisted take-off system for commercial aircraft. This means that aircraft will be able to accelerate along the runway by assistance of an external system that is coupled to the aircraft. The use of this system can be promising to achieve a reduction in the equivalent perceived noise level (EPNL) in the vicinity of the airport. Aircraft that are launched by this system, can use lower thrust settings resulting in a reduction in EPNL. Therefore, the use of this system might create opportunities for noise-constraint airports to expand within current noise regulations.

The research question enclosing the whole thesis assignment has been defined as:

> *"Can a system be designed that utilizes magnetic assisted take-off of conventional passenger aircraft from a conventional airport?"*

In order to answer this question, a design for a launch system is proposed in this thesis. The launcher should meet the following requirements: it should be implemented in existing airport, have motion control, facilitate take-off and communicate with air traffic control (ATC) and the pilot/aircraft. The system should facilitate take-off for passenger aircraft with a maximum take-off weight up to 90,000kg over a maximum launch stroke of 2900m and reach a take-off speed of 113m/s with a mean acceleration of 0.24g. This launch system is designed for three characteristic aircraft, the Fokker-100, the BAe-146 and the A321 and Schiphol is used as conventional airport.

Before a design can be developed, a background search in existing magnetic technology is performed. Existing magnetic levitation technologies and systems have been analysed. Existing technologies are the electromagnetic suspension system (EMS), the electrodynamic suspension system (EDS) and the magnetodynamic suspension system (MDS). From these systems the first two have operating train system such as the German Transrapid (EMS) and the Japanese MLX (EDS). Two types of linear motors have been investigated, the linear induction motor (LIM) and the linear synchronous motor (LSM). The latter is commonly used for high speed operations (>300km/h).

From this background search, different concepts have been created. The first one (Concept 1) applies magnetic levitation with a linear motor for propulsion and the second one (Concept 2) uses only a linear motor, therefore the cart is suspended by wheels. The cart connects with the aircraft and accelerates along the track. In Concept 1, the aircraft is installed on a levitating platform which accelerates along the track to the launch velocity. In both concepts, at the end of the track, aircraft and cart decouple, the aircraft initiates the climb and the cart is decelerated to a standstill. A trade-off is performed between both concepts on performance, energy consumption, electric equipment, runway modifications and airport modifications. Concept 2 has been selected for further elaboration as the final concept due to the following reasons:

- Concept 2 consumes up to 30% less energy. A total amount of electricity of 14GWh/y is consumed by Concept 2 versus 20GWh/y by Concept 1, for launches to a take-off velocity of 120m/s. These numbers are equivalent to the annual energy demand of 2674 and 3761 Dutch five person households.
- Due to the increased energy consumption of Concept 1, a larger amount of electricity for launches needs to be generated and stored at the airport.
- A smaller amount of electromagnetic area on the shuttle is required, 1.4m^2 for Concept 2 and 5.24m^2 for Concept 1. The smaller magnetic area requirement is due to the absence of levitation and the reduced thrust force (559kN versus 786kN).
- The control system is less complex compared to Concept 1 since guidance and suspension systems are substituted by wheels, the control system is restricted to propulsion operations.

The main advantage Concept 1 has over Concept 2, is that it does not require modifications for the main gear attachment while Concept 2 requires aircraft attachment modifications, either at the nose wheel or at the keel beam.

In the final design, keel beam attachment has been selected for the connection of the shuttle with the aircraft since nose gear attachment required nose gear structural modifications. The conclusions resulting from the final design are summarized:

- System operation: The aircraft taxies to the runway. At the runway, the shuttle positions the launch bar for connection with the keel beam attachment. Once connected, the system accelerates to the launch velocity, then, the aircraft is released and initiates the climb. The shuttle decelerates to a standstill and returns to the aircraft pick-up point.
- System equipment and functionality: A linear synchronous motor (LSM) is used to propel aircraft. The stator of the LSM is processed in the track on the runway and the shuttle, the moving part of the motor, is equipped with electromagnets with a total area of 0.57m^2. On the shuttle the launch bar is mounted for connection with the aircraft attachment. This launch bar is positioned autonomously by two actuators which are installed on the shuttle. The launch bar has a total length of 4.7m. The movements of the launch bar are restricted in height by 1.84m and in lateral direction by 0.5m, from the centreline of the track, with a maximal positioning accuracy of 2cm. The movements of the shuttle are controlled by a control system installed at the airport. This control system also facilitates communication between the launcher, the pilot/aircraft and ATC.
- Aircraft modifications: An attachment object is mounted underneath the fuselage at the keel beam. A display is installed at the cockpit giving information on the shuttle operation and connection. The pilot is able to initiate the launch.

- Airport modifications: The track needs to be installed at the centre of the runway with a maximum track trough width of 10cm. Marks for aircraft positioning at the runway are required. The launcher control system needs to be installed at the airport. Power storage and power generation systems are required to provide the needed amount of electricity per launch. A monitor for ATC is installed, to track the launcher operation on the runway.

- System energy consumption: Schiphol Airport will approximately consume 6.7GWh/year of electricity for launching aircraft, with a mean acceleration of 0.2g and 8.3GWh/year with a mean acceleration of 0.24g. These numbers correspond to the annual energy demand of 1269 and 1570 Dutch five person households, respectively.

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Nomenclature

Abbreviations

AC / ac	Aircraft
AMLEV	American Magnetic Levitation High-Speed Ground Transportation
ATC	Air Traffic Control
c.g.	Centre of Gravity
DC	Direct Current
EDS	Electrodynamic Suspension
EM	Electromagnet
EMALS	Electromagnetic Aircraft Launch System
EMF	Electromotive force
EMS	Electromagnetic Suspension
EPNL	Equivalent Perceived Noise Level
HHSTT	Holloman High Speed Test Track
HSST	High-Speed Surface Transport
HVAR	High-Velocity Air Rocket
JNR	Japanese National Railways
LIM	Linear Induction Motor
LSM	Linear Synchronous Motor
MLU	Linear Motor Car
MTOW	Maximum Take Off Weight
NASA	The National Aeronautics and Space Administration
NMI	National Maglev Initiative
PM	Permanent Magnet
PMLM	Permanent magnet linear motor
RC	Runway controller
SC	Superconductive
TRL	Technology Readiness Level
USML	U.S. Maglev

Greek symbols

α	Angle of attack	[°]
γ	Angle of the launch bar in xy plane	[°]
μ_r	Rolling frictional coefficient	[-]
ρ	Air density	[kg/m^3]
σ	Tensile stress	[Pa]
θ	Angle of the launch bar in xz plane	[°]
θ_{screen}	Angle for transitional flight path	[°]
φ	Angle of the launch bar in launch bar orientation plane	[°]

Roman symbols

a	Acceleration	[m/s^2]
f	Frequency	[Hz]
h_{LG}	Height of the landing gear	[m]
l_{LB}	Length of the launch bar	[m]
$l_{\mathrm{A,left}}$	Length of the left actuator	[m]
$l_{\mathrm{A,right}}$	Length of the right actuator	[m]
v_s	Synchronous speed of the linear motor	[m/s]
w	Width of one pole-pitch	[m]
A	Cross sectional area	[m^2]
C_{D}	Drag coefficient	[-]
C_{Dg}	Drag ground roll coefficient (before rotation)	[-]
C_{L}	Lift coefficient	[-]
D	Aerodynamic drag	[N]
D_{mg}	Friction drag, main gear	[N]
D_{ng}	Friction drag, nose gear	[N]
D_{roll}	Drag due to rolling friction	[N]
F_{x}	Resulting force in x direction	[N]
F_{y}	Resulting force in y direction	[N]
F_{z}	Resulting force in z direction	[N]
L	Lift	[N]
M_{c}	Mass of the cart	[kg]
N	Normal force in the drag brace	[N]
N_{c}	Normal force of the cart	[N]
N_{mg}	Normal force of the main gear	[N]
N_{ng}	Normal force of the nose gear	[N]
S	Wing area surface	[m^2]
T	Thrust	[N]
T_{c}	Thrust of the cart	[N]
T_{ac}	Thrust of the aircraft engines	[N]
V	Velocity	[m/s]
V_1	Decision speed	[m/s]
V_2	Take-off safety speed	[m/s]
V_{C}	Climb speed	[m/s]
V_{lev}	Levitation velocity	[m/s]
V_{LOF}	Lift-off speed	[m/s]
V_{MC}	Minimum control speed	[m/s]
V_{mg}	Normal reaction force, main gear	[N]
V_{ng}	Normal reaction force, nose gear	[N]
V_{MS}	Minimum stalling speed	[m/s]
V_{MU}	Minimum unstick or lift-off speed	[m/s]
V_{R}	Rotational speed	[m/s]
V_{SR0}	Reference stall speed	[m/s]
W	Weight	[N]
W_{ac}	Weight of the aircraft	[N]

W_c	Weight of the cart	[N]
W_{tot}	Weight of the total system (aircraft and cart)	[N]

Chapter 1

Introduction

Today and in the future, noise levels are regulated by local and aviation authorities. Because predefined noise levels cannot be exceeded, noise-constraint airports have difficulties to expand and are limited in the amount of daily operations. A magnetic assisted take-off system can be a manner for these airports to be able to expand without violating the noise regulations due to the lower thrust setting that is required by the aircraft to take-off. Since the engine is a primary source of noise pollution during take-off, reducing the thrust directly translates to a reduction in EPNL (equivalent perceived noise level). Furthermore, an external system can accelerate aircraft to a higher velocity than their current lift-off velocity. By achieving a larger lift-off velocity at the end of the runway, the aircraft is able to climb to the cruise altitude faster.

In this thesis a design is proposed for a magnetic assisted take-off system, including the design of an attachment system to (existing) aircraft and the necessary aircraft modifications in order to comply with the take-off system. The envisioned concept would look like an aircraft that is propelled by a cart until a certain speed is achieved at which the aircraft can be released and start climbing to perform its complete flight. This concept is illustrated by Figure 1-1. In this figure, only the purpose of the system is illustrated as design details have not been determined yet.

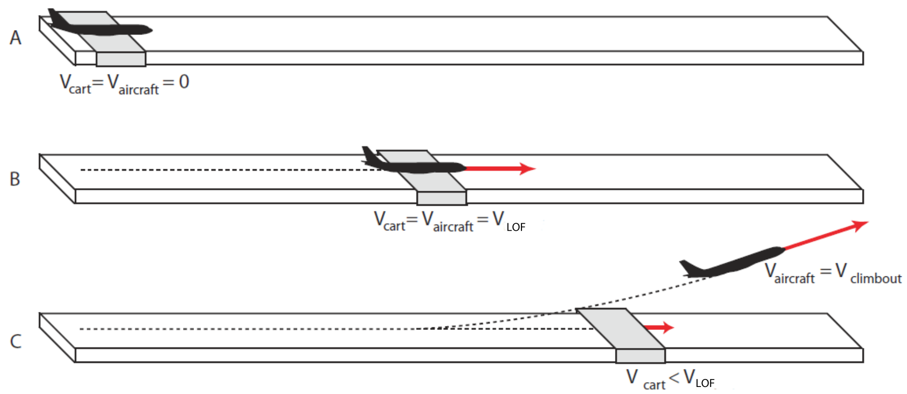


Figure 1-1: The purpose of the to-be designed system [3]

The question that encloses the whole assignment, the research question, will be answered during the course of this thesis is stated as:

> *"Can a system be designed that utilizes magnetic assisted take-off of conventional passenger aircraft from a conventional airport?"*

In order to find an answer to this research question, different sub-questions can be posed. By answering these questions, the research question can be answered. Different sub-questions are:

1. How would such a system function?
2. What aircraft modifications are required?
3. What airport modifications are required?
4. What are the system's power/energy consumptions?

In order to find answers to these questions, it needs to be determined for which aircraft the system will be designed. Three characteristic aircraft, the Fokker 100, the BAe-146 and the A321 are used as model aircraft for the development of the design and Schiphol Airport is used as conventional airport. For the scope of this assignment it is not possible to verify if the design complies with all CS-25 certified aircraft. The BAe-146 and Fokker-100 are regional aircraft with a maximum take-off weight of 38,102kg [4] and 44,455kg [5], respectively. The A321 is considered to be the largest aircraft to be launched by the system. By selecting the A321 as the largest aircraft to be launched, 80% of all commercial aircraft departing from Schiphol Airport are considered [6].

1-1 Requirements

The requirements for the system can be determined. A distinction is made between *Functional Requirements* (Figure 1-3), *Performance Requirements* (Figure 1-4) and *Constraints* (Figure 1-5), illustrated by Figure 1-2. Together, these should embrace all requirements the system should satisfy. The requirements can be updated during the design process.

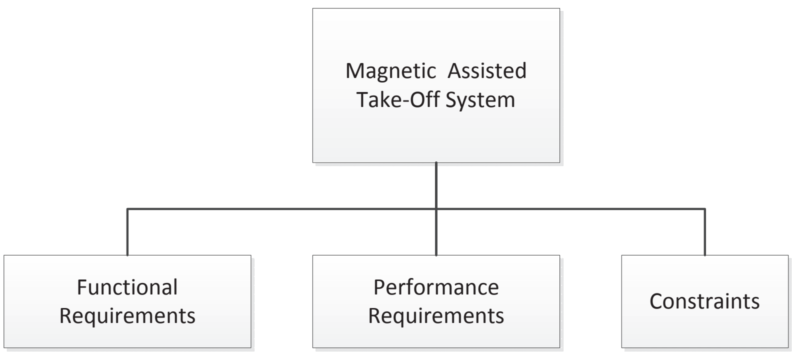


Figure 1-2: Functional Breakdown Structure, top level

1-1-1 Functional requirements

The *Functional Requirements* enclose all technical requirements the system should be able to facilitate (Figure 1-3). They can be grouped in different categories. The system needs to be able to: communicate with the aircraft and air traffic control, it should be implemented in an existing airport, have motion control and facilitate take-off.

Communicate with the aircraft and air traffic control: Communication is an essential part to achieve an operable system between the aircraft, the launcher and air traffic control. Communication examples are: to initiate the launch, communicate errors regarding the launcher or the aircraft, to position the aircraft with respect to the launcher.

Implemented in existing airport: A track needs to be created to accelerate aircraft on within the length of the runway. The cart should fit in the track and its size cannot hinder runway operations. The implementation of the system may not cause major changes in the runway usage. This implies that the runway on which the system is installed should facilitate take-off and landing. Changes in ground operations should be avoided if possible, such as taxiing procedures.

Have motion control: The launcher should be able to operate autonomously. A docking system is required to connect the launcher to the aircraft and keep it fixed to the launcher. At the end of the track when the end launch velocity is reached, the aircraft should be released. The system needs to be designed to allow aircraft rotation at the end of the track.

Facilitate take-off: The system will assist aircraft during take-off. The acceleration should be achieved by magnetic propulsion.

Since conventional passenger aircraft are used for assisted take-off launches, it is advised to design the launcher such that the resulting amount of aircraft structural changes are limited and result in a minimum increase of take-off weight.

1-1-2 Performance requirements

The *Performance Requirements* are quantified requirements (Figure 1-4). They evaluate the usefulness of the system. These requirements are driven by the client.

Maximum mean launch acceleration: A maximum acceleration of 0.6 should be achieved by the system. Accelerating passengers with a maximal acceleration of 0.6g is considered to be still not uncomfortable for passengers.

Maximum take-off weight: The A321 is considered to be the largest aircraft to be launched by the system and has a maximum take-off weight of 90,000kg.

Minimum end launch velocity: The system should be able to accelerate aircraft to a velocity at least as high as their current lift-off velocity. The Fokker 100 achieves lift-off at 75m/s with maximum take-off weight [5].

Flush with runway: The track should be implemented in the runway such that no changes in runway height result.

1-1-3 Constraints

The *Constraints* are all the factors the system should comply with (Figure 1-5). The constraints are shown for completeness, however, they have not been incorporated during the design of a magnetic assisted take-off system. For the implementation of the launcher, it is necessary that research is performed on how the system will meet the constraints given in Figure 1-5.

Before the design of the launcher starts, first, research is performed on the different magnetic propulsion technologies in Chapter 2. Once information is gathered on the magnetic technologies, different concepts of a launch system are created and compared with each other, in Chapter 3. A final concept is proposed in Chapter 4. Conclusions and recommendations related to the launch concept can be found in the final chapters (Chapter 5 and Chapter 6).

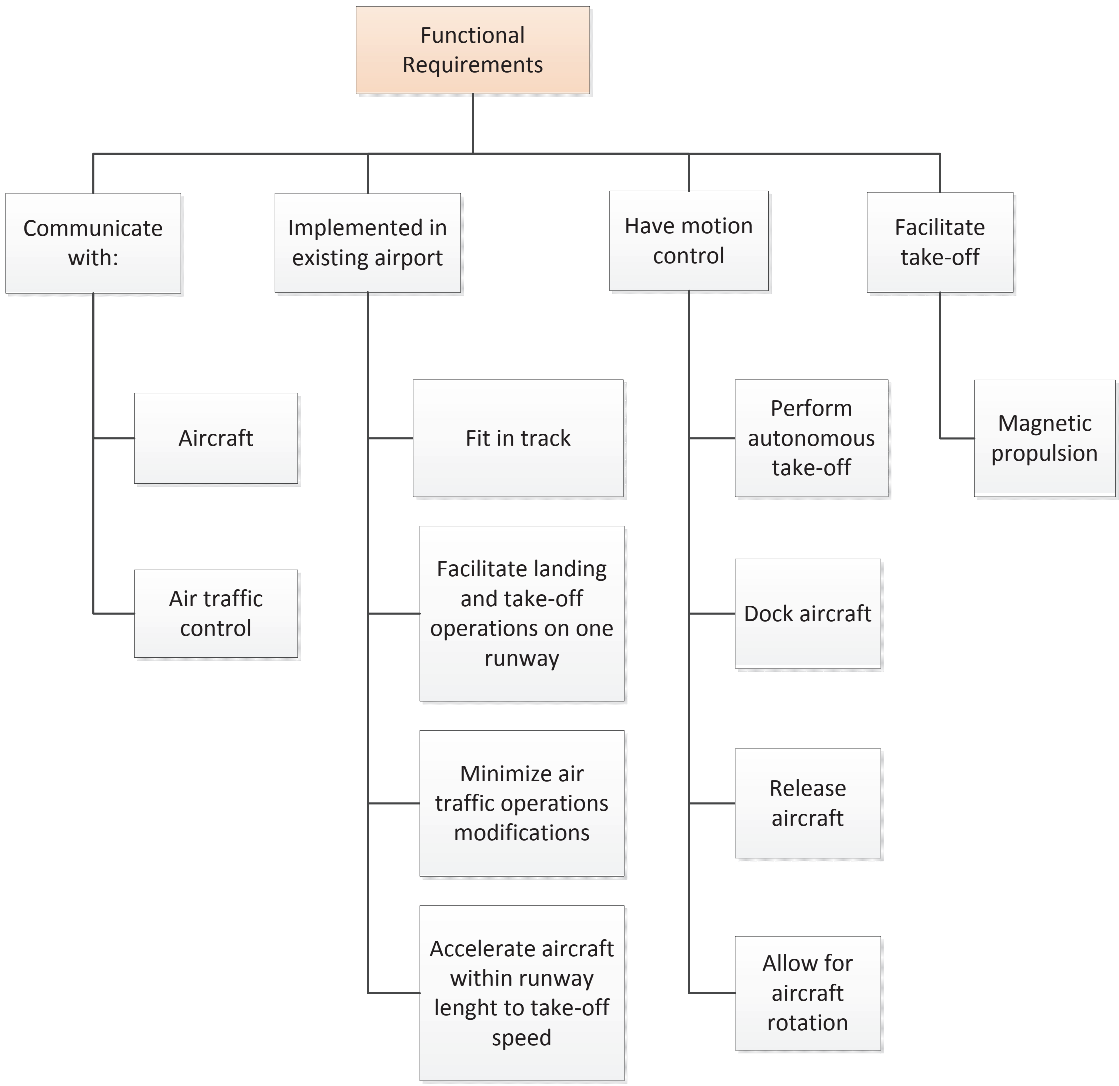


Figure 1-3: Functional requirements

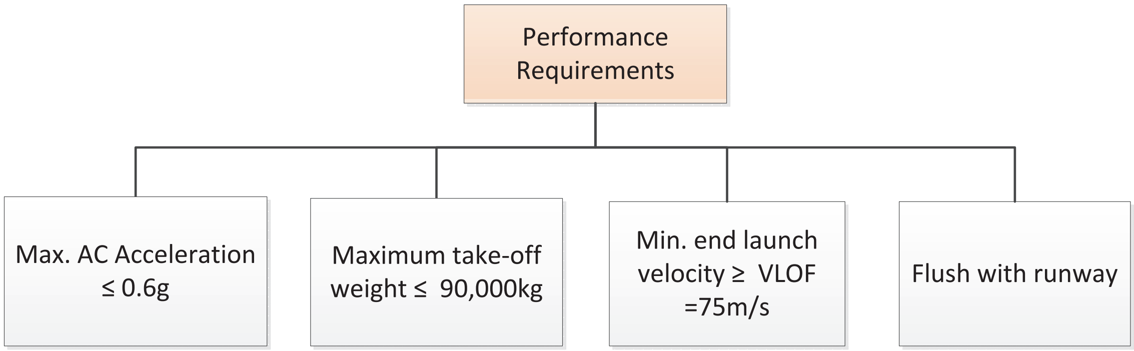


Figure 1-4: Performance requirements

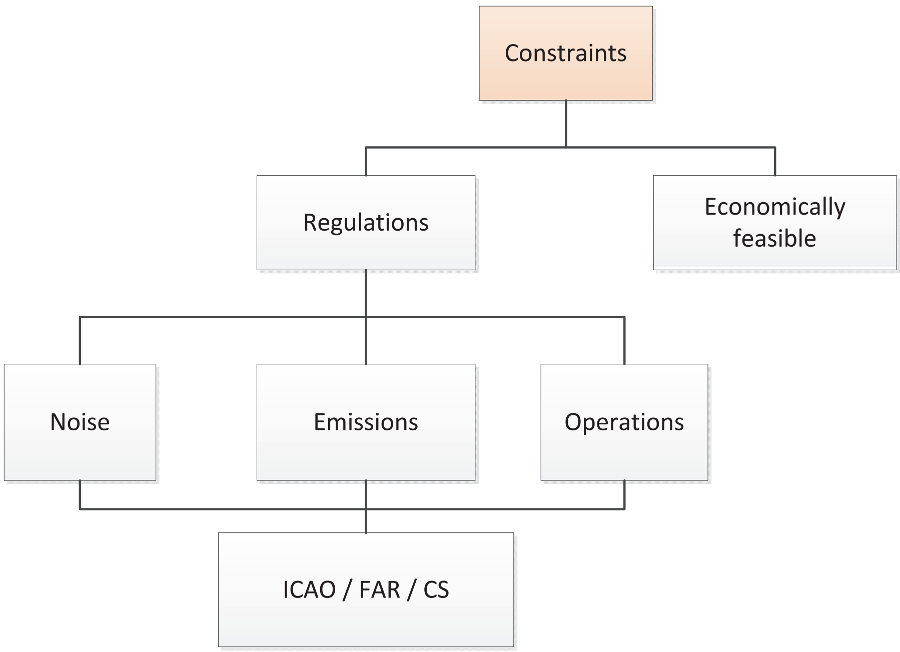


Figure 1-5: Constraints

Chapter 2

Background

2-1 Conventional take-off

The take-off is the manoeuvre by which an airplane is accelerated from rest on the runway to the climb-out speed V_C over a 10.7m (35ft) obstacle for civil transports [7]. The take-off distance consists of two main parts, the ground run distance and the airborne distance. The ground run part comprises the pre-rotation phase and the rotation phase, herein the aircraft is accelerated from standstill to the rotation speed V_R. The airborne distance is the phase when the aircraft's velocity goes from V_R to the lift-off speed V_{LOF}, Figure 2-1 gives a representation of all the different speeds occurring during take-off. The rotation velocity is the speed at which the pilot initiates upward rotation of the airplane [7]. Beyond this velocity the angle of attack is gradually increased from the ground attitude toward the lift-off condition such that at V_{LOF} the airplane becomes airborne.

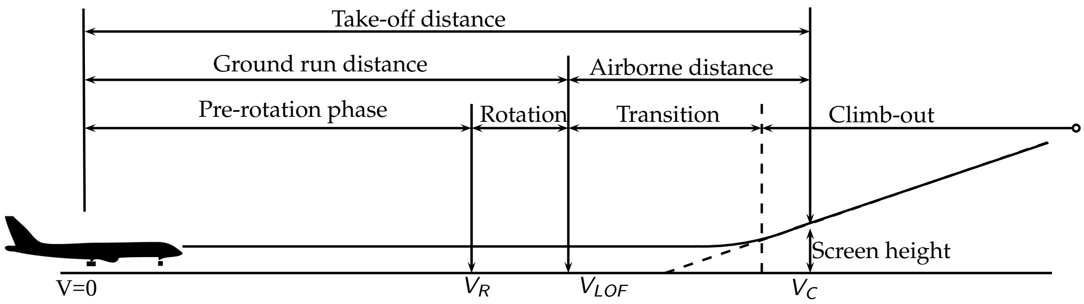


Figure 2-1: The take-off manoeuvre, adapted from [7]

Another important velocity is the decision speed V_1, this speed is selected in case an engine failure is detected at this speed. The pilot is able to abort the take-off and can make a full stop on the runway, or continue the take-off to the screen height with one engine out, in the same distance. The take-off distances based on this condition are called balanced field lengths and is illustrated in Figure 2-2.

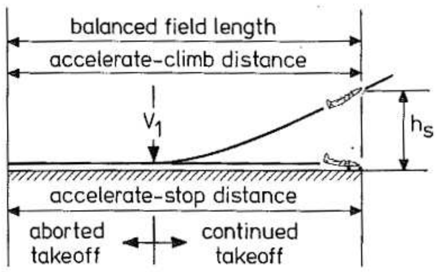


Figure 2-2: Representation of the balanced field length [7]

Aircraft are able to accelerate on the ground and perform a take-off manoeuvre due to the presence of a landing gear. Therefore it is interesting to investigate which different landing gear configurations exist in order to properly design a magnetic assisted take-off system. The landing gear could be a suitable candidate for connection of the aircraft with the launch system. On carrier-based aircraft, the landing gear is provided with a launch bar to connect the aircraft with the launch system (the steam catapult). Currently, the U.S. Navy is investigating the possibilities of an aircraft-carrier based magnetic launch system which will be discussed more in detail in Section 2-4. The system the U.S. Navy developed is called EMALS and stands for "Electromagnetic Aircraft Launch System". The U.S. Navy performed their first test runs in December 2010 [8]. In order to use the landing gear as attachment point of the magnetic launch system, it is important to know which configurations exist.

A conventional landing gear is considered to fulfil functions like manoeuvring of the aircraft on the ground, to act as a shock absorber, to provide rolling, steering and to provide a comfortable ride. Its size and shape is dependent on the size, the weight and the design of the aircraft, and the loads that are exerted on it [9].

Through the years different landing gear layout configurations were created. Examples of these different configurations are: the tricycle landing gear, the bicyle landing gear, the single main landing gear, the quadricycle landing gear and the multi-bogey landing gear [10]. Of these systems, the most common is the nosewheel tricycle gear for large as well as small aircraft. All these landing gear layout configuration can be found in Figure 2-3.

2-2 Magnetic levitation

2-2-1 Definition

Today a range of different transportation systems exist, air transportation, ground transportation and water transportation. Within these groups of transportation systems a whole range of different systems exist and they can make use of different vehicles. The ground transportation can make a distinction in road transportation, rail transportation and since a few decades, transportation based on magnetic levitation exists. This system is called "Maglev" which comes from Magnetic + Levitation. The application of this system is in general known through existing train systems which offer an alternative to conventional high speed train systems. Maglev implies a system in which vehicles are levitated from the guideway by using electromagnetic forces between (super-

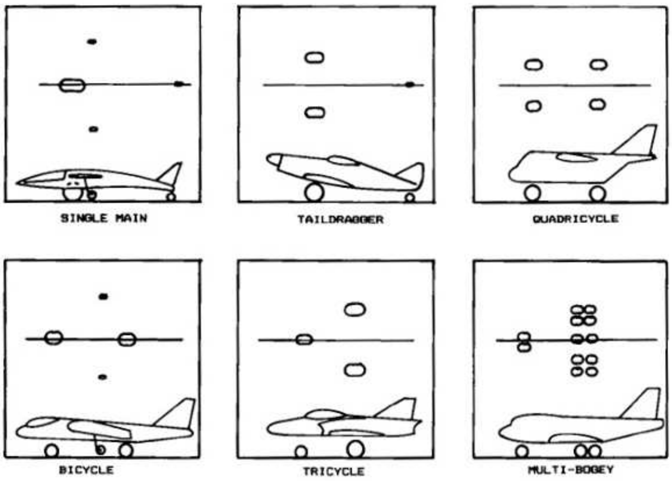


Figure 2-3: Landing gear arrangements [10]

conducting) (electro)magnets on board the vehicle and coils on the ground. In different parts of the world Maglev systems exist, in countries such as Japan, Germany, the U.S. and China. The system uses magnetic forces to perform the functions of vehicle propulsion, levitation, guidance and motion control (response to disturbances).

First an overview of the development of magnetic levitation systems is given and how it evolved during the years. Then the different magnetic levitation and propulsion systems will be elucidated and illustrated by working (train) systems. There exist two type of magnetic suspensions: attractive and repulsive. The electromagnetic suspension (EMS) system establishes levitation by magnetic attraction forces. The electrodynamic suspension system (EDS) and the magnetodynamic suspension system (MDS) facilitate levitation by magnetic repulsion forces. The first two mentioned systems (EMS and EDS) are the most common levitation systems used and have operational train systems.

2-2-2 History of Magnetic Levitation

To understand the working of the magnetic levitation, one has to go back to the basics of electricity and magnetism. The discovery of magnetic levitation originates from observations of phenomena occurring in nature while conducting scientific experiments. An important discovery (in the history of electricity and magnetism) was the natural ability of certain materials to attract or repel each other. In the 18th century Benjamin Franklin suggested the law of conservation of charge. André-Marie Ampère discovered the magnetic effect and turned wires carrying a current into a magnet. Georg Ohm was able to quantify the electric flow. In 1831, Michael Faraday made one of the most important discoveries in electromagnetism, being the first to discover induced current *recognized as such*. His law is now known as *Faraday's law of electromagnetic induction* in which he revealed a fundamental relationship between the voltage and flux in a circuit. Maxwell unified the laws of electricity and magnetism and established the *Maxwell's equations*. Many more scientists have contributed knowledge in the field of electricity and magnetism by observations from experiments and this knowledge has unravelled the idea to use magnetic forces into a transportation system which has led to "MagLev". Duffin [11] gives more information on the history of electromagnetism.

2-2-3 Maglev applications

The first Maglev systems

The first Maglev systems were developed in the 20th century. Since the early 1900s research has been conducted in electromagnetic methods for supporting rotating and moving masses. However, the development of electromagnetic systems started yet, late 1960s and begin 1970s when the disadvantages of the test projects based on the aircushion principle became apparent. The idea rose to use electromagnetic methods in the application to high-speed trains in late 1960s. Two countries took the lead in the development of electromagnetic high-speed transportation systems, Germany and Japan. In Germany the development of the first passenger-carrying test vehicle Transrapid05 (TR-05) started in 1976 on a test track of about 100 meters long. In 1979, the Transrapid TR-05 became the first Maglev vehicle licensed for passenger transportation at the Transportation Exposition in Hamburg and is shown in Figure 2-4. The results of this test project were promising and the system needed to be tested under realistic conditions. Therefore, the building of a new test facility started in Germany in 1983. This test facility was built within four years and was the beginning of the German Transrapid system which is still in operation.
Japan started at a similar time, performing research in the field of electromagnetic levitation. Two projects started in the 1970s in Japan, a project initiated by Japan Air Lines, the High-Speed Surface Transport (HSST) and a project initiated by the Japanese National Railways (JNR) called the "Linear Motor Car" (MLU). The HSST uses a similar technology as the German Transrapid. The second project started with superconductive magnetic levitation of which the first test vehicle ML-100 was demonstrated in 1972 [12]. In 1977, their first Maglev Test Center opened in Miyazaki [13].

Figure 2-4: Transrapid 05 in 1979 [14]

In the UK research in magnetic levitation was also initiated and led in 1984 to the opening of a Maglev shuttle link at Birmingham Airport. The system was called the Birmingham Airport People Mover and was the first purely Maglev system to provide a transit service to the public; it was the first commercial Maglev transportation system. The system was operational since February 1985, providing a shuttle service to passengers between Birmingham Airport and the Birmingham

Railway Station. The vehicle operated on an electromagnetic suspension system and was used for low speed operations (about 50km/h) [12]. This system was operational from 1984 till 1995.
In the U.S., the National Maglev Initiative (NMI) was established in 1991 by the U.S. Department of Transportation to support funding for maglev concept development studies. Its purpose was to investigate the possibilities of maglev systems and their economically feasibility for U.S. purposes. The goal was to recommend if the U.S. federal government should invest in a maglev prototype development program. The focus of the NMI was put on an urban high-speed maglev systems and its potential to offer an alternative high-speed transportation system. The principal conclusions of the 36-month project study on the potential for maglev in the future U.S. transportation system and the role of the Federal Government in achieving that potential, are [15]:

- U.S. industry can develop an advanced U.S. Maglev (USML) system.
- A USML system has the potential for revenues to exceed life cycle costs in one corridor, and to cover operating costs and a substantial portion of capital costs in others. The high initial investment will require substantial public assistance.
- A USML system would provide an opportunity to develop new technologies and industries with possible benefits for U.S. businesses and the work force.
- A USML system is not likely to be developed without significant Federal Government investment."

It can be noted that the U.S. is showing a great interest in the development of maglev applications and is quite determined to develop their own system. They are involved in substantial maglev projects of which some of them will be elucidated later.

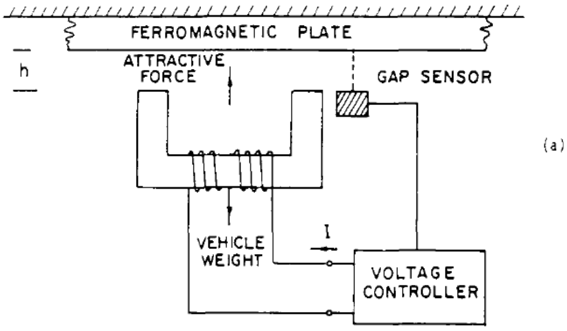
Up to the nineties, the two big players in successful maglev development systems are Germany and Japan. Today, the U.S. is conducting and has conducted a lot of research and will become a important player towards the future, especially within maglev aerospace applications.

The next sections will give information on the different existing maglev suspension systems and which of these are suited for the to-be designed maglev system.

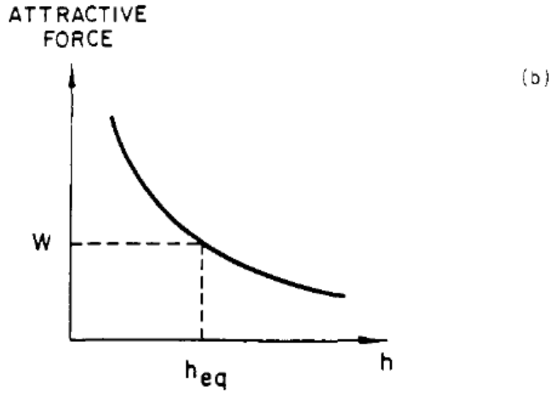
Electromagnetic Suspension (EMS)

Electromagnetic Suspension (EMS) creates vehicle levitation by a *magnetic attractive force* between the guideway and electromagnets. The electromagnet (see Appendix A-1) is attracted into the ferromagnetic rail and a typical force characteristic is generated, as shown in Figure 2-5. As the force increases, the air gap between the magnet and the guideway decreases, therefore this motion is unstable and should be controlled. The air-gap should be controlled precisely to maintain a uniform air-gap. In general, the air gap of the system is about 10mm. Maintaining such a small air gap at high speeds is difficult and requires a lot of control devices.

An advantage of this system is that levitation can occur at zero velocity, which is not possible in the electrodynamic suspension system (see Section 2-2-3). Two types of levitation technologies are possible, an integrated levitation and guidance type or a separated levitation and guidance type. Examples of existing EMS train systems of the first type are the Korean UTM and the



(a) EMS configuration



(b) Force vs. gap characteristics of a typical EMS system

Figure 2-5: Electromagnetic Suspension configuration [16]

Japanese HSST, and of the second type the German Transrapid. The Korean UTM and Japanese HSST are systems which operate at low-to-medium speed conditions (with a maximum velocity of 300km/h). The German Transrapid is designed for high-speed operation, with an operational velocity of about 400km/h [17]. The separated guidance and levitation type is favourable for high-speed operations since these two systems do not interfere with each other. A disadvantage is that this system requires a higher number of controllers and electromagnets. This results in a more expensive and more energy consuming system.

In general EMS technology uses electromagnets (EM) to create levitation but it is also possible to use superconductive (SC) magnets. The superconductive state can be achieved in certain metals and alloys when they are cooled to about a few degrees above $0K$. This state is special because at these temperatures the electric resistance in materials is very low such that it can operate at a minimum energy consumption. If a current is initiated in a superconductor, it will continue to flow without presence of a voltage source in the circuit. Liquid Helium is used to achieve this state and it needs active cooling to conserve this liquid state (which also consumes energy). More information about superconductivity can be found in Appendix A-3.

The characteristics of the German Transrapid will be explained since this is the best well known application of the EMS technology. Moreover, this train system operates at high speed. High speed performance is one of the design criteria of the to-be-designed Magnetic Assisted Take-off System in order to achieve the necessary lift-off velocity of aircraft at the end of the track.

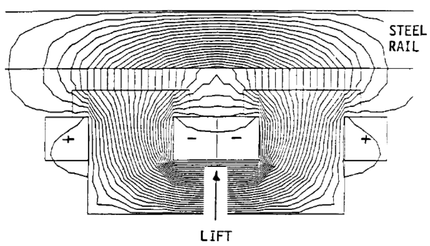


Figure 2-6: The magnetic field distribution of electromagnetic suspension [12]

German Transrapid The German Transrapid train system is based on Electromagnetic suspension, as mentioned before, and uses attractive forces produced by U-shaped electromagnets to achieve levitation. It is designed to travel at high speed ($\geq 400 km/h$) and is operational in Germany and Shanghai. For propulsion and braking, it uses a synchronous long-stator linear motor. There are two sets of electromagnets on board, one for levitation which are the excitation electromagnets for the LSM and another set for guidance which provide lateral stabilization. The excitation system of the LSM and the electromagnetic suspension of vehicles is integrated. As a result, the mass of the vehicle determines the excitation of the LSM. The train is illustrated in Figure 2-7.

The attractive and lateral forces are controlled by the currents of support and guide electromagnets. By changing the magnitude and phase angle of the armature current, the thrust can be varied. If the phase sequence is reversed, the LSM becomes a synchronous generator which provides electrodynamic braking forces.

To reduce the energy consumption, the long-armature LSM of the guideway is divided into sections, the section on which the vehicle is running, is activated only. The Transrapid TR07 with two sections develops a drag force of 35.5kN at 400km/h [18]. For the Japanese high-speed train, the MLX this number is unknown. In December 2003, the Shanghai Transrapid achieved a speed record of 501km/h [19]. The maximum theoretical velocity of the Transrapid is 550km/h [18]. An overview of characteristics between existing maglev train technologies is given in Tables 2-3 and 2-4.

Figure 2-7: The Transrapid 09 on the test track in Lathen (Germany)[20]

It is the only train system up till now that had a fatal accident. On September 22, 2006 the Transrapid 08 was doing trial runs on the test track in Lathen (North-Western Germany) and was carrying some passengers during these runs. A maintenance vehicle was moving along the track to check it for debris when the train hit at a velocity of about 200km/h [21]. Twenty-tree people were killed on this day. The accident was due to human error instead of technical fault [21]. The Transrapid produces low noise emission relative to other train systems and the pass-by noise levels of the Transrapid have been measured at the Transrapid test Facility (TVE). It can be concluded that at speed above 250km/h the noise is mainly determined by aerodynamic noise. In Table 2-1 a comparison of noise production levels of the Transrapid and the TGV is given [22]. Note that the scale of decibel is a logarithmic scale. From this table, it can be concluded that the Transrapid produces a lot less noise than the TGV does. To give a reference of perceived noise levels, a level of about 60 dB(A) is comparable to a normal conversation and a level of about 90 dB(A) corresponds to a truck passing by closely.

Table 2-1: Pass-by level at distance 25m in dB(A)

Velocity [km/h]	Noise production Transrapid [dB(A)]	Noise production TGV [dB(A)]
200	73	85
300	80	92
400	88.5	–

The Transrapid system is relatively unaffected by the weather since the propulsion components are protected underneath the guideway from snow and ice. A special vehicle is also capable of clearing the track in case of high snow fall. Cross winds and gusts seem to have little effect on the Transrapid because of the control and guidance system. Wind velocities up to 30m/s have no effect on the operation. At the Transrapid Test Facility (TVE) the operations of the Transrapid have been investigated, the vehicle can operate without difficulties at speeds up to 350km/h with wind gusts of 150km/h [22].

The strength of the magnetic field that is generated when operating the system seems to have a minor impact, the field intensities are 20 to 1000 times lower than the admissible limits in the Bundesimmissionsschutz-Verordnung (German Federal Immission Control Act). Adverse effects on magnetic cards or pace-makers are ruled out. Though, it should be investigated how it can influence the avionics [22].

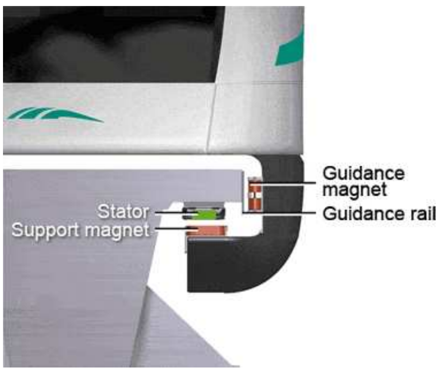


Figure 2-8: Electromagnetic Suspension of the Transrapid [22]

Electrodynamic suspension (EDS)

Electrodynamic suspension uses repulsive forces for the levitation. A magnetic field is created when the magnets attached to the vehicle move forward on the inducing coils or conducting sheets located on the guideway, this creates induced currents that flow through the coils or sheets generating a magnetic field. A repulsive force originates between the magnetic field and the magnets which levitates the vehicle. EDS is magnetically stable such that it is unnecessary to control the air gap. This air gap is larger than in the EMS system and can be about 10 cm or more. EDS is not very sensitive to variation of the load. High load variation and the lack of necessity to control the air gap makes this system suited for high speed operations. Additionally, the levitation force is speed-dependent, at low speed, the levitation force is too weak to lift the vehicle, therefore wheels are required to support the vehicle at low speeds and a minimal velocity should be achieved before the vehicle levitates. This minimum lift-off velocity (the transition speed) is dependent on the design and can be in the range from 40 to 100 km/h. When this velocity is reached, the wheels can be retracted, which is comparable to a landing gear retraction. The EDS system is a passive suspension system as an initial velocity is required before levitation is possible. On the other hand, the EMS system is an active suspension system [12]. This EDS system is generally considered suited for high-speed transport travelling at velocities beyond 300 km/h. Two kind of magnets can be used for levitation and/or propulsion in this system, either (superconductive) electromagnets (EM) or permanent magnets (PM). Two systems using EDS technology are discussed below, the Japanese MLU system and the U.S. Inductrack.

Japanese JR-Maglev The Japanese Linear Chuo Shinkansen Project *MLX* makes use of EDS. Repulsive forces are produced between stationary short-circuited coils and moving superconductive electromagnets [23]. These SC electromagnets require cryogenic refrigeration and are located on the vehicle itself. The track of the MLX has a concrete U-shape. Through the interaction of the inductor currents and the induced currents vertical and lateral forces are created. The MLX uses a linear synchronous ironless motor (LSM) for propulsion (see Section 2-3-2). When the train is propelled by the LSM at high speed, strong repulsive and lateral stabilizing forces are produced on the vehicle by induced currents in the short-circuited coils together with the magnetic field excited by superconducting electromagnets. These superconducting EMs are used for levitation, lateral guidance and propulsion. The propulsion coils and levitation-guidance coils are attached to concrete side walls of the guideway, see Figure 2-9. It are eight-shaped coils and consist of two sections, providing levitation and lateral stabilization of the vehicle. The guidance sections are electrically connected under the track forming a *null flux connection*, which is illustrated in Figure 2-10. These sections are facing each other at two opposite sides. This connection prevents the train from deviating from the centre of the guideway. If deviation would occur, the deviation is reversed by the attractive forces of the superconducting electromagnet on the distant side of the guideway and repulsive forces on the near side (see Figure 2-11).

The bogie itself is equipped with superconducting magnets underneath and a refrigeration system for freezing the helium. It, the bogie, serves to transmit the propulsion and levitation forces to the vehicles. The landing and guide gear wheels are also fitted on the bogie for travelling at low speeds.

USA Inductrack The Inductrack is a Maglev system developed in the U.S. and is a passive magnetic levitation system for moving objects that employs special arrays of permanent magnets, “Halbach arrays”, in the moving object (see Appendix A-2). Halbach arrays are used to increase the magnetic field in the active air gap and to decrease the field on the outside surface. Induced currents in the “track” are created by the magnetic field from these arrays and create strong

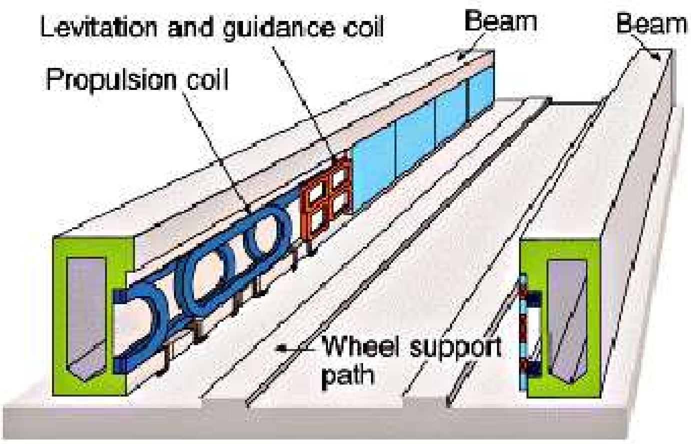


Figure 2-9: Electrodynamic MLX infrastructure [18]

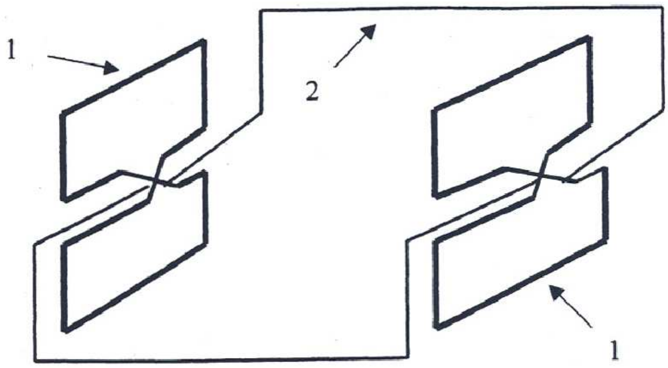


Figure 2-10: Null-flux connection of levitation and guidance coils. 1 - coils, 2 - null-flux cable [23]

lifting forces by interacting with the magnetic field. As in the MLX, the Inductrack has an air gap exceeding 80 mm. A high ratio of lifting force to drag force can be achieved and a levitation force of about 500 N/m is obtained. This system does not require superconducting magnet coils (MLX) or servo control circuits (Transrapid).

The system is an induction-activated repelling-force system. It needs lateral and vertical wheel bogies to guide the vehicle at low speed (<100km/h), similar to the MLX. As long as the train is in motion (at a velocity higher than the transition speed), it will be stably levitated. If failure of the drive system occurs to the Inductrack, the train would slow down to low speed and the auxiliary wheels deploy prior to stopping.

There exist no operational full-scale systems of the Inductrack yet, but small-scale systems are being constructed and tested. NASA is sponsoring the Lawrence Livermore National Laboratory in the construction of a new higher speed model with the application of Inductrack technology to investigate the feasibility of launching large rockets by accelerating them up a sloping maglev track to velocities of the order Mach 0.8 before firing the rockets. NASA's objectives in research of maglev launch systems are to reduce rocket launching costs and save rocket fuel. The NASA model is currently under construction and is designed to electromagnetically accelerate a levitated

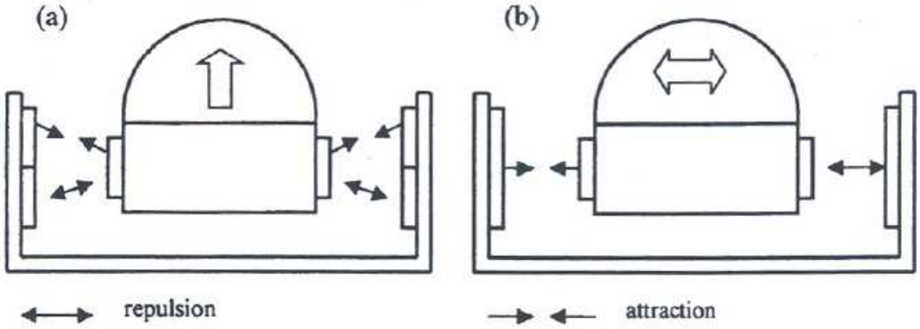


Figure 2-11: Operation of 8-shaped coils: (a) levitation, (b) lateral stabilization (guidance) of the vehicle [23]

10kg cart, at 10-g levels, up to a velocity of the order Mach 0.4 over a track that will be 100 meters in length. The aim of the project is to demonstrate stable acceleration at high g-levels up to speeds approaching those needed for the final application.

Magnetodynamic suspension (MDS)

The Magnetodynamic suspension system uses permanent magnets and steel cores to produce magnetic forces. It is a passive system that uses repulsive forces for levitation, similar to the EDS system. A minimum velocity should be achieved before levitation of the vehicle is possible ($V > V_{\text{lev}}$). When a velocity equal or higher than the levitation velocity (V_{lev}) is achieved, the vehicle flies stable along the track. Stable equilibrium is achieved when the stabilizing force acting on the vehicle is equal to zero. The vehicle is supported by wheels for speeds lower than the levitation velocity ($V < 40$m/s).

The stiffness of the stabilizing force is an important parameter for the qualitative index of a suspension system which can achieve a force up to 3×10^7 N/m (for a vehicle with a length of 22m). This force exceeds the maximal stiffness of the stabilizing force in the electrodynamic suspension system exploiting superconductive magnets (at least 10 times) [24]. This stiffness can be further increased by increasing levitator's magnets' weight [25]. Every vehicle travelling with a velocity higher than 25m/s experiences stabilizing forces, keeping the vehicle on the track.

Advantages of using this system are: the high stabilizing forces to keep the vehicle on its track, no current or super cooling is required for the permanent magnets. These magnets can be produced in different shapes as well [24]. However, note that this system has no existing operating system so far, maybe towards the future, it might become interesting. The concept of Amlev applies MDS and will be discussed briefly.

The concept of Amlev AMLEV stands for American Magnetic Levitation High-Speed Ground Transportation and is based on MDS technology which makes use of permanent magnets and steel cores, producing magnetic forces with maximum efficiency while eliminating dynamic instability. The suspension and propulsion motor are both self-regulating and in [25] it is stated that the power system is simpler, more reliable, and cheaper than those of other Maglev types.

The Amlev system consists of three components; a MDS system, a linear motor based on permanent magnets and a conventional power system. The maximum design velocity of the system equals 540km/h along the track [25]. Similar to the EDS system, the vehicle is equipped with supporting rolling wheels for low speed applications. A different motor than the LSM - the most commonly applied motor in high-speed Maglev systems - is used on Amlev, namely a permanent magnet linear motor (PMLM). More information on the permanent magnet linear motor design can be found in [25].The vehicle operates in a U-shaped propulsion channel.

2-3 Magnetic Propulsion

The Maglev train receives its propulsion force from a linear motor. This linear motor is different from a conventional rotary motor since it does not use the mechanical coupling for the rectilinear movement. A conventional rotary motor creates a moment (torque) which is transformed in a rectilinear movement, what happens in conventional train systems. The linear motor is actually a cut-open rotary motor (see Figure 2-12). The stator, rotor and windings of the rotary motor have been cut open flattened and placed on the guideway. The structure of such a linear motor is simple and robust [16].

The main difference between both types of motor (rotary and linear) is that the linear motor has a finite length but both operating principles are the same. Both motors have an efficiency dependent on the size of the air gap; the bigger the gap, the lower the efficiency. An advantage of the linear motor compared to the rotary motor is the superior rectilinear motion, the amount of vibration and noise generated from the mechanical contact of components is substantially lower.

Two commonly used linear motors are the Linear Induction Motor (LIM) and the Linear Synchronous Motor (LSM) and both types are used in Maglev systems. Neither the LSM nor the LIM require sensor techniques for their operation and are alike in reliability and controllability [16] .

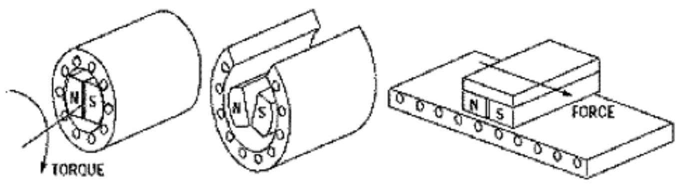


Figure 2-12: Concept of linear motor from the rotary motor [16]

2-3-1 Linear Induction Motor (LIM)

The Linear Induction Motor (LIM) has the same operating principle of an (ordinary) induction motor [26]. The only difference is that the stator is laid out flat (as shown in Figure 2-12). The shape and the speed of the magnetic field of a linear induction motor are identical to that of an induction motor. The flat stator produces a field that moves a plate at constant velocity in a straight line. The magnetic fields are generated by the primary part across the air gap and induce an electromotive force (EMF) in the secondary part. This EMF generates the eddy currents which interact with the air-gap flux and so produce the thrust force Lorenz's force [16]. Two types exist: a short primary (SP) type and a long primary (LP) type. The SP type is characterised by on-board stator coils and conducting sheets on the guideway. The LP type has a reversed configuration, on-board conducting sheets and stator coils on the guideway. In high-speed operations, the LP type is used since the SP type cannot exceed speeds around 300km/h. The SP type is less expensive in construction than the LP type but it has low energy efficiency. Figure 2-13 illustrates the LIM LP-type.

A difference between a linear induction motor and a regular induction motor is that the linear synchronous speed is not dependent on the number of poles, but on the pole-pitch. The pole-pitch is the spacing between poles. In case of an induction motor, the synchronous speed depends on the amount of poles. The linear synchronous speed is given by:

$$v_s = 2 \cdot w \cdot f \tag{2-1}$$

where
v_s = linear synchronous speed [m/s]
w = width of one pole-pitch [m]
f = frequency [Hz]

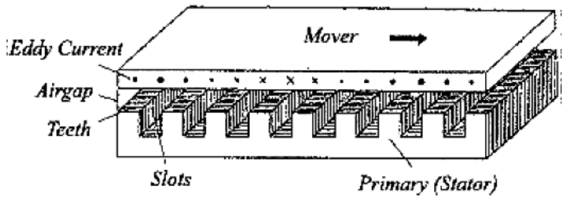


Figure 2-13: Linear induction motor (LP-type) [16]

2-3-2 Linear Synchronous Motor (LSM)

A Linear Synchronous Motor (LSM) is another linear motor which can be used in Maglev applications and has a similar lay-out as the LIM, illustrated in Figure 2-14. Characteristic to a linear synchronous motor is that the mechanical speed is equal to the speed of the travelling magnetic field. This implies that the mechanical motion is synchronized with the magnetic field. The speed of the moving part v is equal to the synchronous speed v_s of the travelling magnetic field and its formula is equal to the one given in equation 2-1. The speed is controlled by the controller's frequency.

The German Transrapid system uses an LSM with vehicle mounted steel core excitation electromagnets and stationary slotted armatures. The armature is the part producing the travelling magnetic field. The Japanese MLX01 also uses an LSM with superconducting air-cored electromagnets and a stationary three-phase air-cored armature winding distributed along the guideway [23].

The LSMs operating on the principle of the travelling magnetic field can have the following excitation systems (cited by [23]):

1. PMs in the reaction rail
2. PMs in the armature (passive reaction rail)
3. Electromagnetic excitation system (with winding)
4. Superconducting excitation system
5. Passive reaction rail with saliency and neither PMs nor windings (variable reluctance motors).

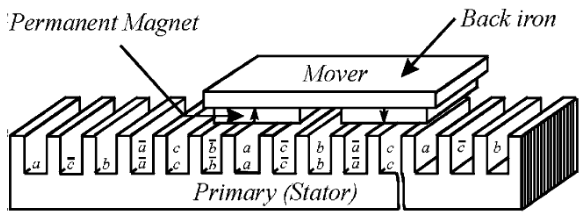


Figure 2-14: Linear synchronous motor (LP-type) [16]

The third excitation system can be found in the Transrapid system and the fourth excitation system is used in the Japanese MLX system.

For high speed (larger than 300km/h) all worldwide Maglev trains systems have linear synchronous motors with long or short stators due to their higher efficiency and power factor compared to the LIM [26]. Electric power consumption is of economical importance for high-speed operation. Both Transrapid and MLX use LSMs, LIM is used on the HSST, the Korean UTM and EMALS. The HSST and UTM are both train systems operating in the low-medium speed range [16] and the EMALS is the Navy's substitute for the steam catapult on aircraft carriers which can reach a velocity up to 370km/h (see Section 2-4).

The main difference between an induction motor and a synchronous motor is the starting torque (load) which can be considerably greater for the synchronous motor. The reason for this is that the resistance of the squirrel-cage winding can be high without affecting the speed or efficiency at synchronous speed [26].

2-4 Magnetic Aerospace Applications

In this section different applications of magnetic propulsion and or levitation in Aerospace will be discussed. Maglev technology is currently considered for space launch applications and magnetic propulsion will be applied on aircraft-carriers to launch naval aircraft, it will replace the steam catapult.

U.S. Navy EMALS The U.S. Navy is doing research in magnetic propulsion systems and has developed in collaboration with partners a new launch mechanism, the *Electromagnetic Aircraft Launch System (EMALS)*, to safely launch carrier-based aircraft. This system will serve as a substitute for the steam catapult which is currently used on aircraft carriers. The system ran its first launch test with the F/A-18E Super Hornet on Saturday December 18, 2010 at Naval Air Engineering Station Lakehurst, N.J. [8]. The test track was built on a U.S. Navy land base station and is not yet installed on an aircraft carrier. The goal is to have the system installed by 2015 on the new generation of aircraft carriers [27]. The Electromagnetic Aircraft Launch System is shown in Figure 2-15 and the test track is shown in Figure 2-16.

Figure 2-15: The Electromagnetic Aircraft Launch System launches its first F/A-18E Super Hornet on Saturday Dec. 18 at Naval Air Engineering Station Lakehurst, N.J. [28]

The steam catapult is being replaced because it is approaching its operational limit in terms of delivered launch energy [29]. It has a design limit of approximately 95 MJ while the EMALS has a delivered energy capability of 122 MJ which is almost a 30% increase [29]. The steam catapult operates without feedback control, it is difficult and time-consuming to maintain, and the systems availability is low. The steam catapult system exerts large transient loads to the airframe. The trend towards future design of naval aircraft is that these aircraft will become heavier and faster, which will result in higher launch energy requirements that cannot be delivered by the steam catapult [29]. An electromagnetic launch system offers higher launch energy capability and reduces the stresses exerted on the airframe by a smooth acceleration profile [29]. Figure 2-17 shows the force profiles of EMALS and the steam catapult. In case of EMALS, the acceleration goes gradually while in the steam catapult there are small peak forces. Figure 2-18 gives an overview of the power capacity evolution of different catapult types [29].

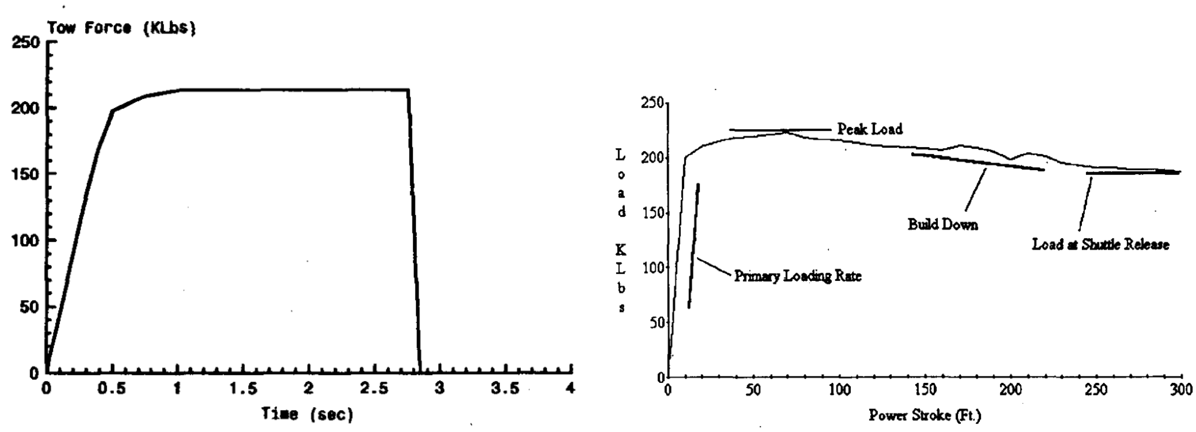
Figure 2-16: Full-scale, EMALS test facility in Lakehurst, NJ. [27]

The performance requirements set by the U.S. Navy for the development of the EMALS are given in Table 2-2. The system is designed with a linear induction motor and has a "real time" closed loop control [27]. The system works as follows, power is fed to the launch motor and a travelling magnetic wave is created which interacts with the launch system's shuttle. An aircraft is attached to the shuttle, then, it is accelerated along the length of the launch stroke to the required speed for launching the aircraft. Braking is achieved by reversing the magnetic wave, thereby a "negative" force is created and the shuttle is decelerated to a standstill after the aircraft has disengaged. The shuttle is able to decelerate to standstill within six meters [27]. The shuttle is brought back to its original launch position by reversing the direction of the travelling magnetic wave at a slow speed [30].

Table 2-2: EMALS requirements [29]

Endspeed	$28 - 103 m/s$
Max Peak-to-Mean TowForce Ratio	1.05
Launch Energy	$122 MJ$
Cycle Time	$45 s$
Weight	$< 225,000 kg$
Volume	$< 425 m^3$
Endspeed Variation	-0 to $+1.5 m/s$

The external layout of the launch system is very similar to the steam catapult system. The trough is the same as the catapult trough. The main disadvantage of EMALS is the creation of high electromagnetic interference with electronic equipment. Through proper electromagnetic control design and a "magnetically closed" motor design, electromagnetic interference can be minimized as described in [29].



(a) EMALS force Profile **(b)** Steam Catapult Force Profile

Figure 2-17: Acceleration Profile of EMALS and the Steam Catapult [29]

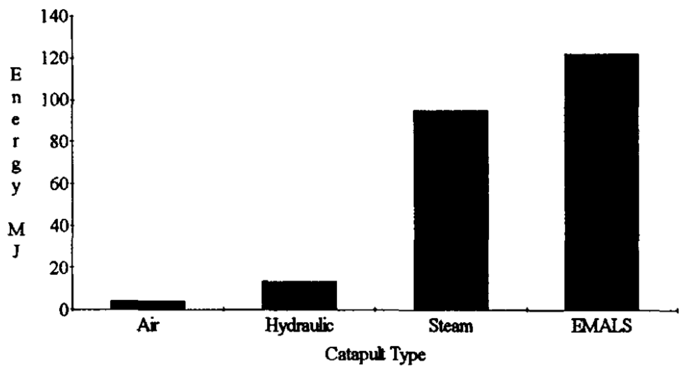


Figure 2-18: The power capacity of different catapult types [29]

NASA's Maglev Investigation The National Aeronautics and Space Administration (NASA) research centers are investigating maglev applications within its program called the Advanced Space Transportation Program, to reduce the cost of getting to space from todays $10,000 per pound to only hundreds of dollars per pound. Nasa's goal is to mature maglev technologies and to achieve by 2025 full sized space vehicle launch for under $300 a kilogram [31]. The approach to achieve this goal is described in [31] and aims to develop magnetic levitation, and linear motor technologies. This will be realized by: making scaled concepts representative of the future goals, investigating the stability and control over the operating range of the system, investigating the integration and interaction between the thrust cradle and the vehicle, developing energy storage and distribution concepts over the operating range, and finally, developing a full scale technology demonstrator. Therefore NASA has contracted with three companies to initially produce magnetic levitation concepts, namely, Foster-Miller located in Waltham, MA; Lawrence Livermore National Laboratory, located in Livermore, CA; and PRT Advanced MagLev Systems, Inc. from Park Forest, IL. Projects in which these contractors have been involved are: the Inductrack for the Lawrence Livermore National Laboratory (see Section 2-2-3), the build of the working model of the Maglifter for the PRT Advanced MagLev Systems, Inc. and the Holloman Maglev System for Foster-Miller. All these mentioned projects are explained in this report.

Holloman, Space Launch Concept

The Holloman High Speed Test Track (HHSTT) of the U.S. Air Force is a unique test track that can operate at hypersonic speeds. With the aid of rocket boosters, velocities of Mach 10 are achieved with a maximum achieved world land-speed record of 10,385.1km/h, set in April 2003 [32]. Test articles are intended to simulate various regimes of flight. At speeds this high, the vibration forces are huge and a solution to this problem is to develop a magnetic levitation technology which reduces the vibrational forces through the levitated state. The aim is to achieve a velocity of Mach 1 with the Maglev test track. The system uses superconducting coils cooled by liquid Helium and is still under development. In 2007, tests were conducted with this system and speed of 676km/h (420mph) were achieved by using 6 HVAR (High-Velocity Air Rocket with 5,000lbs[1] thrust) motors. Figure 2-19 gives a drawing of the magnet sled design concept.

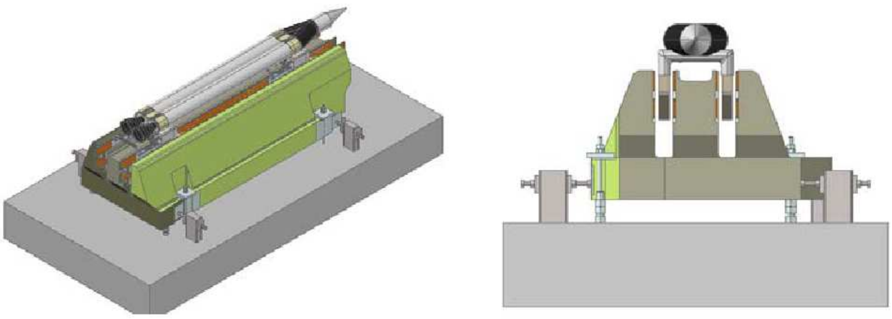


Figure 2-19: Holloman Magnet Sled Design Concept Drawing [32]

Maglifter Concept

The Maglifter concept is being created for maglev-assisted space launch and its potential use is being investigated. For a Maglifter assisted launch, a launch vehicle is mounted on a carrier vehicle. The carrier is propelled by a maglev propulsion system and is given an initial launch velocity to approximately Mach 0.75. After this initial velocity boost, the launch vehicle uses its own onboard propulsion to achieve orbit [33]. The trajectory for the initial velocity boost can be either level or go slightly upward.

Concepts such as the Maglifter are being developed for maglev-assisted space launch because of their ability to increase the payload capacity and to reduce the costs of launch by providing an initial velocity boost. As a consequence, the fuel and launch weights are reduced. A drawback of these launch systems is the enormous amount of energy required to drive the magnetic sled and to overcome the aerodynamic drag. The Maglifter concept is being studied and is considered to be a good candidate for the next generation of launcher systems [33].

[1] equals 2268kg

2-5 Discussion of Magnetic Technologies

To summarize, an overview of different types of Maglev Systems has been created and is shown in Figure 2-20. The systems are classified according to the levitation technology that is used. The same has been done for magnetic propulsive systems, the different existing systems are sorted according to the motor that is used for propulsion, see Figure 2-21. The operational systems are indicated in **bold**, this does not include full-scale demonstrators. These diagrams give an overview of different existing systems, this does not mean that all existing systems are incorporated.

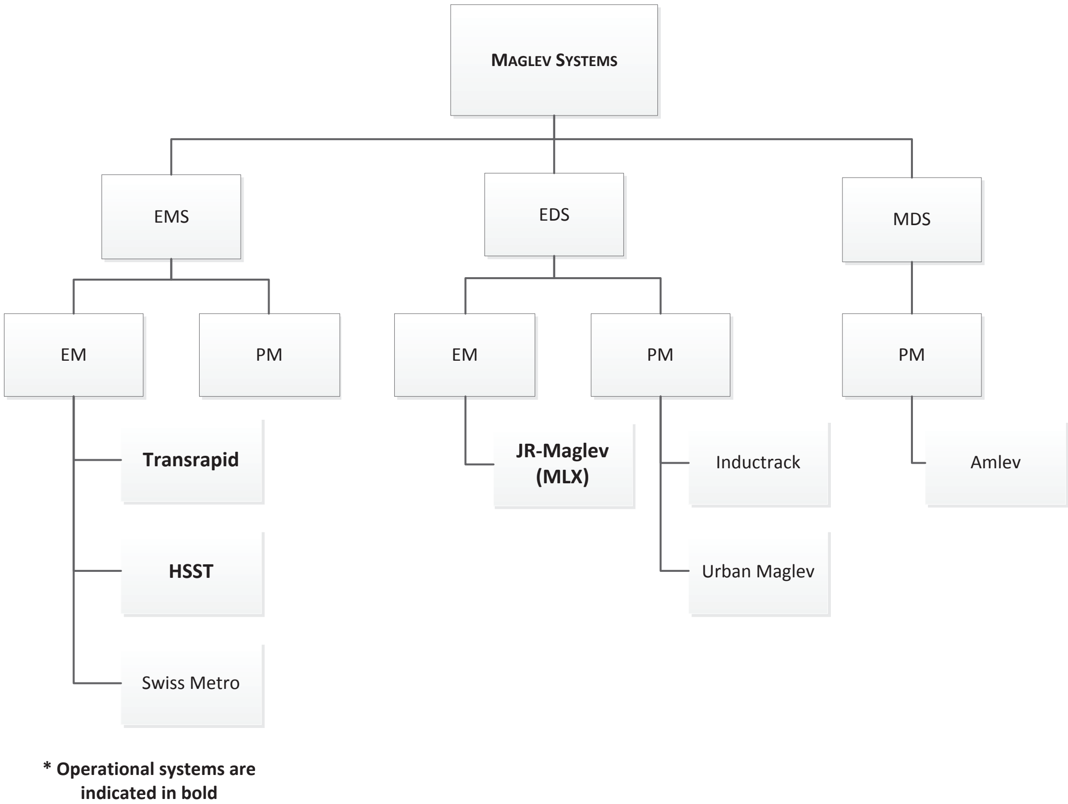


Figure 2-20: Classification of Maglev Systems (not all existing systems are included)

Note that some systems as EMALS only use magnetic propulsion and no magnetic levitation forces. Maglev systems as the train systems use magnetic levitation forces in combination with magnetic propulsion forces. It is thus also possible to only use linear motors without levitation.

All the collected information in this report can be used to compare different systems against each other and a selection can be done of the most suited system(s) for the design of a magnetic assisted take-off system for commercial aircraft. The main criteria are: *Technology Readiness Level (TRL), speed, motor, controllability, power, acceleration, weight / load*.

In Tables 2-3 and 2-4 information about different magnetic systems, described in this report, is given. Only the high speed systems have been selected for discussion since the to-be-designed system will also operate at speeds larger than 250km/h. The selected systems are the Transrapid TR08, the JR-Maglev MLX01, the Inductrack, the EMALS and the Amlev concept. All these

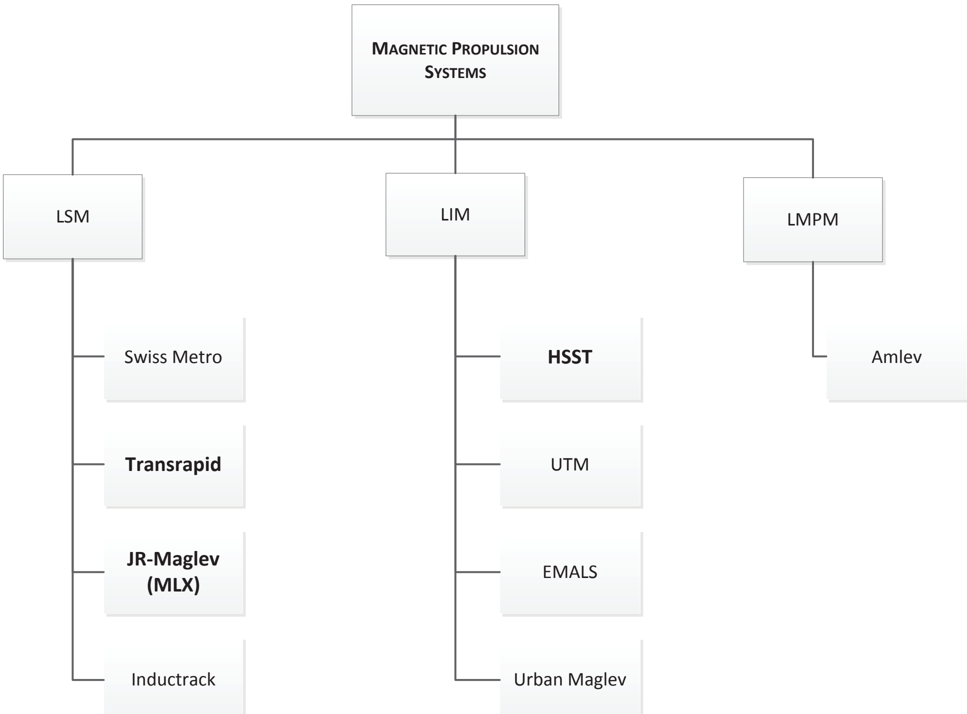


Figure 2-21: Classification of Magnetic Propulsion Systems (not all existing systems are included)

systems are train systems except for the EMALS which is the U.S. Navy's substitute for the steam catapult. The Inductrack concept is in general considered as a train system but is also applied as a rocket launcher. In Tables 2-3 and 2-4 data of the Inductrack train concept is used. A distinction should be made between EMALS and the other systems because EMALS is the only purely magnetically propelled system while the other considered systems are maglev systems. The Transrapid is an example of electromagnetic suspension, the JR-Maglev and Inductrack of electrodynamic suspension and the Amlev of magnetodynamic suspension, as can be found in Figure 2-20. The criteria on which the discussion is based, are given in Tables 2-3 and 2-4. For some systems, information is lacking or is not applicable, this is indicated by "-" or "n/a". The EMALS system is additionally interesting since the goal of this system is similar to the to-be-designed system; to give aircraft an initial velocity during take-off. Since this system is developed for military purposes, little information can be found.

The Amlev concept is still in a theoretical stage, this concept might be promising, but since no working prototype exists yet, it will not be considered any further. The technology readiness level (TRL) can be considered as TRL 2 which stands for: Technology concept and/or application formulated [34]. The ranking of TRL goes till level 9 at which the actual system is "mission proven" through successful mission operations (ground or space). The definitions for technology readiness level given by NASA can be found in reference [34].

The remaining systems operate on electromagnetic and electrodynamic suspension (except for EMALS). The main advantage the EMS system offers, is the zero levitation velocity, compared to the MLX and the Inductrack, where a levitation velocity higher than 170km/h and 100km/h is required. For these two systems (MLX and Inductrack) wheel bogies are needed for suspension at low speeds which adds complexity to the system.

An advantage of the EDS system is the large air gap (in the order of 10cm) which facilitates a less sophisticated air gap control system. The EMS system has a small air gap (in the order of 1cm) and to maintain this uniform air gap, an expensive control system is required. Irregularities in the track of EMS are also highly unwanted because of this. On the other hand, EMALS does not require air gap control as it has no levitation system.

The electromagnets of the Transrapid are stored on-board, which makes the cart heavy and demanding a lot of power. In case of the Inductrack, a system operating on EDS with permanent magnets, the high on-board power demand is absent due to the use of permanent magnets to create levitation. Concerning the weight of the Inductrack system, the bogie becomes very heavy with all the permanent magnets installed on it, and because it are rare-earth PMs, it is expensive and problems with demagnetization can occur.

The TRL of EMALS is considered at level 7: System prototyping demonstration in an operational environment (ground or space). The Transrapid and MLX have achieved the highest TRL (TRL 9) and the TRL of the Inductrack is considered at level 4: Component/subsystem validation in laboratory environment. When a certain system achieves TRL 6 or higher, (TRL 6: System / subsystem model or prototyping demonstration in a relevant end-to-end environment, ground or space), it can be considered for implementation.

Comparing the take-off speed of commercial aircraft (about 270km/h for the A320 [35]), with the maximum achievable speed of the systems (500km/h, 580km/h, 500km/h, 370km/h and 540km/h resp.), it can be stated that all considered systems achieve the take-off speed. Acceleration is another important requirement. EMALS has the highest acceleration. Though a take-off with an acceleration speed higher than 2g is not allowed by the airworthiness regulations. Therefore, it is assumed that a not uncomfortable take-off occurs at an acceleration of maximum 0.6g (5.8m/s^2). Considering a maximum acceleration of 0.6g means that EMALS and Inductrack satisfy this requirement.

All systems except EMALS operate on a synchronous linear motor. For the EMALS system the linear synchronous motor was considered, but in the final design the linear induction motor was selected [27]. However, no explanation in literature has been found why the induction motor was preferred over the synchronous motor. Both types of linear motors can be designed in such a way that high speed and good acceleration properties are met for a specific system. The speed generated by the LSM and LIM is dependent on the frequency and the pole-pitch. The motor properties are also dependent on the chosen hardware configuration. Possible hardware configurations are stated in Section 2-3. Since the electromagnetic knowledge of the author on the design of linear motors is limited, this thesis will not go any further in depth on this topic. Additional information on LSMs can be found in [23] and on LIMs in [36].

The system should be able to propel aircraft of the size of an A321 or smaller. A maximum allowed take-off weight of 90,000kg is considered. The to-be designed take-off system should be able to carry this load with the additional load of the system itself. The Transrapid and MLX system are designed to transport heavy loads, the EMALS is designed to propel naval aircraft with a take-off weight of 25,000kg [37] which is almost a factor four lighter compared to the A321. Comparing the requirements set for the launch system, it can be concluded that no magnetic propulsion system exists yet that can accelerate aircraft with a maximum take-off weight of 90,000kg and an acceleration of 0.6g to a lift-off velocity of at least 270km/h.

From Tables 2-3 and 2-4 it can be concluded that the Transrapid and MLX both are suited systems as long as the acceleration can be increased. Both systems are able to propel high loads and their technology level is mature. The EMALS is also suited but should be redesigned to propel heavy weight aircraft. The EMALS system has reached an operable stage and the system itself had successful aircraft test launches. The fact that this system does not use levitation does not make is a less valuable candidate compared to other systems. The levitation ability is not a requirement for the design of the system. Wheels or other means can be used for suspension purposes. The propulsion force in combination with the acceleration ability of the system are the driving requirements for the performance of the system. The advantage levitation offers is friction reduction due to the absence of wheels which can result is a lower energy consumption.

An advantage the Inductrack has over the Transrapid and MLX, is the passive levitation created by permanent magnets. By using permanent magnets, power failure in the suspension system will not lead to a situation where the cart will stop floating and comes in contact with the rail. Certification-wise is this a safe option. However, all currently operating systems (Transrapid and MLX) are provided with redundancy options in case of for example a power failure.

In general, it can be concluded that both motors (LSM and LIM) are suited but it will be a great challenge to design a system that can propel heavy loads to a velocity of nearly 300km/h with a reasonable acceleration ($0.6g$). Suited levitation suspension systems are EMS and EDS of which operating train systems have shown the technology maturity, the high-speed operations and the heavy load transportation (up to 250,000kg). However, choosing for a system which uses levitation as suspension means in combination with magnetic propulsion, might offer only a small benefit over simply magnetic propulsion in terms of rolling friction, and adds extra complexity to the system. Especially when selecting the EDS system which needs wheeled support at low speeds. On the other hand, the EMS system requires a very sophisticated control system to maintain the small airgap (of approximately 1cm), which might become additionally complex for heavy loads.

In the next chapter, different launch concepts are created and discussed. At the end of the chapter a trade-off between these concepts is performed.

Table 2-3: Summary of High-Speed Linear Motor Systems (1)

Criteria	Transrapid TR08	JR-Maglev MLX01	Inductrack	EMALS	Amlev
Suspension system	EMS	EDS	EDS	n/a	MDS
Technology Readiness Level	9	9	4	7	2
Nominal speed [km/h]	430	500	-	-	-
Top speed [km/h]	501	581	500	370	540
Maximum acceleration [m/s^2]	0.15g	0.25g	2.1g [a]	2.8g	-
Motor	LSM	LSM	LSM	LIM	LMPM
Air Gap [mm]	8-12	80-150	80-150	n/a	
Air Gap control	Yes	No	No	No	No
Total mass [kg]	250,000 (vehicle + passengers)[18]	120,000 (vehicle + passengers)[18]	-	26530 [b]	-

[a] acceleration of small scale demonstrator [38]
[b] Maximum airframe mass [39]

Table 2-4: Summary of High-Speed Linear Motor Systems (2)

Criteria	Transrapid TR08	JR-Maglev MLX01	Inductrack	EMALS	Amlev
Power [Wh/(seat x km)]	- at 300km/h: 33-38 - at 400km/h: 57-65 - acceleration from 0 to 400km/h: 158-182	-	-	n/a	-
Power [MJ]	-	-	-	122	-
Lift-off velocity [km/h]	0	>170	>100	n/a	>40
Magnet type	Electromagnet	Superconducting Electromagnet	Permanent Magnet	-	Permanent Magnet
On-board power demand	high	high	low	-	low
Sensitivity to load variation	-	Insensitive	-	-	Insensitive
Levitation force [N/m]	-	-[a]	500	-	-

[a] The MLU002 (the precursor of the MLX01) has a vehicle length of 22m and a levitational force of 196kN (the vehicle weight equals 17,000kg)

Chapter 3

Concept Exploration

Before different concepts can be created, the different functions to be performed by the launcher are determined in the functional flow diagram, see Figure 3-1. In this diagram the functions during normal operation of the system are given.

An aircraft should taxi to the runway as it normally does. Stop at the pick-up point to be attached to the system. At the pick-up point, the take-off is prepared. The pilot communicates with air traffic control to start the take-off, and the thrust of the launch system and the aircraft are adjusted for launch. The aircraft is accelerated until the desired launch velocity is reached. At this point the system unlocks the aircraft attachment. The angle of attack and the thrust of the aircraft are set ready for climb. The aircraft rotates, lifts off and the cart is decelerated to a standstill. When the cart is halted, the direction of the cart is reversed such that it can return to the pick-up point to launch another aircraft. When a problem occurs during launch, the launch should either be aborted or continued, dependent on the severity of the problem. Worst-case scenario's are worked out in detail in Section 4-1-1.

Two concepts have been developed based on the requirements given in Figure 1-3 and Figure 1-4. The concepts are designed to propel aircraft equally big or smaller than the A321, with a maximum take-off weight of 90ton. This covers about 80% of all the aircraft departing from Schiphol Airport [6]. If the system would be designed to propel larger aircraft than the A321, the system could be overpowered and too heavy for small aircraft. Since small to medium sized aircraft perform more take-offs and landings, the benefit of designing the system for these aircraft will be larger. First, the first concept is explained, then, the second concept follows and at the end of this chapter a comparison with a trade-off is given between both concepts. Figure 3-2 illustrates both concepts.

3-1 Concept 1: Aircraft mounted on cart

The first concept makes use of Maglev. The system has a cart on which the aircraft is mounted on. This cart levitates above the guideway and is accelerated by means of a linear motor. Figure 3-2(a) illustrates Concept 1.

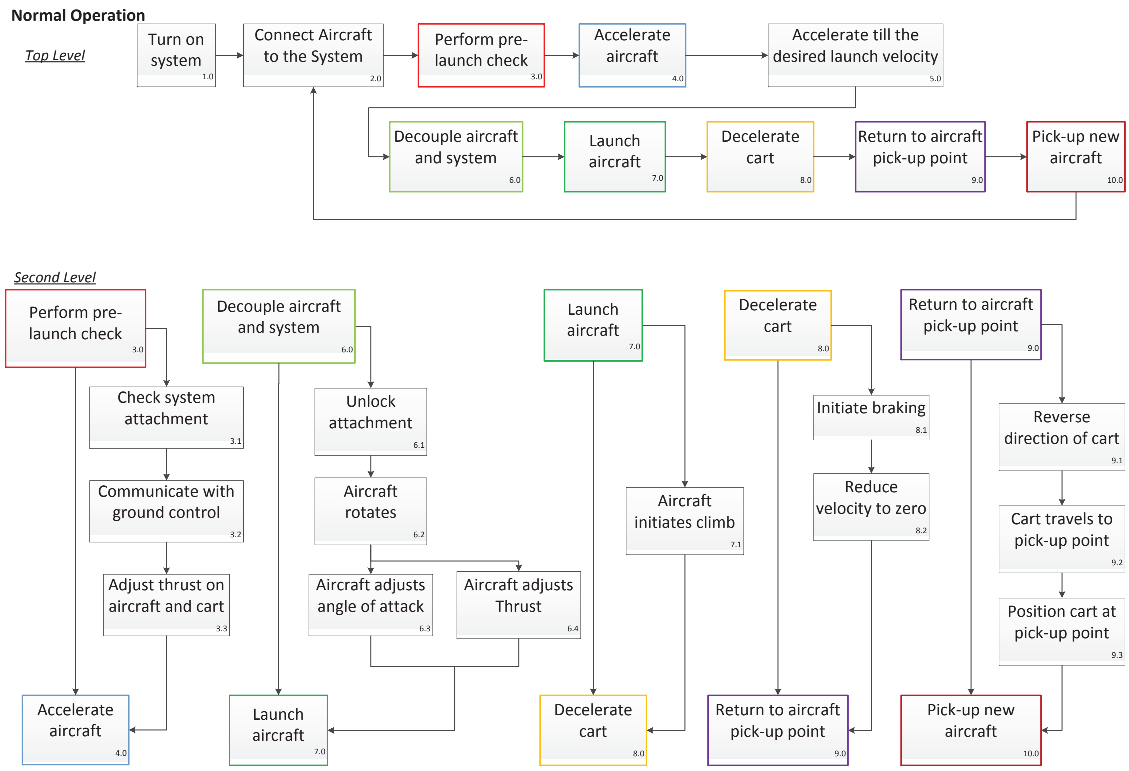


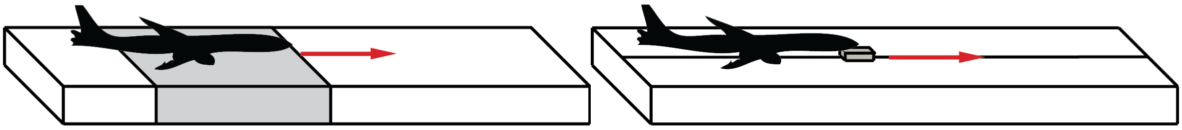
Figure 3-1: Functional flow diagram, normal operation

3-1-1 System lay-out

Electromagnetic layout of the system

The electromagnetic forces acting on the system are shown in Figure 3-3. There are three different forces: one for propulsion, one for guidance and one for levitation. One set of electromagnets is used for levitation and propulsion, a combined system, and another set of electromagnets is used for guidance and are placed at the side of the cart, see Figure 3-4. The electromagnetic suspension (EMS) has been chosen over the electrodynamic suspension (EDS) for the following reasons: it offers levitation at a velocity of 0m/s, therefore no additional wheel bogies are needed, and secondly, no wheel bogie retraction mechanism should be installed for the short launch period. If EDS would have been chosen, the wheels need to be fold out at low speeds, retract at high speed and fold out again when the cart brakes, and all this happens in less than half a minute.

For propulsion, a linear synchronous motor is used. The stator is put on the guideway and the excitation electromagnets are mounted on the cart, Figure 3-4 clarifies the layout. Both, the stator and the electromagnets need to be powered. Inductive power transfer (IPT) is a contactless power supply system that can transfer power from the track to the cart. This system is applied on the Transrapid as well [40]. Achieving levitation requires constant power, when using the EMS, about 1kW is typically consumed per ton of lift. The launch system with the A321 mounted on it (weight = 133.5ton), will consume about 133.5kW of continuous power [41]. For magnetic levitation is



(a) Concept 1: Aircraft on cart **(b)** Concept 2: Aircraft with shuttle

Figure 3-2: Concepts

is assumed that the maximum weight of the cart equals half of the weight of the launch vehicle (the aircraft) [31], [33]. Since the A321 is the largest aircraft considered for the launch system, the weight of the cart equals 45ton.

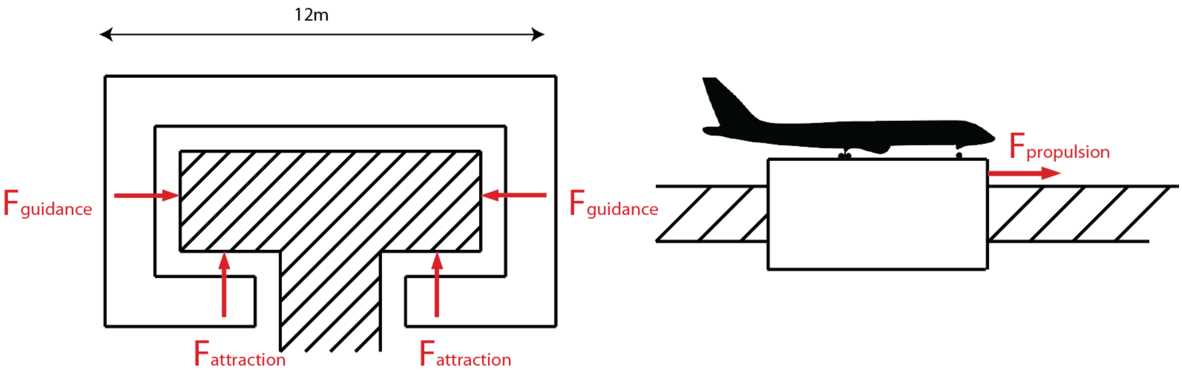


Figure 3-3: Electromagnetic forces acting on system

However, care should be taken with the application of the electromagnetic suspension system. This suspension system has been applied on the Transrapid which can be considered as a non-lifting body. Now, this suspension system is applied on an aircraft launch system of which the aircraft generates lift. The suspension system requires a constant airgap of about 1cm and changing the airgap between the track and the cart will distort the performance of the system. At the end of the track, the aircraft will rotate and detach from the platform. As a result of this, a gradual weight decrease will be experienced by the platform, going from a total weight of 135ton to 45ton during a period of 5seconds (the release time), in case of an A321 launch. A highly sophisticated control system is required to maintain the airgap size.

Electromagnetic area sizing

In order to make a working cart, the area of the electromagnets needs to be determined. It can be assumed that electromagnets are able to deliver a force of 400kN/m^2 [37] and a maximum propulsion force of 786kN (with an acceleration of 0.6g) is required. This results in an electromagnetic area of almost 2m^2 while the levitation force needs an area of 3.3m^2. These numbers represent the total area of electromagnets, thus each side will require a total area of 2.75m^2 for propulsion and levitation.

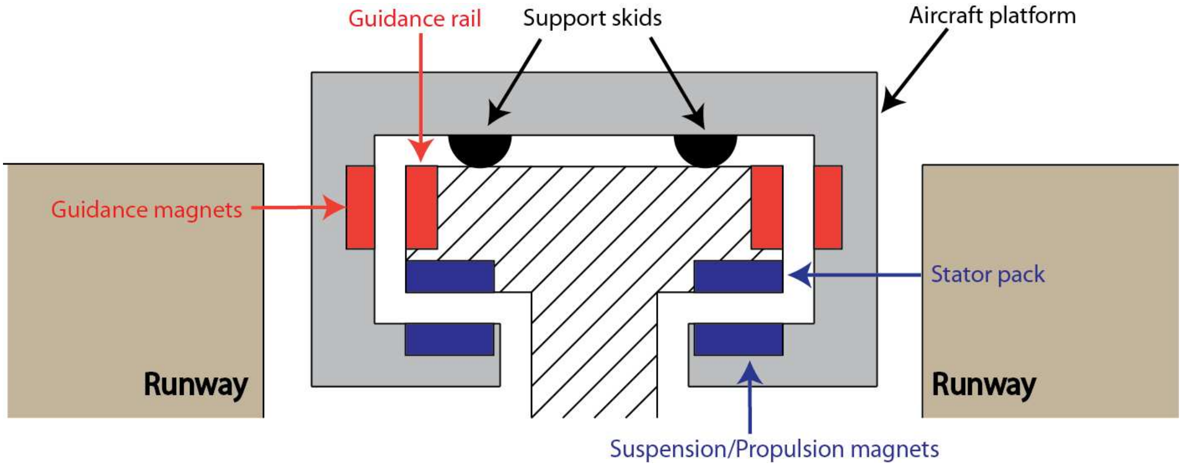


Figure 3-4: Cross section of the cart with electromagnetic lay-out

The stator needs to be divided in sections for optimal performance of the launch track. In this way, only the section on which the cart is travelling needs to be powered and the current, voltage and frequency of each section can be controlled differently. The amount of current, voltage and frequency define in each section the maximum speed that needs to be reached. This principle has been applied on the EMALS as well [37], with sections varying from 5m to 15m. The EMALS has been designed to accelerate until the lift-off speed is reached which requires a constantly changing current, voltage and frequency in order to accelerate the shuttle.

It should be investigated how large the strength of the magnetic field is. The cart needs to be designed for magnetic shielding and if necessary, measures should be taken to shield the aircraft from the magnetic field created by the track as well. This is necessary to minimize the influence on flight avionics.

Support skids are put on the cart, in case the system is not operative. It is supported by these skids as indicated in Figure 3-4.

Cart design

To start with the sizing of the cart, it is important to know what the wheel base and the wheel track variation is of the selected aircraft range. The wheel base, the distance between the nose and the main gear, varies between 10m and 17m. The wheel track, the distance between the left and the right wheel of the main gear, varies between 3 and 8m. A safety distance of two meters at each side (longitudinal and lateral direction) has been selected, resulting in a cart of 12x21m. The landing gear has been selected to be the best accessible part of the aircraft to connect the cart with. Two attachment options exist:

Main gear attachment: For main gear attachment, the location of the locking system is located towards the rear of the cart and panels can be used to keep the aircraft in place, as shown in Figure 3-5. Multiple panels are used to cope with the wheel track variation in order to minimize the additional production of aerodynamic drag. The shape of the panels is not definitive, it is represented in the figure to give an idea on the working principle.

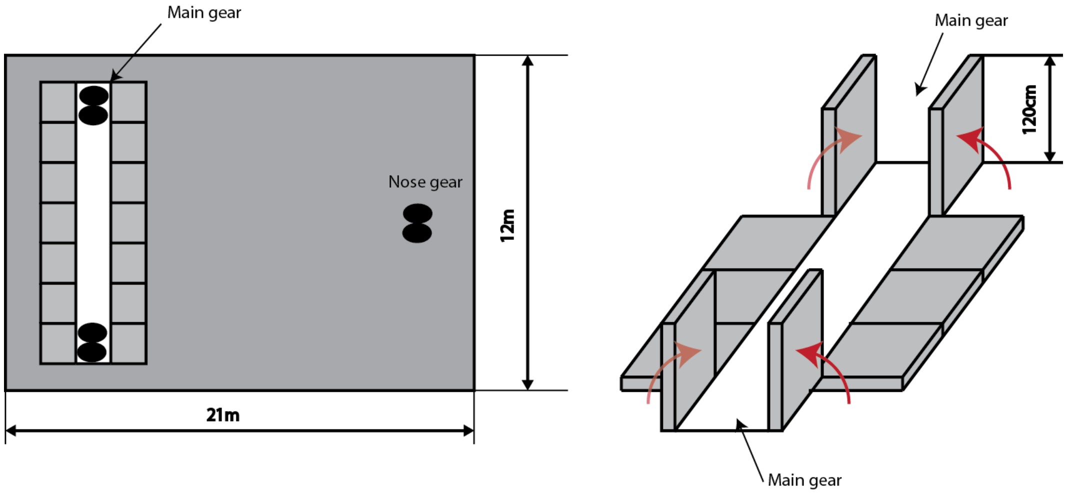


Figure 3-5: Cart lay-out with main gear attachment system

Nose gear attachment: For nose gear attachment, panels can be used as well. These panels can create an additional amount of drag due to their size. Therefore, it can be chosen to use a connection with bars, similar to the nose wheel connection of the steam catapult (see Figure 3-6) to reduce this drag. It is more difficult to use bars for main gear attachment due to the wheel track variation. If nose gear attachment with bars is chosen, a connection point on the nose gear should be provided.

Figure 3-6: Attachment of the F-14 with the shuttle of the steam catapult [42]

Now, two possible aircraft attachment locations have been proposed in this chapter, nose gear attachment and main gear attachment. Before, selecting one of these two locations, it should be investigated if the nose gear and the main gear are able to withstand the towing forces exerted on them. In case they are not capable of supporting these towing loads, structural reinforcements are needed which can increase the operational empty weight of the aircraft.

3-1-2 Landing gear forces

The main gear is in general already designed to withstand larger forces than the nose gear, so it is less likely that main gear attachment requires structural modifications. However, this statement needs to be supported with numbers. A landing gear is designed to fulfil many functions such as [43]:

- ◇ To absorb landing shocks and taxi shocks
- ◇ To provide the ability for ground manoeuvring (taxi, take-off roll, landing roll and steering)
- ◇ To provide for braking capability
- ◇ To allow for aircraft towing
- ◇ To protect the ground surface (runway)

Vertical, lateral and longitudinal loads are exerted on the landing gear. It should be investigated if the landing gear can cope with the thrust force of the launch system exerted on the landing gear. Therefore, the maximum longitudinal force for which the landing gear is designed, needs to be determined and compared to the system's launch force. The horizontal (longitudinal) force acting on the main gear has been determined for two-point level landing, the maximum spin-up (at touch down) and two-point braking. For the nose gear the maximum towing loads and maximum spin-up loads have been determined. The results for the A321 and F-100 are summarized in Table 3-1 and Table 3-3. The total sum of the forces of the main gear is given in Table 3-1, if the forces for only the left or the right gear want to be determined, these forces need to be divided by two.

For the aircraft weight distribution on the main gear and nose gear, 0.08 of the aircraft weight is assumed to be supported by the nose gear and the rest is carried by the main gear. A resulting normal force of the nose gear equal to 0.08 of the aircraft weight is considered to be the minimum weight to provide adequate steering capabilities to the aircraft [43]. In order to determine the maximum longitudinal loads acting on the landing gear, first consider the loads on the main gear, starting with the *two-point level landing* analysis (see Figure 3-7). The forces in horizontal and vertical direction equal [44]:

$$\sum F_x = 0 : D_{mg} = n_x \cdot W_{ac} - D + T_{eng} \tag{3-1}$$

$$\sum F_z = 0 : V_{mg} = n_z \cdot W_{ac} - L \tag{3-2}$$

For $\sum F_x = 0$, it is assumed that at landing the thrust of the engines equals the drag $D = T_{eng}$, resulting in $D_{mg} = n_x W_{ac}$ and $D_{mg} = \mu_r V_{mg}$ where V_{mg} is the total vertical normal force of the main gear (left and right gear). According to the regulations, CS25.479(d)(1), the drag load acting on the landing gear cannot be larger than 25% of the maximum vertical ground reaction during level landing conditions. For the forces in vertical direction, by definition in CS 25.473(a)(2), it can be assumed that in landing mode the lift equals the aircraft landing weight, resulting in a maximum vertical ground reaction of $n_z = 1 + V_{mg}/W$. Rewriting this equation to $V_{mg} = W(n_z - 1)$, gives $D_{mg} = \mu_r W(n_z - 1)$. n_z limit equals 2.5

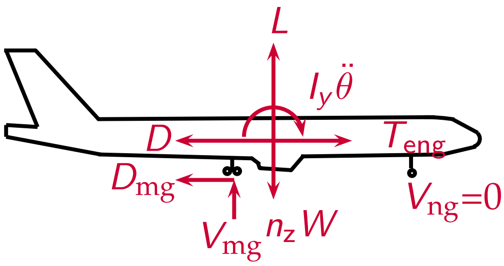


Figure 3-7: Two-point level landing condition, reproduced from [44]

and ultimate 3.75. The outcomes for the horizontal force calculations are summarized in Table 3-1.

The maximum *spin-up loads* are calculated and represented in Figure 3-8. At touch down, the non-rotating wheels from the aircraft touch the runway surface and are accelerated to the specified ground speed. An instant peak drag load results when this happens, $D_{mg} = \mu_r V_{mg}$. The maximum dynamic frictional coefficient μ_r may not exceed 0.8 and the $V_{mg,max} = 1.7 V_{mg,\text{ static}}$ with $V_{mg,\text{ static}} = W_{\text{landing}}$. 1.7 is a typical design goal for the maximum reaction force [45]. Spin-up can also occur at the nose gear, then the $V_{ng,\text{ static}} = 0.08 W_{\text{landing}}$. The loads created during spin-up do not last long, eventually the rotational speed will become equal to the forward speed V at the ground and the frictional force will diminish. The backward bent strut will then spring back forward. This phenomenon is called the spring back load case [45].

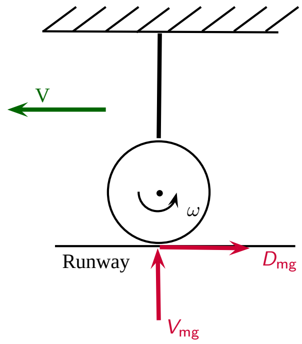


Figure 3-8: Spin-up loads, reproduced from [45]

In the *two-point braked-roll* analysis by CS25.493(b)(2), the nose gear is off the ground and the aircraft is considered to be in a level attitude. No wing lift may be considered. The maximum $\mu_r = 0.8$ and $n_{z,\text{limit}} = 1.0$ at design taxi weight and $n_{z,\text{limit}} = 1.2$ at design landing weight. Considering $D_{mg} = \mu_r V_{mg}$ and $V_{mg} = n_z W_{ac}$. Table 3-1 gives a summary of all calculated longitudinal forces of which the largest resulting force comes from the spin-up. Comparing this force to the launch force of the system (786kN for the A321 and 523kN for the F-100 with an acceleration of 0.6g) shows that the main gear should be capable of handling these launch forces. Though, these forces calculated in Table 3-1 are rarely achieved during operations. The chance of having a load factor n_z of 1.75 equals 0.005 per thousand runway landings [45], higher load factors are even less likely to occur.

Considering nose gear attachment, the current strength of nose gears should be evaluated. The maximum longitudinal forces acting on the nose gear happen during spin-up at touch down and

Table 3-1: Summary of maximum total longitudinal main gear loads (left and right gear)

Main gear horizontal forces	*Spin up, D_{mg} [kN]*	*Two-point landing n_z limit, V_{mg} [kN]*	*Two-point landing n_z ultimate, V_{mg} [kN]*	*Two-point braking [kN]*
F100	532	147	269	376
A321	1,007	278	509	701

when towing the aircraft to the taxi area. The loads resulting from braking affect the main gear friction loads but barely the nose gear as it is assumed that no brakes are installed on the nose gear. Spin-up has been handled in the previous paragraph. The maximum towing loads are specified in the CS 25.509 as a function of the airplane maximum design taxi gross weight as shown in Table 3-2. Note that this table is adopted from CS 25.509 and the values and outcomes of the equations are given in pounds. When towing the nose gear straight the maximum towing force of Table 3-2 can be applied. In case of changing the towing direction, a lower force ($0.5F_{\text{tow}}$) is applied. A summary of the results for the nose gear loads is given in Table 3-3. At the nose gear

Table 3-2: The maximum nose gear tow loads defined by CS25.509

Ramp Weight [lb]	*n_z limit*	*Towing loads [lb]*
$< 30,000$	1.0	0.3W
$30,000 - 100,000$	1.0	(6W+450,000)/70
$> 100,000$	1.0	0.15W

Table 3-3: Summary of maximum longitudinal nose gear loads

Nose gear horizontal forces	*Spin-up [kN]*	*Towing loads [kN]*
F100	42.6	44.0
A321	80.6	132

the same launch force is applied as it would be on the main gear. For the Fokker-100 this force equals 523kN and for the A321, 786kN to achieve an acceleration of 0.6g. As can be noted from Table 3-3, the longitudinal forces for which the nose gear is designed are too low to withstand the launch force. The nose gear will need reinforcement.

To conclude, a newly designed nose gear is required if nose gear attachment is selected. Otherwise, main gear attachment can be chosen. Main gear attachment is likely to withstand the launch forces but the main gear will become sensitive to fatigue since the order of magnitude of the launch forces equals to forces which are rarely experienced by the main gear. Further research is required to decide if a new main gear is required, if this attachment option is selected. If it seems that no structural modifications to the main gear are required, it is advantageous choosing this attachment system as it requires no aircraft modifications.

3-1-3 Airport and Runway modifications

The system track needs to be implemented in the runway. Schiphol airport has been chosen to act as an example airport. The length of the track is dependent on the chosen mean acceleration and the maximum velocity of the system. 0.4g and 0.6g are the two possible mean accelerations. The longest track is achieved at the lowest acceleration (0.4g) and the highest velocity (120m/s), resulting in a track length of minimum 2435m, a safety distance for decelerating the cart to full stop of 100m is considered. Thus, a total track length of roughly 2600m is desired. In case a shorter track is desired, it can be chosen to decrease the maximum velocity and/or increase the acceleration to 0.6g.

Schiphol Airport has a tangential structure of runways in contrast to most other airports who have a parallel structure of runways [46]. This is due to the fact that there is too much variation in wind direction at Schiphol Airport. The runway structure is given in Figure 3-9. The most used runways are the North-South runways. It would be best to implement the system in one of these runways as most aircraft take-off in this direction. It should also be investigated how sensitive the system is for cross wind as the air gap for guidance and suspension is small (about 1cm) and should be kept constant for optimal performance. Since the air gap is small a sophisticated control system is required to maintain the position of the cart with the aircraft mounted on. There are three runways in the North-South direction: Polderbaan (18R-36L), Zwanenburgbaan (18C-36C) and Aalsmeerbaan (18L-36L), with runway lengths of 3800m, 3300m and 3400m respectively. The Zwanenburgbaan is considered for the implementation of the system as it is the shortest runway with a length of 3300m and a width of 45m.

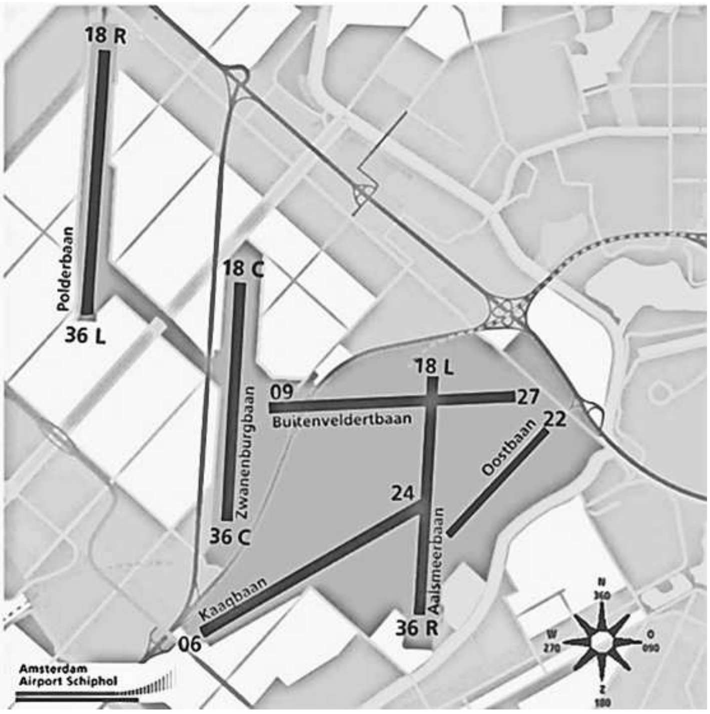


Figure 3-9: Runways of Schiphol Airport [46]

In case the system would be relatively insensitive to cross wind, the Oostbaan can be considered as it is the shortest runway of all with a length of 2041m and width of 45m. Note that this runway is shorter than the maximum determined track length of roughly 2600m (for a mean acceleration of 0.4g and launch velocity of 120m/s). This means that either a lower maximum velocity or a higher acceleration (0.6g) should be chosen. If 120m/s is kept and an acceleration of 0.6g is selected, a track length of 2000m is sufficient. The track can be put at the side of the runway such that it covers the least amount of space of the runway (see Figure 3-10). If needed and if possible, it can always be opted for widening the runway. The track width would be about 13 meters wide. The marked "red" box in Figure 3-10, indicates the possibility for widening the runway by 10 to 20 meters.

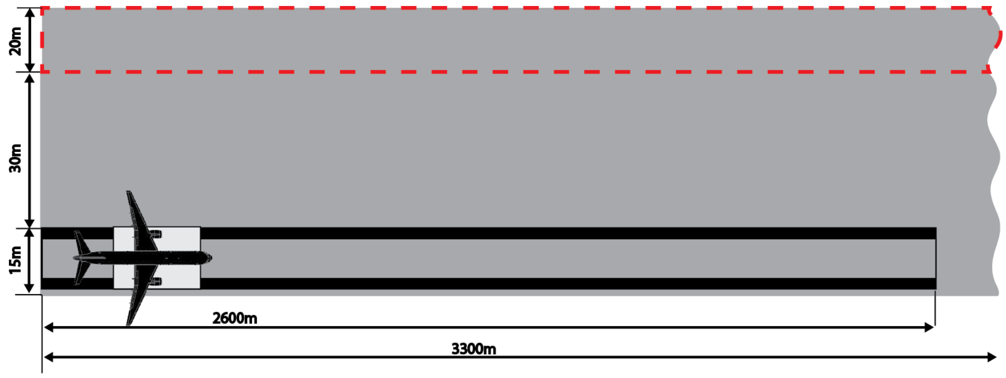


Figure 3-10: Concept 1: Runway

Airport operations

The flow chart in Figure 3-11 explains how the aircraft goes from the gates to climb phase under normal operation of the system and the aircraft. The path the aircraft follows is shown in Figure 3-12. A runway controller (RC) will be required at the runway to assist the pilot with the positioning of the aircraft on the runway, before it is mounted on the cart. The red lines on the runway in Figure 3-12 give an indication to the pilot where to position the aircraft on the runway before rolling on the cart. The runway controller will also communicate with the Tower to approve the launch and confirm the attachment of the aircraft on the cart. This person will be able to control the movements of the cart and the attachment system by an external device. On-board the aircraft, an additional device with specifications of the launch system needs to be installed such that the pilot can initiate the launch him-self after approval of the Tower.

When the launch velocity is reached, a release time of 5 seconds is considered. During this amount of time, the attachment system unlocks and the aircraft is able to rotate, lift off and follow a specific customized departure profile. Worst-case scenarios happening during operation of the launch system are not handled in this section but will be discussed in Chapter 4-1-1.

To conclude, the major change is that an additional person (the runway controller) will be needed at the runway to assist with the launch. Its main functions will be assisting the pilot with positioning the aircraft and checking the attachment of the cart with the aircraft.

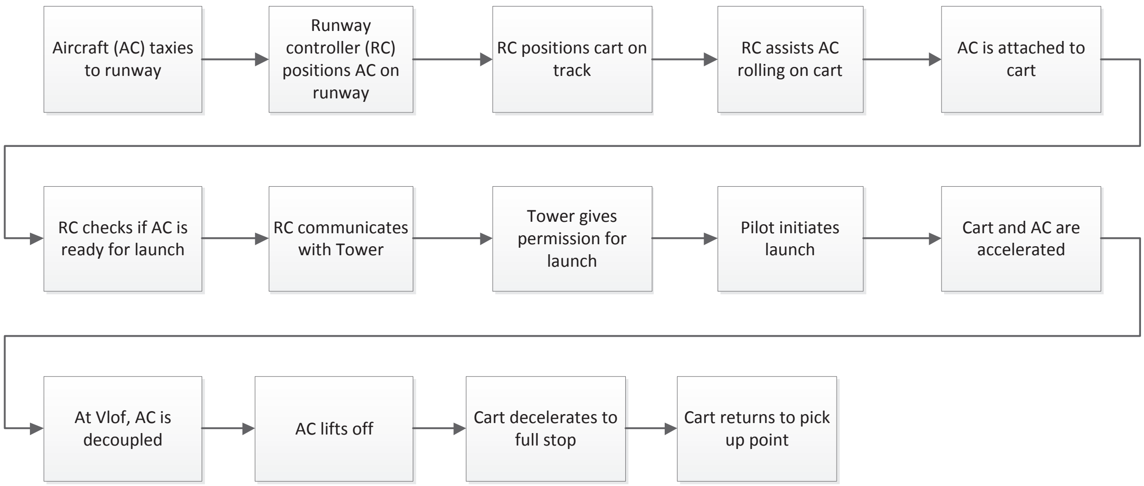


Figure 3-11: Concept 1: Flow chart airport operations under normal circumstances

3-2 Concept 2: Aircraft connected to shuttle

The second concept differs from the first one as no maglev technology is used. The system operates on a linear synchronous motor for propulsion and is not suspended by electromagnets to eliminate rolling friction, see Figure 3-2. This means that there is an additional drag force present compared to Concept 1, D_{roll}, created by the friction between the wheels of the aircraft and the runway. In this concept, the aircraft is not mounted on a carriage but is connected with a launch bar to a shuttle, similar to the connection of a fighter to the steam catapult (Figure 3-6). The equations of motion for this concept are given in Equation 3-6. The electromagnetic force acting on the cart is the propulsion force and wheels are used to provide guidance and suspension forces, see Figure 3-13.

3-2-1 System Layout

Electromagnetic systems

The selected propulsion system is a double-sided linear synchronous motor with an electromagnetic (EM) or permanent magnetic (PM) excitation system. Double-sided implies that the magnets are put at both surface sides of the shuttle (left and right) to reduce the size of the shuttle as shown in Figure 3-15, representing the layout of the shuttle. The stator is implemented in the runway track. For the shuttle itself, two layouts are possible, the blade shuttle or the inverted-U configuration [37]. The blade shuttle can be represented as a sheet with excitation magnets mounted on it, moving in between the track as shown in Figure 3-14a. The inverted-U configuration has the shape of a horse-saddle with integrated excitation magnets hanging over the track (see Figure 3-14b). The overall weight of the whole system (incl. track) is heavier in case of the blade shuttle but it has better thermal properties and a lighter blade compared to the inverted-U configuration. The track can absorb more heat created by the losses in the system and electrical braking is easier as the blade is relatively light compared to the inverted-U configuration. Therefore no active cooling

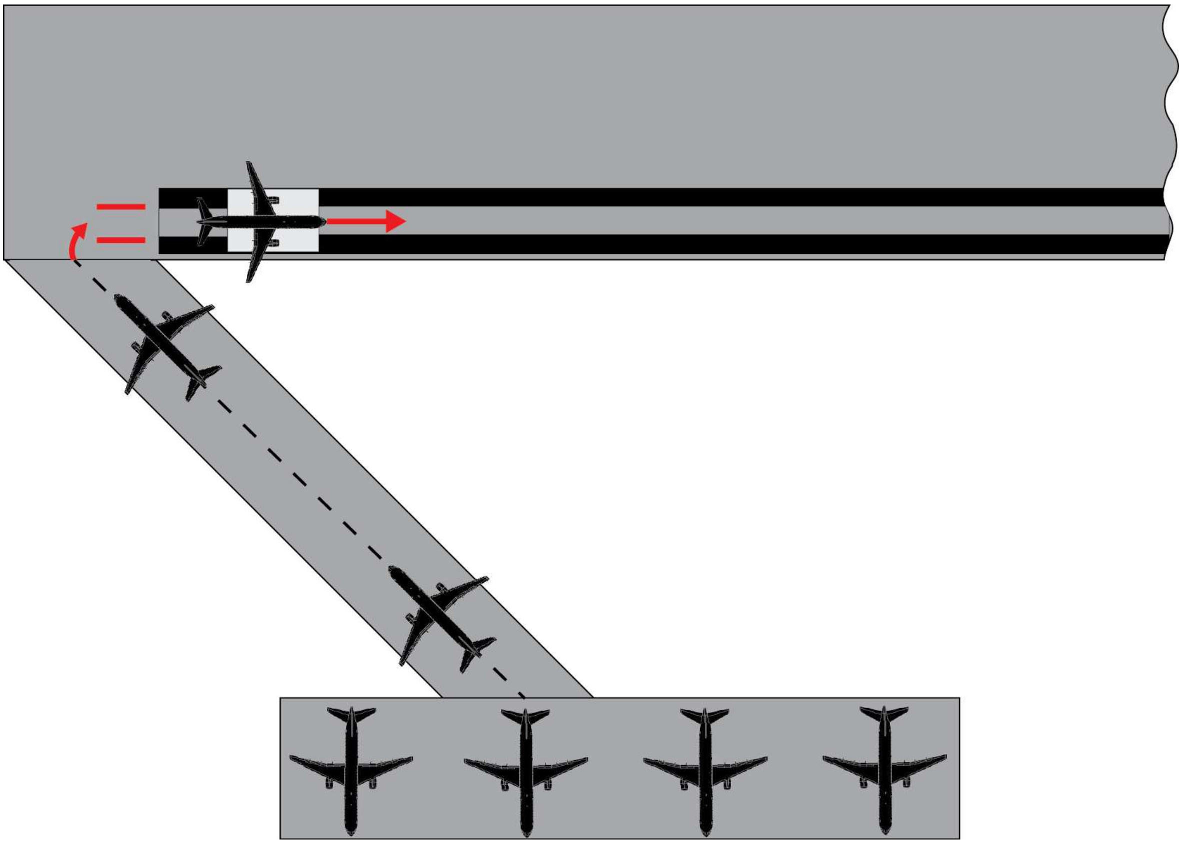


Figure 3-12: Concept 1: Airport operations

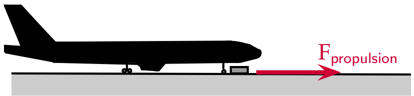
is required [37]. The blade-shuttle configuration is selected due to the superior thermal properties and the lighter blade which reduces the shuttle weight.

The excitation magnets can be either EMs or PMs. The main difference between PMs and EM is that EMs require a power source for excitation and PMs do not. The force created by PMs is however smaller than for EMs. The magnetic force strength of PMs can be assumed equal to 200kN/m^2 and for EMs 400kN/m^2 [37]. Table 3-4 gives a representation of the magnetic area needed on the shuttle based on the launch of the A321. Note that the area numbers in Table 3-4

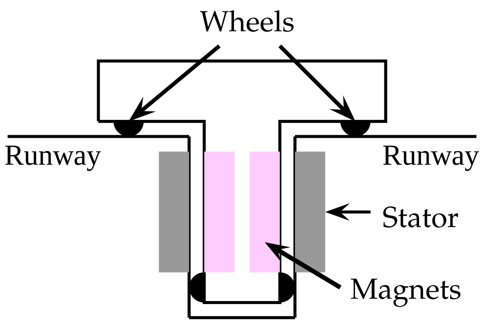
Table 3-4: Magnetic area required for different accelerations based on A321

Acceleration	F [kN]	EM area [m^2]	PM area [m^2]
0.4g	372.39	0.93	1.86
0.6g	558.59	1.40	2.79

represent the total area, in case of a double-sided configuration, the magnetic area is spread out on both sides of the shuttle. A shuttle in double-sided configuration with a height of 1m effective magnetic area, needs a length of 0.47m to achieve an acceleration of 0.4g with electromagnets for the A321 launch. A possible layout of the cart is shown in Figure 3-15, the location of the magnets is indicated and the armature (stator) in the track. The placement of the wheels and the shape of the shuttle are not definitive, they are shown to give an indication of a possible layout of the cart.

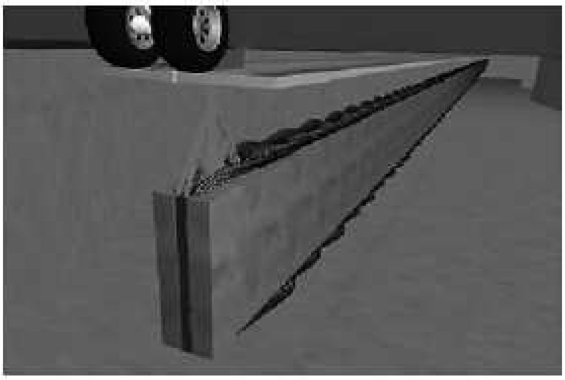


(a) Electromagnetic propulsion force acting on shuttle

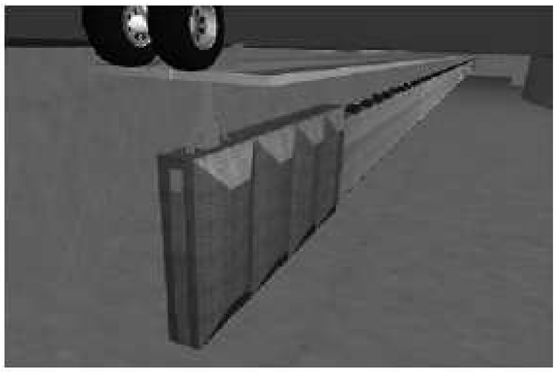


(b) Shuttle layout, wheels support guidance and suspension

Figure 3-13: Propulsion, guidance and suspension forces of the system



(a) Blade shuttle



(b) Inverted-U configuration

Figure 3-14: Different shuttle configurations [37]

In both concepts sectioning of the track is a requirement as the voltage, the current and the frequency demands differ too much in the low speed section compared to the high speed section [37]. In this way, only the section where the shuttle is passing through needs to be powered instead of the whole track and the section lengths can be optimized to achieve the desired velocity at each section. A separate study will be required to achieve a detailed motor/track design in order to get the launch system operable.

Aircraft attachment possibilities

Different possibilities are available for finding an attachment point on the aircraft. The most likely are nose gear attachment and fuselage attachment. There are two options for nose gear attachment, either the connection bar is mounted on the nose gear, connecting it with the shuttle (Option 1) or the connection bar is mounted on the shuttle, connecting it with the nose gear (Option 2). Option 3 holds attachment underneath the fuselage, at the keel beam. This latter requires the connection bar to be installed on the shuttle, similar to Option 2. Conversely, Option

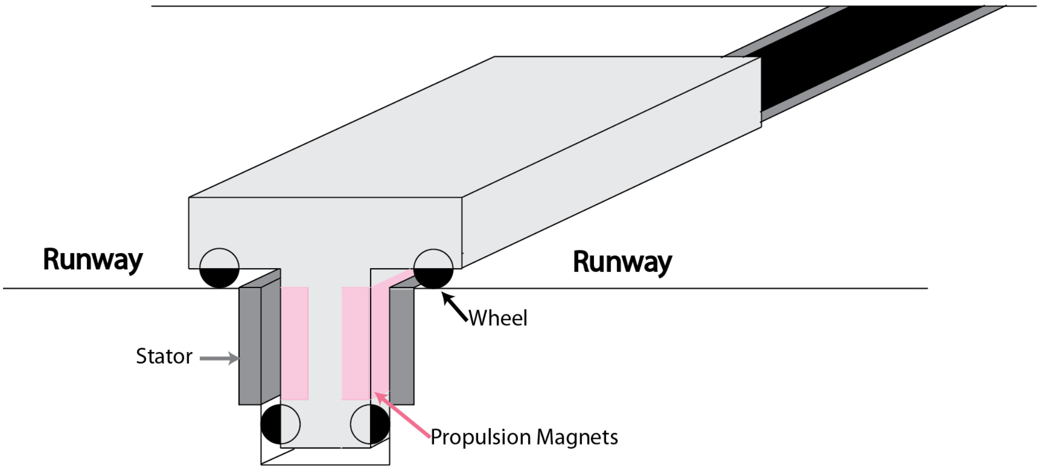


Figure 3-15: Concept 2: Cart and track layout

1 requires an additional bar to be mounted on the nose gear. For all attachment possibilities, it is important that the connection can be quickly connected/released and cannot fail at any time.

In Section 3-1-2, the longitudinal forces the landing gear can handle are discussed and it is concluded that a new nose gear should be designed for this configuration to withstand the launch forces. In case a new nose gear is designed, the location of the attachment point can be carefully selected and integrated in the design. When choosing Option 1, the connection bar may not interfere during nose gear retraction. The resulting aircraft weight will have increased slightly. The advantage of Option 1, is that the bar will be designed for each specific aircraft. Therefore, it is able to withstand the forces acting on it, in an optimized configuration. This option is applied on carrier-based aircraft. A runway controller connects the launch bar with the shuttle, as illustrated by Figure 3-16. On the left figure, the launch bar is not attached and on the right figure it is. The main disadvantage of choosing this option is that each aircraft will require a new modified nose gear.

(a) Launch bar mounted on nose gear **(b)** Launch bar connected to shuttle

Figure 3-16: Launch bar mounted on nose gear

The second option will have a universal bar installed on the shuttle. This bar needs to fit for the whole aircraft selection and be compatible with different sizes (thickness and height) of nose gears. A universal attachment point needs to be searched for on nose gears and perhaps, an attachment point needs to be installed on the gear. Considering the nose gear in Figure 3-17, the most convenient location is the space between the wheels, indicated with the red box. A hook can be used to connect with the nose gear, as illustrated in Figure 3-18a or a system which embraces the strut of the nose gear (see Figure 3-18b). Quick release, is offered by the hook configuration. As soon as the aircraft rotates, the connection between shuttle and aircraft is removed. A smart release/locking system for the enclosed configuration needs to be determined, in case this option is selected.

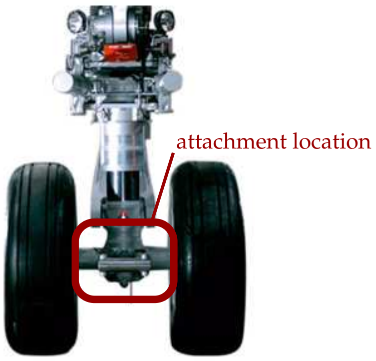
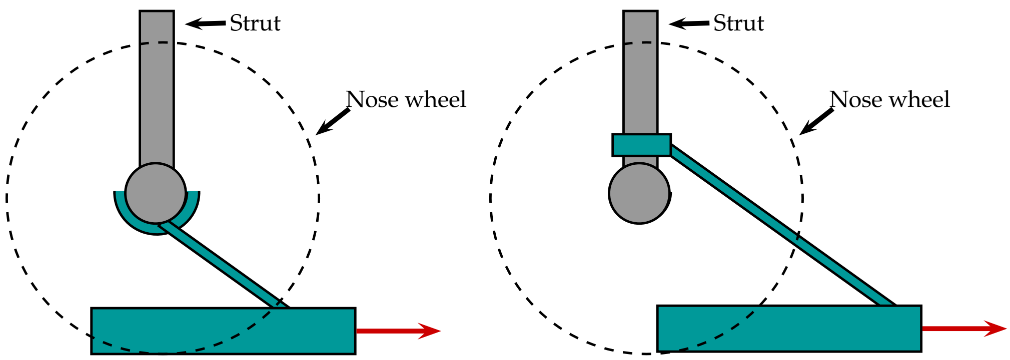


Figure 3-17: Nose gear attachment location



(a) Hook attachment to nose gear

(b) Strut nose gear enclosed by shuttle attachment

Figure 3-18: Nose gear attachment possibilities

The last option (Option 3), attachment at the fuselage, connects the shuttle with the keel beam as shown in Figure 3-19. The keel beam is located at the wing box and is the most reinforced part of the fuselage. An attachment object should be mounted on the fuselage and a connection from the shuttle is required. If Concept 2 comes out of the trade-off, the attachment options will be explored more in detail and a selection between all options is performed in Chapter 4.

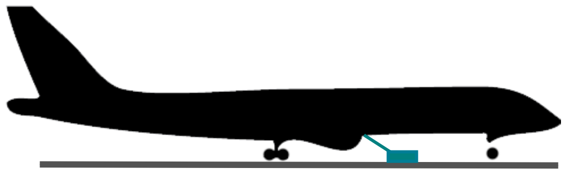


Figure 3-19: Option 3: Keel beam attachment

3-2-2 Airport and runway modifications

Runway layout

The size of the trough for the shuttle sliding in, determines whether the runway operations will be influenced by the presence of a launch system or not. The launch system is put in the centre of the runway. The aircraft will be attached to the shuttle at the centre of the track. It is important that the track width does not interfere with the aircraft tire thickness. The nose wheel tire thickness of the DC-9 equals 17cm [47] and this tire is considered to be one of the smallest tires of the aircraft selection. Therefore, it is assumed that a trough width of maximum 10cm will not hinder the wheels during operations on the runway. When the system is inactive, the runway can be used for landings. It is important that the shuttle size and the shuttle storage location on the track does not hinder approaching aircraft using this runway. The system can be installed on all runways of Schiphol airport, preferably on a runway with the North-South orientation since this is, in general, the main take-off direction. Perhaps the Zwanenburgbaan can be used, similar as in Concept 1, since it is the shortest runway in the North-South orientation.

The procedure aircraft follow, for going from the gate to the climb phase, is similar to the procedure followed in Concept 1 (Section 3-1-3). The main procedure difference between Concept 1 and Concept 2, is that in Concept 2 aircraft connect to a shuttle instead of rolling on a cart. The same operations flow chart of Concept 1 can be used for Concept 2 (see Figure 3-11), as long as the latter notes are taken into consideration. The airport area will look similar to the configuration shown in Figure 3-20. At the runway, a controller could be needed to secure the attachment of the aircraft with the shuttle.

3-3 Joint concept aspects

The main performance characteristics for the system to be determined are the maximum thrust to be delivered by the system, the maximum energy consumption, the take-off distance required for accelerations of $0.4g$ ($\approx 4\text{m/s}^2$) and $0.6g$ ($\approx 6\text{m/s}^2$) till the launch velocity is reached. The maximum launch velocity of the system is assumed to be 120m/s. In this way, high speed take off is possible for the selected range of aircraft. Aircraft usually take-off at velocities between 60 m/s and 85 m/s, dependent on the take-off weight and the head wind velocity. This statement is based on the take-off safety speed ($V_{2\,\text{min}}$) at maximum take-off weight of the Fokker-100 which equals 77 m/s [5] and $V_{2\,\text{min}}$ of the A320 equals 75 m/s [35]. At low take-off weights, this safety take-off speed equals 61m/s for the F-100 [5] and 62m/s for the A320 [35]. The maximum velocity of the Fokker-100, allowed by the landing gear to operate on, equals 103m/s [5]. Allowing a maximum

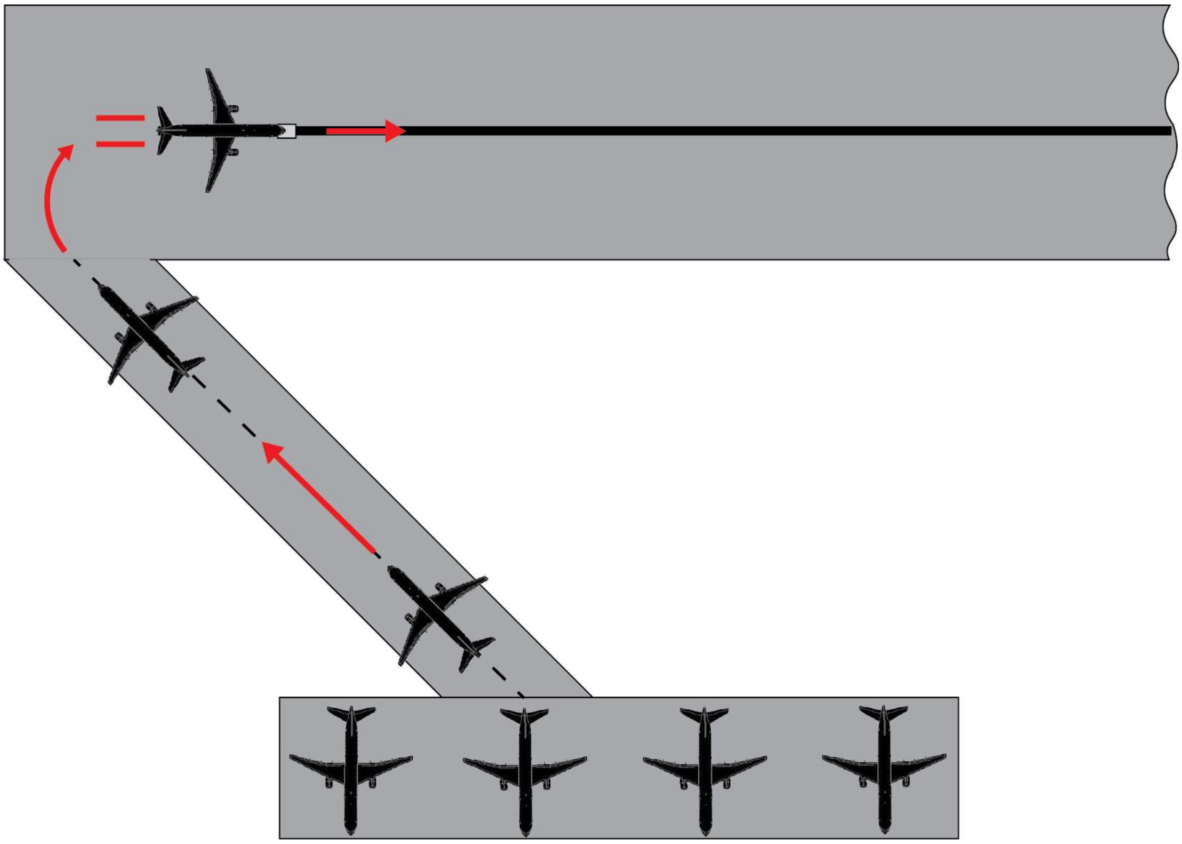


Figure 3-20: Concept 2: Airport operations layout

system's velocity of 120m/s, offers possibilities to perform high speed take-off's for a range of conventional aircraft.

The first concept implies a system on which the whole aircraft is mounted on a cart. It uses electromagnetic suspension (EMS) with a linear synchronous motor (LSM) for propulsion. The second concept connects the aircraft with the shuttle, either at the nose gear or at the keel beam. For further elaboration in this section, nose gear attachment is used. The shuttle is propelled by a linear synchronous motor. The LSM has been selected over the LIM as it has a higher power factor and higher energy efficiency, see Section 2-3. Both concepts are presented once more in Figure 3-2.

3-3-1 Performance parameters

The aircraft is considered as a point mass and the forces acting on the system during launch are presented in Figure 3-21 for both concepts, resulting in the following equations of motion for:

Concept 1 :

$$F_{\text{lev}} = \int_0^l f_{\text{lev}} dx \tag{3-3}$$

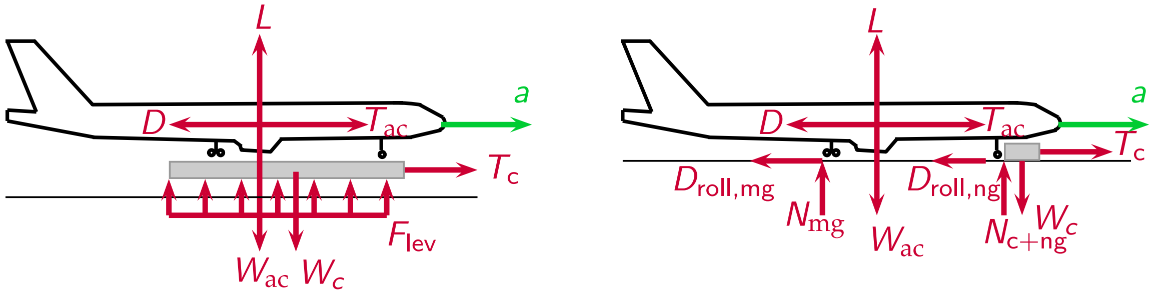


Figure 3-21: Forces acting on concept 1 (left) and concept 2 (right)

$$T_{ac} + T_c - D = (W_{ac} + W_c)/g \cdot a \tag{3-4}$$

$$F_{lev} + L - W_c - W_{ac} = 0 \tag{3-5}$$

T, D, W, F and L are expressed in Newton
where the lift $L = \frac{1}{2}\rho V^2 S C_{Lg}$ and the aerodynamic drag $D = \frac{1}{2}\rho V^2 S C_{Dg}$ with C_{Lg} and C_{Dg} being the lift and drag coefficient during ground operations before rotation (at α =0). W_{ac} is the aircraft weight at take-off, W_c the weight of the cart, a the acceleration, g the gravitational acceleration (=9.81m/s^2), and F_{lev} the resulting levitation force of the distributed load, as indicated in the figure.

Concept 2 :

$$T_{ac} + T_c - D - D_{roll} = (W_{ac} + W_c)/g \cdot a \tag{3-6}$$

$$N_{mg} + N_{ng} + N_c + L - W_c - W_{ac} = 0 \tag{3-7}$$

where the lift $L = \frac{1}{2}\rho V^2 S C_{Lg}$ and the aerodynamic drag $D = \frac{1}{2}\rho V^2 S C_{Dg}$ with C_{Dg} being the drag coefficient during ground operations before rotation (at α =0). The drag created due to rolling friction is represented by D_{roll} and is equal to the sum of all ground friction forces:

$$D_{roll} = D_{roll,mg} + D_{roll,ng} = \mu_r(N_{mg} + N_{c+ng}) = \mu_r(W_{ac} - L) \tag{3-8}$$

The aerodynamic drag force D of the system for Concept 1 and Concept 2 is assumed to be equal to the aerodynamic drag of the aircraft, thus it is assumed that the cart does not create additional aerodynamic drag. The friction coefficient of the aircraft wheels (μ_r) is assumed to be equal to 0.018 [48] and the friction coefficient of the cart has been neglected. At low speeds there is also always electromagnetic drag present, but for simplicity, it is neglected as the force is small [49].

Before examining the details on the two concepts, a summary of estimated values on the maximum performance parameters of the system is given. As the system needs to be designed for the a range of aircraft, the maximum values for thrust, energy, take-off distance are to be determined. The A321, being the heaviest aircraft in the range, is used to determine these values. The Fokker

100 is another aircraft that has been used for this analysis because specific data such as the lift and drag coefficients are known. As no specific data (lift and drag coefficients) is available on the A321, the calculations are very basic.

First, the maximum thrust to be delivered by the system is calculated. In order to calculate this, assumptions on the initial weight of the cart have to be made, in [31] a concept for space vehicle launch similar to Concept 1 is used, with the difference that a space vehicle instead of an aircraft is installed on the levitating platform. The weight of the levitating carrier is assumed to be half the weight of the vehicle [31], [33]. The weight of the carrier in Concept 1 equals 45ton. The weight of the shuttle for Concept 2 is estimated by [37], describing the design of EMALS, and equals 7% of the weight of the aircraft. The resulting cart weight equals almost 6 ton. The calculation of the maximum total thrust delivered by the system is a simplification from Equations 3-4 and 3-6 by assuming that the thrust delivered by the aircraft during take-off is equal to the drag created by the system. The thrust equation becomes:

$$T_c = (W_{ac} + W_c)/g \cdot a_{max} \tag{3-9}$$

where the maximum acceleration $a_{max} = 0.6g$. This results in a maximum thrust for Concept 1 of $786kN$ and for Concept 2 of $559kN$.

The maximum ground run distance is calculated by:

$$s_g = V_{max}^2/2a + \Delta t_{release} \cdot V_{max} \tag{3-10}$$

The take-off distance is larger for lower accelerations thus s_g is calculated for $a = 0.4g$ and a maximum velocity of $120m/s$. A 5 seconds release time ($\Delta t_{release}$) for the aircraft to unlock from the system is taken into consideration as well. This results in a runway length of 2435m for both concepts. If this time is not considered a distance of 1835m would be required.

The total energy required by the system for propulsion can be obtained by [50]:

$$E_{prop} = \int_0^{s_g} (T_c) ds = T_c \cdot s_g \tag{3-11}$$

When operating a system, there is always energy loss, an efficiency factor of 50% has been assumed [31]. Per launch of the A321 at a launch velocity of 120m/s and with an acceleration of 0.6g, 1.92GJ is consumed by Concept 1 and 1.37GJ by Concept 2.

3-3-2 Annual energy consumption

It is highly desirable for an airport to get an estimation of the annual energy requirements. To determine the maximum annual energy consumption for this system at Schiphol Airport, first, the total number of movements (departures and landings) needs to be determined. From [51] it can be found that Schiphol Airport has about 465,000 movements per year. From these movements per year there are about 46,500 departures per runway per year of which 80% is performed by the range of aircraft selected for this project [52] and results in about 37,200 departures per runway per year. The annual energy consumption of the launch system can be estimated. In Table 3-5 an overview is given for different energy requirements dependent on the aircraft performing the system launches. For lower accelerations and lower launch velocities, the energy requirements are lower. The first energy values in Table 3-5 are calculated for the Fokker-100 and for the Airbus

Table 3-5: Annual system's energy consumption

V_{launch}=102m/s	MTOW [kg]	Acceleration	Annual Energy Req. [GWh]	
			Concept 1	Concept 2
F100	44,455	0.4g	9.69	5.7
departures		0.6g	9.69	5.7
A321	89,000	0.4g	14.35	10.21
departures		0.6g	14.35	10.21
V_{launch}=120m/s				
A321	89,000	0.4g	19.86	14.13
departures		0.6g	19.86	14.13

A-321 with a launch velocity of 102m/s. This velocity represents the maximum allowable velocity of the Fokker-100. The second part of Table 3-5 gives energy values for the A321 launched with the maximum system's velocity of 120m/s. This is done to give an indication of the annual power consumption at higher speed launches. The energy values have been calculated with a system's efficiency of 50% [31]. In case the Fokker-100 is launched at its conventional lift-off velocity (75m/s), dependent on the acceleration and the concept that has been used, an annual energy consumption between 2.9 and 5.2 GWh is required. The values given in Table 3-5 are estimates of the maximum system energy requirements, this means that idle thrust settings are used for the Fokker 100. In case the Fokker would be launched with normal take-off thrust settings, the annual energy consumption of the system reduces to 7.3GWh for Concept 1 and to 3.3GWh for Concept 2.

The most energy consuming scenario holds launching mainly A321s at a velocity of 120m/s independent on the acceleration used, see Table 3-5. The difference between launches of 0.4g and 0.6g is that more power needs to be fed to the track over a shorter time duration. This annual energy requirement of 19.9GWh can be achieved by 3 Vestas 3.0MW wind turbines. One of these wind turbines delivers annually between 7.6 GWh to 14.5 GWh, dependent on the wind velocity [53]. The lowest energy requirement of 5.7GWh only requires 1 Vestas 3.0MW wind turbine. The 3.0MW Vestas wind turbines are currently the largest on-shore Vestas wind turbines available, with a blade length of 54.65m. To give another comparison on the power consumption of the system, the nuclear power plant in Borssele produces an annual energy amount of about 4TWh [54], about 0.14% to 0.5% of this amount of energy will be consumed by the launch system. The amount of power required can also be compared to a normal Dutch household of five persons. Such a family typically consumes about 5282kWh/year, the largest launch system's energy value (19.86GWh/y) corresponds to the energy consumption of about 3761 Dutch households with five persons annually [55].

3-3-3 Runway and airport changes

Runway implementation

A difficulty with the implementation of the launch system is that not all aircraft can make use of the system. For air traffic control this adds complexity to the work, as not all aircraft performing a take-off on a runway will follow the same procedure. This does not mean that the runway cannot function at the same time as a conventional one for large aircraft, and as a launch system for smaller ones. Currently, at Schiphol Airport, during peak hours either two runways for landing and one for departures are used, or visa versa. Off-peak hours, a runway for landings and one for departures are used [56]. When the system is implemented at Schiphol, the airport can decide to either use a specific runway for only launches, another runway will be used to facilitate take-offs for larger aircraft. A second option is to use one runway which facilitates launches and conventional departures. A consequence of option 1 is that always two runways have to be used for departures of small and large aircraft. Option 2 results in different procedures (for launches and conventional departures) to be followed for different aircraft on the same runway. It can be investigated what the opinion is of people working in air traffic control for handling the system (and the sequence of departing aircraft).

Runway maintenance

Both concepts require a clean runway, free from filth and rubbish. The trough needs to be free from dirt. Regular cleaning of the track is recommended and special attention can be put on this aspect while designing the trough. Additionally, the track should also be designed to minimize the electromagnetic interference with flight instruments located above the launch motor. There is a possibility that shielding of the avionics is required on the aircraft.

Airport changes

For implementation of the system, many things in an airport can be changed. One of them is the additional electricity provision to power the launch system. It is preferred that the airport possesses its own energy producing facility as it does not want to be dependent on the regular power grid.

In case of power failure of the regular power grid, it is highly desirable that the airport manages its own energy facilities. If power is generated somewhere, not necessarily at the airport, the airport needs to have power storage facilities, to have a continuous energy flow to power the system. These power storage facilities need to be able to release a large amount of energy per launch in a very short amount of time. This energy will be transported to the launch system with very high performance electricity cables. Flywheels can be used for power storage systems. They store energy in a rotating mass and their energy capacity is limited to the mass and the form of the rotor and its rotational speed. The flywheel is sped up by an accelerating torque, storing energy, by slowing a flywheel down, it regenerates energy. Flywheels are often used in applications requiring the flywheel to charge and discharge at high rates for many cycles [57]. They can spin up in between launches. Flywheels are used in large energy producing facilities for energy storage, like in the ITER, a nuclear 500MW fusion project [58]. Flywheel disk alternators are also used in EMALS for energy storage [29]. The airport will need space to install these systems.

3-3-4 Concept comparison

In this section, a trade-off is performed among different criteria like performance, cart design, electrical systems, airport and runway modifications.

The numbers used in the trade-off Table 3-6 are derived for an A321 launch with an acceleration of 0.6g to the maximum launch velocity (120m/s). The values from Concept 1 are compared to the results from Concept 2. For performance (energy and thrust) it can be seen that Concept 1 consumes 29% more energy compared to Concept 2, see Table 3-6. This is mainly due to the increase cart weight and the required levitation energy. For EMS, it is assumed that 1kW per ton of lift of continuous energy is consumed by the system for levitation [41]. A total amount of levitation energy consumed per launch equals 2.72MJ, for a launch velocity of 120m/s with 0.6g. However, the energy consumed in Concept 1 for propulsion is roughly 500 times larger than the energy consumed for levitation. It can be concluded that the cart weight has a substantial influence on the energy consumption. Since the cart of Concept 1 weights almost 8 times more than the cart of Concept 2. The energy consumption is signifficantly higher in Concept 1. When launching smaller aircraft than the A321, the take-off weight is reduced but the cart weight is constant. The differences in energy consumption between both concepts will be influenced even more by the cart weight. For the Fokker 100, Concept 2 consumes 43% less of the total amount of energy compared to Concept 1.

The attachment of the landing gear to the cart is easier in Concept 1 when main gear attachment is opted for. Panels can be used to lock the main gear to the cart, no attachment point needs to be searched for on the gear itself. It has been determined that the main gear should be able to withstand the launch forces for both accelerations 0.4g and 0.6g. However, at an acceleration of 0.6g, the thrust force approaches the peak design loads. For attachment of the shuttle in Concept 2, an attachment point on the nose gear or on the keel beam needs to be installed, or a launch bar should be mounted on the nose gear which attaches with the shuttle. Nose gear attachment requires a new reinforced nose gear, as current nose gears are not able to withstand the thrust forces (for 0.4g and 0.6g) generated by the system. For keel beam attachment, a suited attachment location needs to be found but in general, it should be able to withstand the launch forces.

Comparing the electromagnetic area that is required for Concept 1 and Concept 2, the latter needs 29% less area for propulsion magnets and because suspension and guidance systems are substituted by wheels, electromagnets for levitation and guidance are not needed in Concept 2. This reduces the energy transfer amount to the cart.

Concept 2 needs less electric systems for the launch system to operate. The control system of Concept 2 is less complex as for Concept 1 because guidance and suspension systems are substituted by wheels, the control system only needs to control the shuttle for propulsion.

Comparing the runway modifications needed for Concept 1 and Concept 2, one can conclude that the runway needs to be broken open to install the launch system for both concepts. Concept 1 will require two troughs, as can be seen in Figure 3-10 while Concept 2 only needs one, see Figure 3-20. A ramp needs to be provided for Concept 1 to assist aircraft rolling on the platform which is installed above the runway surface (see Figure 3-4). In case the size of the track of Concept 1 (13m x 2600m), would take too much space, widening of the runway could be an option. The changes in ground operation procedures are similar for both concepts except for the system connection. In Concept 1, the aircraft rolls on the platform by assistance of a ramp and in Concept 2, the aircraft is connected to the shuttle.

At the airport, more power storage is required for Concept 1 than for Concept 2. An increased power storage capacity of roughly 6GWh/y is required by Concept 1 additional to the 14GWh/y requirement of Concept 2.

From these tables, it can be concluded that overall, Concept 2 is more promising than Concept 1. Concept 2 has been selected to be elaborated more in detail which will be discussed in the next chapter.

Table 3-6: Concept trade-off

A321: V_{launch} = 120m/s & a=0.6g				
Criteria		**Concept 1**	**Concept 2**	$\frac{C1-C2}{C1}$ **[%]**
Performance	Total T [kN]	786	559	-29%
	Cart weight [kN]	436	58	-87%
Energy requirements	Per launch (excl. levitation) [MJ]	1,922	1,367	-29%
	Levitation energy per launch [MJ]	2.7	–	–
	Total energy per launch [MJ]	1,925	1,367	-29%
	Annual (prop.+lev.) [GWh]	20 (=72TJ)	14 (=51TJ)	-29%
EM magnetic area	Levitation [m^2]	3.27	–	–
	Propulsion (0.6g) [m^2]	1.96	1.40	-29%
	Levitation + propulsion area [m^2]	5.24	1.40	-73%
Attachment	Ease of attachment	Universal attachment, no LG adaptations	Make attachment point on nose gear or keel beam	
	Structural reinforcements	No main gear reinforcement	New reinforced nose gear Or no keel beam reinforcement	
Electric systems	Levitation system	Yes	No (wheels)	
	Propulsion system	Yes	Yes	
	Guidance system	Yes	No (wheels)	
	Linear Induction Power	Yes	Yes	
	Control system	Sophisticated	Simple	
	Magnets	Yes	Yes	
Runway modifications	Runway space by system required	13 x 2600m	1 x 2600m	
	Amount of troughs	2	1	
	Location launch system	Side of runway	Centre of runway	
	Widening of runway required	Maybe	No	
	Cleaning	Yes	Yes	
	Ramp required	Yes	No	
Airport modifications	Power storage systems	5.77GWh/y more power storage (Concept 1) compared to Concept 2		
	No changes between both concepts for:			
		Operations		

Chapter 4

Elaboration of the concept launch system

Concept 2 has been selected for elaboration from the trade-off in Section 3-3-4 and will be referred to from now on as "the concept" or as the "launch system". This concept consists of a linear motor for acceleration and deceleration. The aircraft will be connected and propelled by a launcher, supported by its own landing gear. Wheels are mounted on the cart for support and guidance along the track.

First, the changes in performance will be elaborated, then the attachment possibilities and required structural reinforcements will be explained to arrive at the final launch system design.

4-1 Performance Analysis

Since the length of the runway is fixed and the system will be implemented on the runway, the accelerations of the system can depend on the length of the runway and the desired launch velocity. This results in a decrease of the previously defined accelerations, 0.4g and 0.6g, to lower accelerations of 0.2g and 0.24g. The Zwanenburg runway is used as an example for the implementation of the system and has a total length of 3300m. 2900m is selected as the effective launch stroke length, the remaining 400m can be used for the deceleration of the shuttle and as a safety margin. The release time to unlock the aircraft with the system is reduced to 2 seconds. Table 4-1 gives values for the launch load with the mean acceleration based on the launch velocity

Table 4-1: Launch loads [kN] exerted on aircraft

Launch load [kN]	Acc. = 0.2g	Acc. = 0.24g	Acc. = 0.4g	Acc. = 0.6g
F100	97.23	120.31	214.94	313.77
A321	183.18	226.66	372.39	558.59

and the track length. The first acceleration (0.2g) reaches a launch velocity of 102m/s, the second one (0.24g) a launch velocity of 113m/s. These launch velocities stand for the maximum velocity allowed by the landing gear of the F100 (102m/s) and of the A321 (113m/s). Since the A321, the largest aircraft of the launcher aircraft selection, cannot be accelerated to a velocity larger than 113m/s, it has been decided to reduce the maximum launch velocity from 120m/s to 113m/s. The accelerations on the right-hand side of Table 4-1 are given for comparison of the current launch loads with the higher acceleration launch loads (see Chapter 3). It can be seen that the launch loads are reduced with a factor 2 or 3 compared to the previous ones. This means that the structure probably needs less reinforcement as the load cases are reduced.

These structural reinforcements will be elaborated later in this chapter. Now the worst-case scenarios are described as they influence the operability and functionalities of the launcher.

4-1-1 Worst-case scenarios

Worst case scenarios influence the operations of aircraft and the functionality of the system. It is important to find out what possibly can go wrong when launching aircraft with this system. Different scenarios of failures during operation of the system are considered and what should happen to prevent the failures from ending in an incident. Possible scenarios during take-off for example are: the connection breaks between the aircraft and shuttle, the aircraft has an engine failure, or the catapult cannot deliver full power. The most characteristic scenarios happening while the system is operating at a certain velocity V are given in the worst case scenario diagram, Figure 4-1. Because of safety considerations, it is decided that the launch system will only be

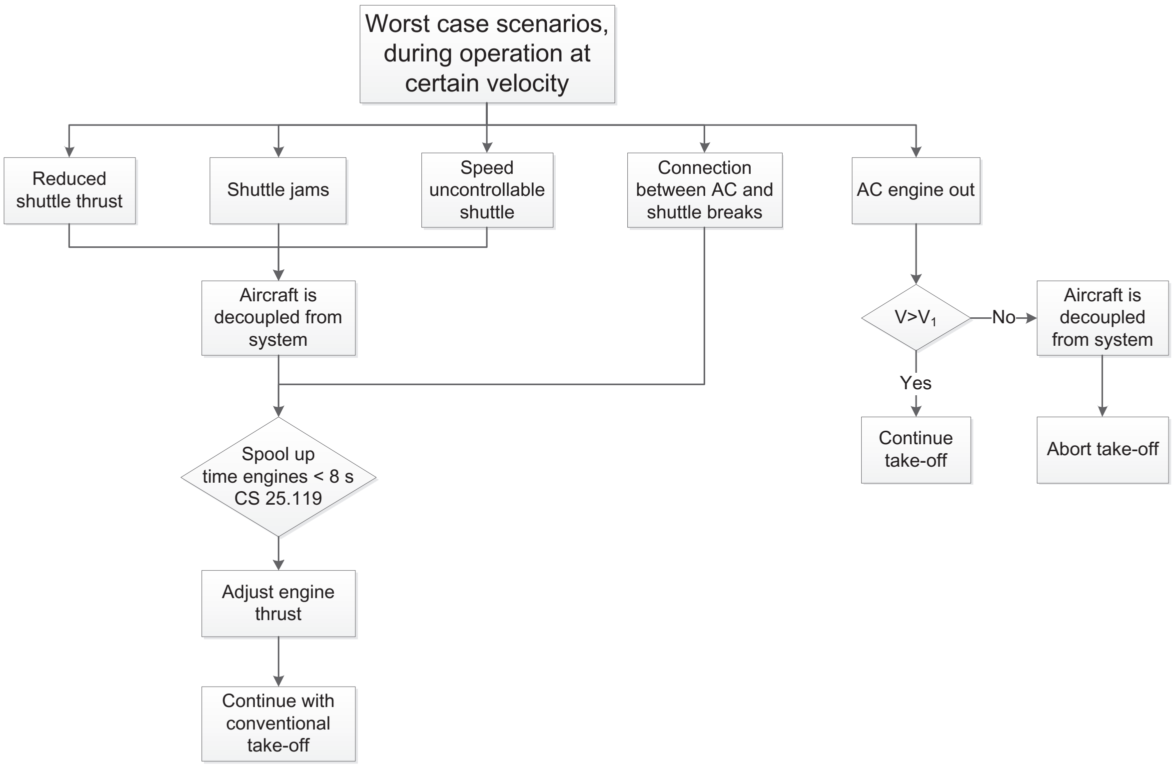


Figure 4-1: Worst case scenarios

used to accelerate aircraft and not decelerate them. If a problem occurs, the aircraft is decoupled and the pilot has control. By using the launch system only for acceleration, the loads acting on the aircraft are minimized. The design of the decoupling system can be kept simple as the launch load is only acting in one direction (the acceleration direction). In this case, not a lot of changes occur to the procedures of the pilot.

The spool up time, given in Figure 4-1, defines the amount of time for the engines needed to go from idle operation to full thrust operation. It has been defined in CS 25.119, that no engine can take longer than 8 seconds to achieve full thrust. When examining the aircraft selection, no aircraft has a take-off distance longer than 2200m [59], and most of the aircraft are able to take off within a distance of 2000m. In case of failure, except for engine failure with aborted take-off (see Figure 4-1), an aircraft needs to take-off within a maximum take-off distance of 3300m. In the next section it has been verified for the different failure cases if it is possible for an aircraft to continue the take-off when at a random velocity the failure occurs .

Continued take-off analysis after decoupling with the launcher

Before the failure occurs, the aircraft is coupled to the system, operating with reduced thrust settings. At an instant velocity, one of the four first-mentioned failures of Figure 4-1 occurs. The aircraft is decoupled and needs a maximum of 8 seconds to achieve full thrust. Then it is able to continue the take-off with full thrust to achieve the lift-off velocity at the end of the runway. The total take-off distance travelled (s_{total}), indicated in green '+' in Figure 4-2, is a summation of the distances travelled by the aircraft at the instant velocity at which the failure occurs. These distances are: the shuttle distant, spool-up distance and aircraft continued take-off distance. The first distance travelled (indicated in red), is the distance before the failure occurred ($s_{\text{AC+shuttle}}$), the aircraft and shuttle are coupled and are accelerated by the system's acceleration. The second distance (indicated in turquoise), is the distance when the aircraft is decoupled from the system and the aircraft's thrust is changed to full thrust ($s_{\text{spool-up}}$). During the spool-up event, it is assumed that the aircraft keeps it current velocity. The last distance travelled (indicated in purple), holds the distance to be travelled by the aircraft to achieve the lift-off velocity ($s_{\text{AC,cont.}}$). A visualization of each distance segment is given in Figure 4-2 with the summation of these distances given in s_{total}. If a failure occurs for example at 30m/s, it has already travelled the distance $s_{\text{AC+shuttle}}$, at this velocity a spool-up distance ($s_{\text{spool-up}}$) and a distance travelled by the aircraft to achieve the lift-off velocity ($s_{\text{AC,cont.}}$) are added. The maximum runway take-off distance ($s_{\text{TO,max}}$) of 3300m has been indicated in blue in Figure 4-2 as well.

In the analysis, a lift-off velocity of 90m/s has been assumed, which is beyond the 'conventional' lift-off velocity of the A321 and F100 (about 75m/s) [35], [5]. The system's mean acceleration (aircraft and shuttle coupled) yields 0.2g and the mean aircraft acceleration to the lift-off velocity has been assumed equal to 0.15g. The mean acceleration during take-off run of the F100 equals 0.2g [5]. For the engine spool-up event, it has been assumed that 8 seconds are needed to bring the engines to full thrust and during this event, the velocity is kept constant for simplicity. In reality, a decrease in velocity will be experienced by the aircraft due the temporary absence of thrust and to the aerodynamic and rolling friction drag. This decrease in velocity is assumed to have a minor effect on the required take-off distance. The travelled distance $s_{\text{spool-up}}$ is calculated by multiplying the instant velocity at which the failure occurs with the spool-up time. To calculate the travelled distance s travelled by the aircraft and the system, the equation $s = 1/2V^2/a$ is used, where a and V are the acceleration and the instant velocity. From these assumptions and the analysis of Figure 4-2, it can be stated that all aircraft should be able to continue the take-off when decoupled from the system at any velocity, except for the engine failure case. This reduces the need for a decision velocity requirement to decide whether to continue or abort the take-off, since continued take-off is always possible.

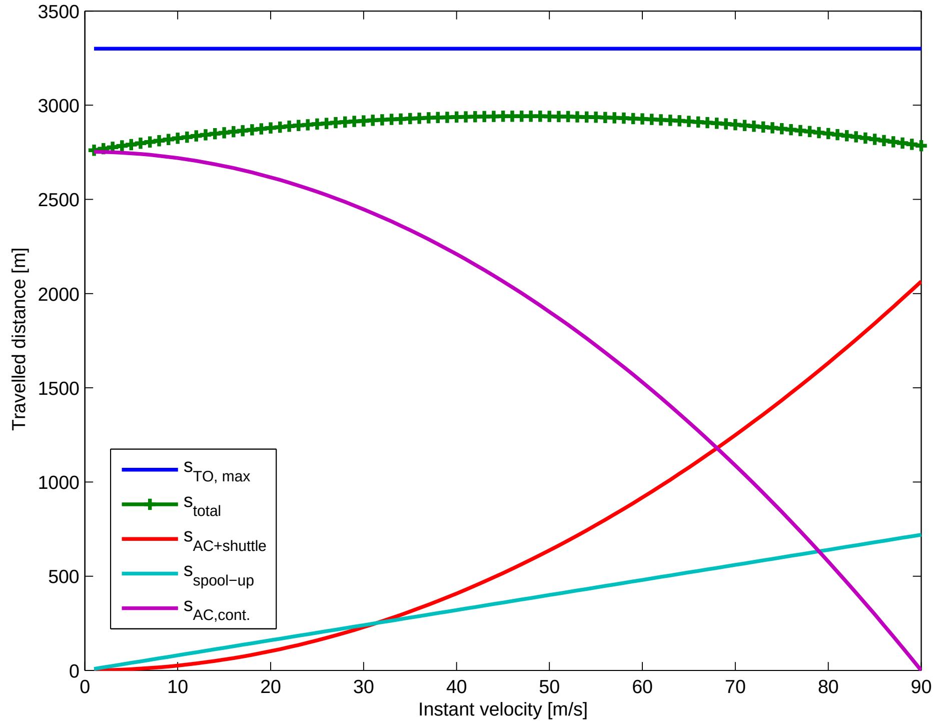


Figure 4-2: Continued take-off distance with spool-up time delay

Discussion of the different failures

Since the spool-up time event has been clarified, the different failures given in Figure 4-1 can be discussed more in detail.

Reduced shuttle thrust: A sensor needs to be installed on the system to notice this problem. In case it happens, the aircraft is decoupled and the shuttle is brought to a standstill. The engine thrust is adjusted and the pilot continues with a conventional take-off.

Shuttle jams: In this case, the same procedure can be followed as in the reduced shuttle thrust case, with the only difference that the shuttle's velocity is already zero, and does not need to be decelerated. The aircraft is decoupled from the system. This is realized by making the connection between the shuttle and the aircraft easy to decouple, which will be elucidated later in this chapter.

Connection between aircraft and shuttle breaks: If the connection breaks between the aircraft and the shuttle, it should be a clean break such that no damage to the aircraft is triggered.

Shuttle velocity becomes uncontrollable: When the velocity of the shuttle becomes uncontrollable, the control system of the launcher should shut down the shuttle's operation and the aircraft is decoupled from the launcher. The control of the track should be fully redundant. Since the track is divided in different sections, each section can be controlled separately. The control system activates the different sections and can reverse the direction to slow down the shuttle to a standstill. A control system should check all parameters of the system.

Aircraft engine fails: In a conventional take-off scenario, the pilot has the possibility to abort or continue the take-off in case of an engine failure. When this happens and the velocity of the aircraft has exceeded the decision speed V_1, continued take-off is performed as the remaining runway distance is too short for the required braking distance. When the launcher is used for departures, the same criteria count. In case an engine failure occurs and braking is possible, V_1 is not reached, it is preferred to brake instead of accelerating with one engine out, perform a climb and return to the airport. Thus, when this happens and the instant velocity is smaller than V_1, the aircraft is decoupled from the shuttle and starts braking on its own. In case the aircraft's velocity is beyond the decision speed, the aircraft is accelerated till the launch velocity is reached and performs the take-off. A signal should be send to the launcher when the pilot hits the brakes to abort the take-off. The shuttle should start braking immediately.

The final design should facilitate safe operation during a worst-case scenario. Since an aircraft can only be accelerated by the launcher, when decoupled, the pilot has control as in conventional operations. Decoupling should be simple and reliable. These criteria will influence the operations and the functionality of the launcher.

4-1-2 Annual energy consumption - Refined analysis

In the previous chapter, the annual energy consumption for Fokker-100 departures and A321 departures with the launch system have been determined in Table 3-5 for accelerations 0.4g and 0.6g. Since the acceleration rates are decreased to 0.2g and 0.24g, a refined estimation of the annual energy consumption for the aircraft selection using the launcher for departures at Schiphol Airport. One of the conclusions coming out of Table 3-5 is, the higher the acceleration, the more energy that is consumed by the system.

The amount of energy consumed by the system depends on which aircraft is accelerated. The different take-off weights vary the total system energy consumption. Therefore, to make a more accurate analysis on energy consumption of the system, it has to be determined how many different aircraft depart from Schiphol each day. This information can be obtained from the operational plan of Schiphol Airport which states the number of departures and landings of different aircraft during an entire year [6]. In this report, aircraft are put in matching aircraft categories based on noise production and maximum take-off weight. The aircraft given in Table 4-2, represent each a different category. As an example, the A320 will probably find itself in the B737-300 category. These aircraft have been used to calculate the amount of energy required per launch and to give a better insight in the prediction of the annual energy requirements for launching aircraft.

Table 4-2 gives the maximum take off weight per aircraft category, the amount of starts it performs per runway and the amount of energy required, per launch and on an annual basis. The numbers are obtained for two different mean accelerations, 0.2g reaching an end velocity of 102m/s and 0.24g with an end velocity of 113m/s. These higher launch velocities are chosen, over the 'conventional' lift-off velocities of about 75m/s, to give the aircraft a higher amount of kinetic energy at the start of its climb. The kinetic energy is converted in potential energy, such that the aircraft can reach a higher altitude sooner. Faster climbing results in a lower noise spread audible to the ground, since the amount of time for the noise to spread is shorter as the cruising altitude is reached sooner.

The aircraft indicated in *italic* belong to the aircraft selection suited for the launch system. These aircraft represent 81% of all starts performed at Schiphol Airport [6]. The total annual energy required for a mean acceleration of 0.2g yields 6,703MWh and for a mean acceleration of 0.24g, 8,295MWh for the *aircraft selection*.

The annual energy requirement of 6,703MWh corresponds to the annual wind energy production of one Vestas 3.0MW wind turbine. These wind turbines are the largest Vestas onshore wind turbines available at this moment, with a blade length of 54.65m [53]. For the higher energy launch requirement of 8,295MWh, two Vestas 3.0MW wind turbines are required. Installing smaller wind turbines is possible as well, the amount of wind turbines needed increases with smaller size wind turbines. The energy launch requirement numbers are also representative for the annual energy demand for 1269 and 1570 Dutch five person households [55].

Table 4-2: Refined launch energy requirements for departures at Schiphol Airport

	MTOW [kg]	Total starts per runway	Energy per launch [MJ]		Annual energy [MWh]	
			Acceleration:		*Acceleration:*	
			0.2g	0.24g	0.2g	0.24g
F100	*44,455*	*899*	*564*	*698*	*141*	*174*
F70	*36,740*	*5,830*	*478*	*591*	*773*	*957*
Bae-146-200	*42,184*	-	*538*	*666*		-
B737-300	*62,800*	*27,016*	*769*	*952*	*5,773*	*7,143*
MD-90	*70,760*	*69*	*858*	*1,062*	*17*	*20*
A310	142,000	185	1,656	2,049	85	105
B757-200	99,790	315	1,183	1,464	103	128
B767-300	185,065	1,286	2,138	2,645	763	945
DC10	259,450	1,869	2,970	3,675	1,542	1,908
B777-200	347,815	1,800	3,959	4,899	1,979	2,449
B747-300	351,535	42	4,001	4,950	47	58
B747-400	362,875	2,347	4,127	5,107	2,690	3,329
Total		41,657			*6,703*	*8,295*

A comment is made on the selection of the launch velocities, 102m/s and 113m/s. These velocities are based on the maximal allowed landing gear extension speed of the F-100 and the A321 respectively. However, the maximal allowed tire speed is not considered. For the A320, this velocity equals 100m/s [60]. Other aircraft might have different tire speed limitations. Either, it can be chosen to reduce the launch velocity to the maximum tire velocity, or the wheel design of the specific aircraft should be reconsidered and the influence it has on the total landing gear, if launches beyond the maximum tire velocity are desired. This latter option requires additional research.

4-2 Attachment possibilities

The selected concept makes use of either nose gear attachment or keel beam attachment. The reduced accelerations, that have been established at the beginning of this chapter, lead to lower launch forces. However, a decisive answer needs to be given whether the attachment options can cope with these launch forces. First, the possibilities for nose gear attachment are analysed, followed by the keel beam attachment possibilities (Section 4-2-3).

4-2-1 Landing gear investigation

Both aircraft, the A321 and F-100, have a tricycle retractable landing gear. It can be assumed that all aircraft of the aircraft selection have a tricycle retractable landing gear. Conventional landing gears are capable of absorbing landing and taxi loads, and transmit part of these loads to the airframe. They are designed to withstand different loads namely, vertical loads (touch down), longitudinal loads (spin up, braking and rolling friction loads), and lateral loads (cross-wind taxiing, ground turning). A conventional nose gear is designed to resist towing forces and landing loads and facilitate steering, as described in Section 3-1-2.

The launch forces act in longitudinal direction and have to be guided through the nose gear into the airframe. The maximum longitudinal nose gear force the A321 can withstand, results from the allowed towing load and equals 132kN (see Section 3-1-2, Table 3-3). Comparing this force to the newly determined launch forces given in Table 4-1 (183 kN and 227kN resp.), it can be concluded that the nose gear is not designed to cope with these launch forces. A structural reinforced nose gear will be needed when applying the launch load to this part of the aircraft. Different parts of the nose gear need to be reinforced. The main component guiding through these longitudinal loads, is the drag brace. The resulting forces transferred by the nose gear to the airframe are illustrated in Figure 4-4b. Additionally, a location for attachment of the launch bar on the nose gear should be searched.

Figure 4-3: Different nose gears

Different nose gears are shown in Figure 4-3, for some aircraft the orientation of the drag brace is not visible, like for the Fokker 100 and the BAe-146 due to panels restricting the view. It can be noted that the A320, the B-737 and the MD-87 all have a drag brace oriented towards the nose. However, the orientation is not similar for all aircraft. The Cessna Citation, which actually does not belong in the aircraft selection, has a drag brace orientation to the rear of the aircraft. This aircraft is added to the selection of aircraft in Figure 4-3 to illustrate the possibility of drag braces with an opposite orientation. Therefore, it cannot be stated that all drag braces of different aircraft run in forward direction (toward the nose). For the force calculations, in Section 4-2-2, the A321 has been used which has a forward drag brace. When the launcher is connected to the nose gear, the drag brace experiences a compression load.

4-2-2 Nose gear reinforcement

Landing gears consist of different components and materials, tires, shock absorbers, braces, wheel housings, shock absorber housing, etc. The braces are fabricated from high strength materials. The material selection for landing gears are based on the following material properties: strength, stiffness, and heat resistance and on the purpose or mission of the aircraft [43]. It is not known out of which material a conventional drag brace consists but for the next analysis Ferrium 53S alloy has been used. This alloy is a ultra high-strength corrosion-resistant alloy which is used on landing gear components [2]. It has similar properties as the high strength steel 300M alloy which has little corrosive resistance but high strength [2]. Since a compression load will be exerted on the drag brace by the launch system, a buckling analysis is performed. Physical properties of the Ferrium 53S alloy are given in Table 4-3.

Table 4-3: Ferrium 53S physical properties[2]

	Density [g/cm^3]	Modulus of Elasticity [GPa]	Yield strength [MPa]
Ferrium 53S	7.98	204	1469

For the analysis, it is assumed that the drag brace is a simple column. The smallest value of buckling load is given by the next equation [61]:

$$F_{\mathrm{CR}} = \frac{\pi^2 EI}{l^2} \tag{4-1}$$

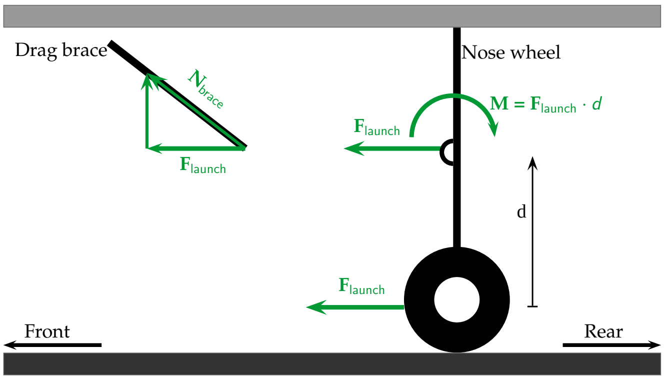
where EI is the flexural rigidity and l the length of the column. A safety factor of 1.5 has been assumed in the determination of the dimensions of the drag brace. The analysis has been performed for the A321. The length of the brace is assumed to be equal to 1.5 meters. The data given in Table 4-4 has been determined by using Equation 4-1 and substituting the critical buckling load with the load for towing and launching with acceleration 0.2g and 0.24g multiplied by the safety factor. The material properties of Ferrium 53S have been used in the determination of the radius and the required thickness. To give an example for comparing the drag brace changes associated with the different applied forces, a radius of 5cm has been chosen and the matching thickness is given in Table 4-4. It can be noted that the weight of the brace almost doubles when applying the largest launch load. These data are only given to have an idea on the required changes of the drag brace. It is possible that the drag brace consists of a different material, and for the redesign of the nose gear, more design analysis are required than a single buckling analysis.

Table 4-4: Drag brace redesign A321

Safety Factor =1.5	Normal force [kN]	Radius [cm]	Thickness [mm]	Weight [kg]
F_{tow}	186	5	1.6	5.9
F (a=0.2g)	259	5	2.2	8.1
F (a=0.24g)	321	5	2.7	10

Since the drag brace guides the launch forces through the aircraft structure (illustrated in Figure 4-4b), this means that the area where the drag brace ends near the fuselage needs reinforcement as well. Figure 4-4b gives the decomposition of the forces and moments resulting from the launch force applied at the nose wheel. Figure 4-4a shows an actual nose gear for comparison with Figure 4-4b. The launch load (F_{launch}) acting in longitudinal direction is taken on by the nose gear, transferred in the drag brace (N_{brace}). The surrounding airframe structure takes on the launch force coming out of the drag brace and distributes it among the airframe. Since the drag brace is not designed on the launch loads, the nose gear surrounding structure might fail at taking on and distributing the launch loads which might result in necessary reinforcements of the surrounding nose gear airframe structure. Additionally, a bending moment results on the nose strut where the drag brace departs, as a result of the applied launch force. Therefore it has been chosen to investigate if other attachment locations on the aircraft are possible which need less aircraft modifications.

(a) Nose gear of A320



(b) Force decomposition

Figure 4-4: Nose gear

4-2-3 Keel beam attachment

The keelbeam area has been selected as alternative attachment location for the nose gear attachment. It is located at the wing box and is the most reinforced part of the fuselage. It should be able to take on the launch force and guide it trough the airframe without requiring additional reinforcements. The keel beam can be found where the fuselage is cut up by the wheel wells at the lower part of the fuselage, shown in Figure 4-5. Its function is to carry the fuselage bending loads [10]. In order to use the keel beam as an attachment point, it should be found out what the size of a keel beam is and if it extends to the most forward centre of gravity for stability issues.

First an approximation for the location of the most forward centre of gravity (c.g.) needs to be

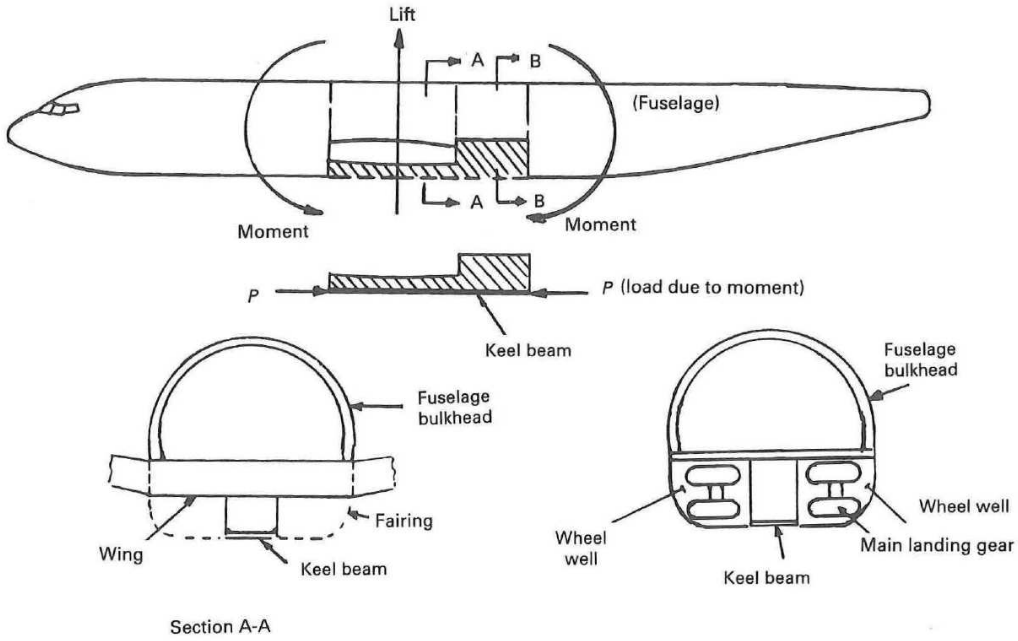
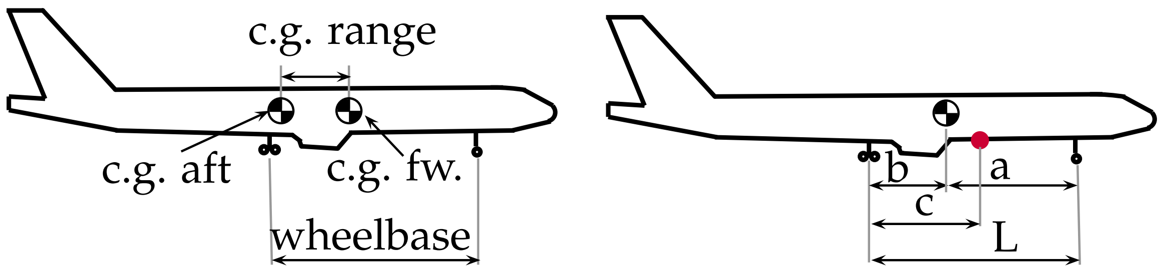


Figure 4-5: Keel beam location [62]

found. Since the location of the c.g. is not fixed, a maximum range between the most forward and most aft c.g. location for each aircraft exists. The c.g. range is determined by the length between the main gear and the c.g., indicated by *b* in Figure 4-6. In extreme cases, the distance *b* in Figure 4-6 varies, in longitudinal direction and static condition, between 6% to 20% of the wheelbase length [9]. Preferably, *b* varies between 8% and 15% of the wheelbase length [9]. In Figure 4-6, *a* represents the distance between the nose gear and the c.g. location in longitudinal direction. In order to attach the aircraft always in front of the most forward c.g., the attachment point should be located at a distance *c* of more than 20% of the wheel base length.

The more forward the attachment point is chosen on the aircraft, the more directional stability is achieved when launching the aircraft. It is higly desirable, that during the launch, the centre of gravity has little deviation with the centreline of the track. The more forward the attachment point is positioned, the more influence on the centre of gravity of the aircraft can be performed by the launcher. When the aircraft deviates from the track, the moment created by the launcher on the c.g. of the aircraft increases as the distance between the attachment and the c.g. of the aircraft in forward direction increases. The launcher has more influence on the direction of the aircraft and can pull the aircraft towards the centreline of the track in case it deviates. This action becomes less effective the closer the attachment point is situated near the c.g. of the aircraft and becomes unstable when it is located behind the c.g. Therefore, the most forward possible attachment point should be selected. Because in this case it is unknown where this suited point finds itself, the attachment is located at a distance *c* of 25% of the wheelbase length, in front of the most forward centre of gravity, indicated by Figure 4-6.

The length of the keel beam of the A350 equals 16.6m, which represents nearly 30% of the overall length of the A350 (60.5m) [63]. It should be determined if the attachment at distance *c* at the keel beam is possible. If it is assumed that, in general, the size of keel beams is scalable and accounts for roughly 30% of the total length of the aircraft and the location of the keel beam is at the main gear. It is assumed that the keel beam extends to the attachment point at distance c. In case the keel beam would extend more forward than the chosen attachment location, it is advised to move the attachment point to the most forward possible location.



(a) Centre of gravity range **(b)** Distances from landing gear to centre of gravity

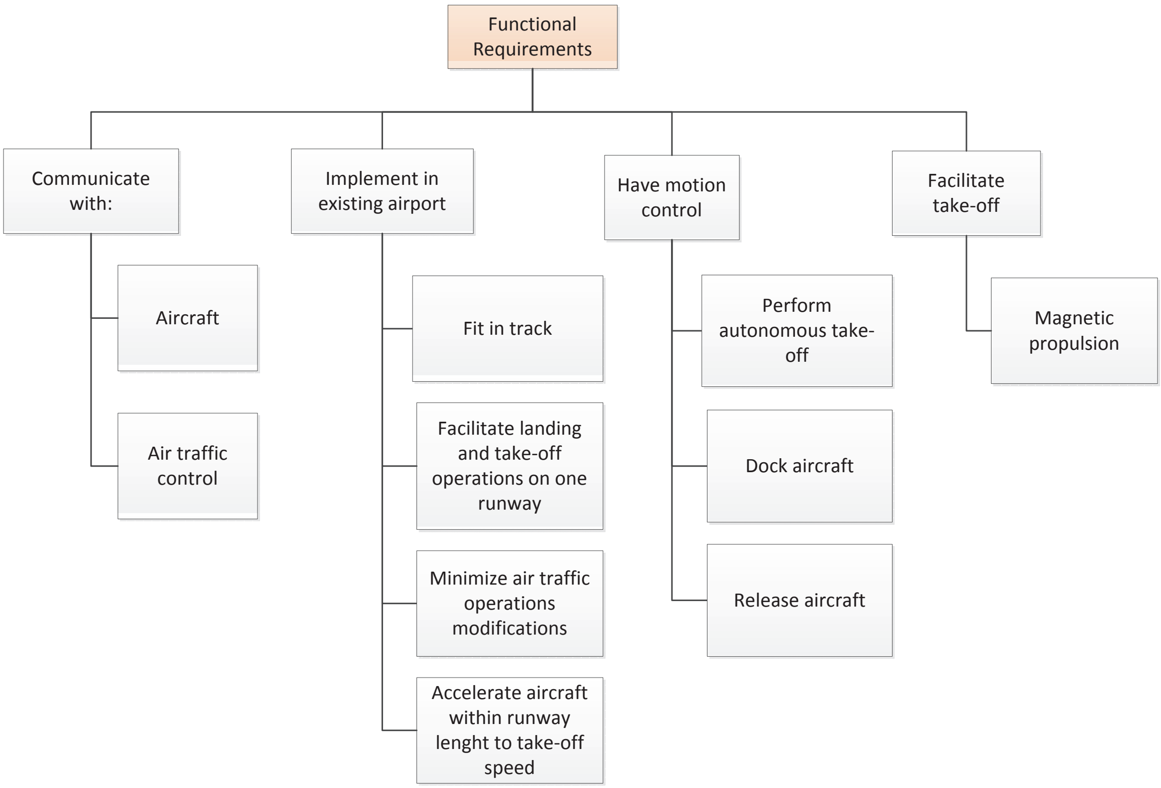
Figure 4-6: Centre of gravity range

Attachment at the keel beam compared to nose gear attachment, offers the advantage that no part of the aircraft needs to be reinforced. The keel beam is considered to be rigid enough such that it can transfer the launch forces into the airframe. The only disadvantage this attachment position gives, is the increase in drag due to an external mounted attachment object underneath the fuselage. For nose gear attachment, a new nose gear needs to be designed and probably the area where the nose gear disappears into the fuselage will require additional strengthening. Eventually, this will lead in an increased aircraft empty weight. However, the advantage nose gear attachment has, is that the attachment point can be blended in the new nose gear design. As a result no aerodynamic drag increase occurs with nose gear attachment.
As a practical matter, it is easier to mount a standard attachment object underneath the fuselage than to design new nose gears for each aircraft. Additionally, the goal of this assignment is to keep the aircraft modifications as limited as possible. Therefore it has been decided to continue investigating the keel beam attachment possibilities.

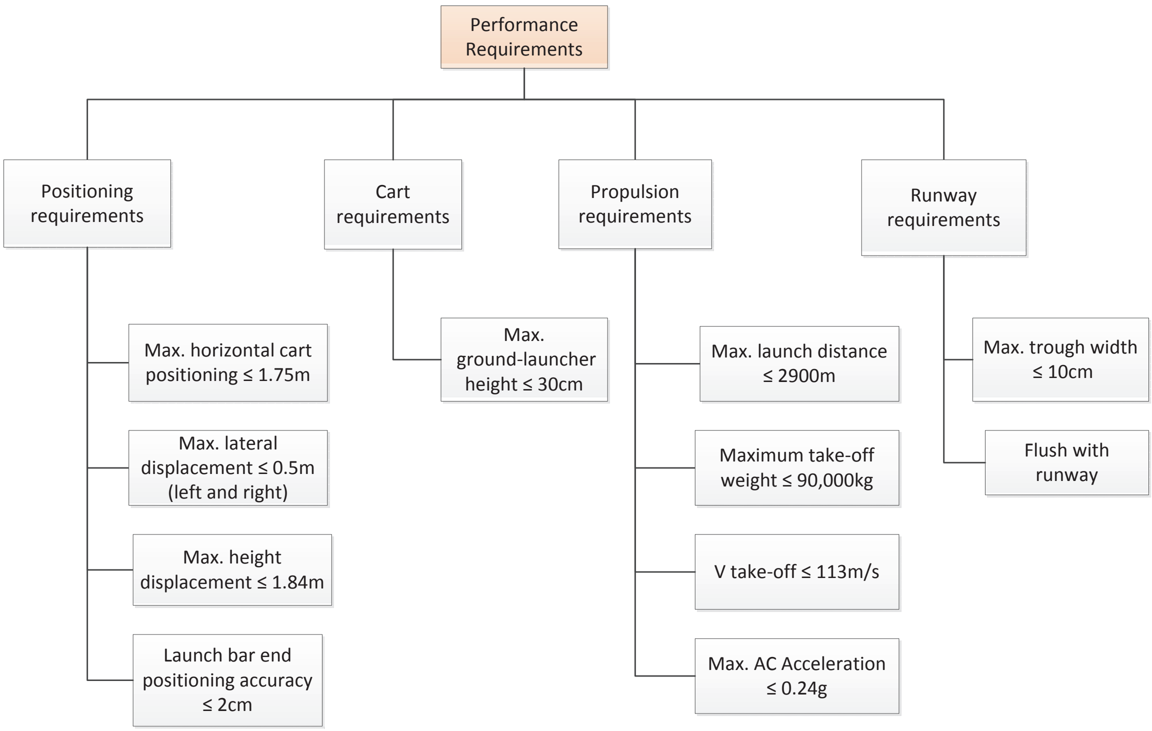
4-3 Launcher design requirements

Since the attachment location is determined, the final design can be developed. First, an update on the launcher requirements is given. The initial functional requirements and performance requirements can be found in Figure 1-3 and in Figure 1-4. Since, more information is gathered on the design of the launcher, an update on the initial requirements is performed. The functional requirements and performance requirements of the final launcher design are given in Figure 4-7a and in Figure 4-7b. The functional requirements are kept the same. The performance requirements have expanded. The maximal mean acceleration of 0.6g is reduced to 0.24g. This maximum mean acceleration is dependent on the length of the launch track (2900m) and the maximal launch velocity of 113m/s.. The maximum trough width of the track is defined and is equal to 10cm. To allow for aircraft rotation, the maximal shuttle height equals 30cm. Positioning requirements are also added for the positioning of the aircraft and launcher.

In order to develop the launcher design, different part designs are required such as a design for the shuttle, the connection between shuttle and aircraft, and the aircraft attachment. For each



(a) Functional requirements



(b) Performance requirements

Figure 4-7: Update of the launcher requirements subsystem of the launch system, different requirements drive the part design of which the most important ones are discussed separately in the next sections.

4-3-1 Aircraft - shuttle connection requirements

For the design of the connection part between the shuttle and the aircraft, the most important requirements to be met are discussed.

Positioning requirements: The shuttle is fixed in longitudinal direction in the track, and since an aircraft has limited steering capabilities, the connection between both systems should be able to move in all directions. The maximal longitudinal variation is determined by the distance variation between the attachment point of different aircraft. The Bae-146 and A321 are considered to be the two most extreme cases in attachment point distance variation with respect to the wheelbase length (distance c in Figure 4-6b). This difference in distance c for the BAe-146 and the A321 equals 1.75m. A maximal lateral displacement of 0.5m and heigh displacement 1.84m is required [1]. The end positioning accuracy of the connection to the aircraft should be equal or smaller than 2cm. This requirement enforces a minimal accuracy requirement to the positioning system and constraints the dimensions of the aircraft attachment design.

Transfer of launch force: The connection should facilitate a transfer of the launch load from the shuttle to the aircraft.

Dock aircraft: The connection should facilitate the docking of aircraft during the whole launch.

Release aircraft: The connection to the aircraft needs to be designed such that quick release is possible even when system failures occur. By designing the system only for pulling aircraft, the complexity of the attachment system is reduced.

Autonomous positioning: For safety considerations, the connection between aircraft and shuttle should go autonomously. In this way, a runway operator is not required at the runway to confirm the connection. An autonomous positioning system should be installed on the shuttle.

Allow aircraft rotation: At the end of the runway, the aircraft is released. The height of the shuttle and the connection means cannot exceed a height of 30cm, measured from the ground. This will reduce the chance of aircraft interference with the shuttle while rotating.

4-3-2 Aircraft attachment design requirements

In Section 4-2-3, it has been determined that the attachment will take place underneath the fuselage, where the keel beam is situated. Now the shape and functionalities of the attachment at this location have to be considered.

Dock aircraft: The attachment should facilitate the docking of aircraft and provide firm attachment when the aircraft is launched.

[1] 1.84m equals the landing gear height of the A321

Release aircraft: Quick release is required when the launch velocity is reached or when a failure of the system or aircraft occurs.

End positioning accuracy: The shuttle connection with the aircraft is allowed to have an end positioning accuracy of maximum 2cm. The attachment and positioning system should be designed such that this requirement is met.

Transfer of launch force: The attachment needs to be mounted to the keel beam such that it can transfer the launch forces into the airframe structure without creating stress concentration areas beyond the airframe allowed stress concentrations. The feasibility of this requirement needs to be investigated. The part itself needs to withstand the launch force as well.

Minimize excrescence drag: Since the attachment will be mounted on the exterior of the aircraft, in-flight drag increase will result. The degree of drag increase depends on the attachment location on the aircraft, the shape and the size of the object. Preferably, the object is small in size and an aerodynamic analysis on the design of the shape should be performed to minimize of the resulting in-flight drag increase.

4-3-3 Shuttle design requirements

Since the connection between the aircraft and the shuttle is installed on the shuttle, the requirements given for the connection part apply to the shuttle as well. It is responsible for the positioning of the aircraft connector. Besides these requirements, other requirements are imposed on the shuttle as well.

Fit in track: The shuttle is designed to fit in the track, this requirement will influence the layout of the shuttle. An additional requirement related to this, is to minimize the runway operations interference, which is explained below.

Minimize air traffic operations modifications: This requirement correlates with the track requirements given in Section 4-3-4. The runway will facilitate take-off's and landings on the same runway as where the track is implemented. The shuttle storage on the track should not hinder other runway operations.

Accelerate aircraft within runway length to take-off speed: In combination with the track, the shuttle is responsible for the accelerations and decelerations of the system within the runway length. The end launch velocity should be reached.

Communicate with the aircraft and air traffic control: Communication between the different subsystems is absolutely necessary to create an operating system. The launcher actions are controlled by an external system installed at the airport (the control system). The launcher should have direct communication with the aircraft and the control system. Air traffic control has direct communication with the control system to approve the launch and receive feedback from the launcher, such as launcher location, velocity, thrust, launcher errors etc. Details of the communication links between the different subsystem can be found in Section 4-6-1.

Equipment storage: The shuttle will be used as a storage device to store all the necessary on-board equipment. Examples are the positioning system, batteries and excitation magnets.

Allow aircraft rotation: Similar as for the shuttle-aircraft connection, the shuttle is constraint in height measured from the ground to a maximum of 30cm. This requirement allows aircraft to rotate at the end of the runway without interfering with the shuttle while rotating.

4-3-4 Track design requirements

The track fulfils the performance requirements and guidance of the system. The requirements driving the track design are stated.

Control the launcher movements: The movements of the launcher should be controlled by the linear motor implemented in the track. It should control the launcher acceleration/deceleration and the maximum velocity the launcher can achieve.

Facilitate take-off: The function of the track is to accelerate the shuttle to the end launch velocity within the track length. Magnetic excitation is to be used for propulsion.

Flush with runway: The runway should be able to function as a conventional runway. This means that landings and take-off's should still be possible. Approaching aircraft cannot be hindered by the location of the track on the runway. This implies a maximum trough width of 10cm [2].

From these requirements, different part designs are created in the next section. When the different part designs are established, an assembly of all the different parts follows with a selection of missing equipment to make the system operable. When the launcher assembly is completed, the implementation of the launcher in the runway can be investigated and a track design is proposed. Further, in the next section it will be discussed how the launcher will operate on the track and the system's communication links are given.

4-4 Launcher part design

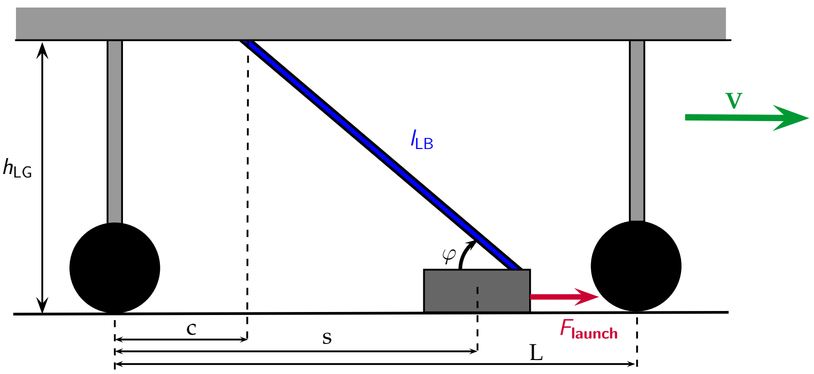
Based on the concept requirements, in this section, the design of the different launcher parts will be discussed and how the preliminary launcher concept was created. First, the design of the aircraft - shuttle connection will be explained.

4-4-1 Aircraft - shuttle connection

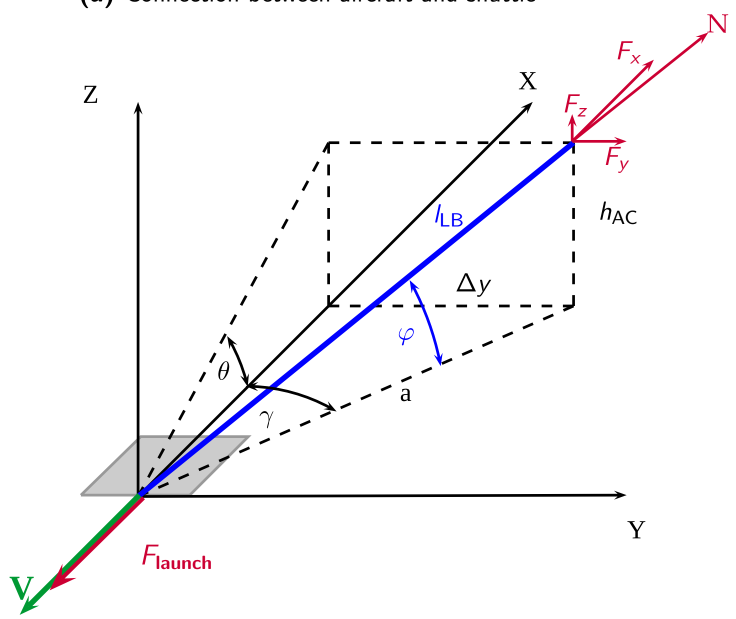
The design of the aircraft - shuttle connection comes from the requirements stated in Section 4-3-1. Since the aircraft can only be pulled by the system, a first question rises, assessing the choice between using a bar or a cable as the connection means. Important requirements influencing this decision are: the autonomous positioning of the connection means and the requirement that

[2] It is assumed that the minimal nose wheel thickness is not below a width of 20cm. Therefore it is assumed that a maximum track trough width of 10cm will not interfere aircraft wheels during take-off's and landings

the aircraft needs to be safely released at all times at the end of the runway. Figure 4-8a shows how the shuttle is connected to the keel beam. Note that the connection is situated between the nose and main wheels of the aircraft. The length of the connection l_{LB} depends on the shuttle location, the height of the aircraft, the location of the attachment on the aircraft and whether the connection length is fixed or variable. Keep in mind that the length of the connection part is considerable, the height of the A321 from the lower part of the fuselage to the ground equals 1.84m [64]. Since the aircraft will not be pulled under an angle φ of 90 degrees, the length of the connection dependent on φ in Figure 4-8a will exceed a length of 2m. Preference is given for the design of the connection means to a launch bar instead of a cable. A bar can be positioned automatically and during release of the aircraft, its movement can be better controlled than a cable's movement. Control of the movements of the connector is important because the attachment location is in the vicinity of the main gear. Therefore, a bar will be used as the aircraft - shuttle connection.



(a) Connection between aircraft and shuttle



(b) Geometry of launch bar

Figure 4-8: Launch bar geometry

Geometry of the launch bar with the shuttle and aircraft

The angle φ created by the launch bar orientation with the shuttle and the aircraft, shown in Figure 4-8, determines the horizontal, vertical and side forces exerted on the shuttle and the aircraft. The launch bar is indicated in blue in Figure 4-8. Figure 4-8b gives the 3D orientation of the launch bar connected from the shuttle to the aircraft. The resulting angles and forces are shown for the launch bar orientation and the launch load application. The angle θ is the projection of φ in the longitudinal direction (xz-plane), and γ the angle in lateral direction. The resulting side forces are created when the aircraft is not perfectly aligned with the track. Due to the aircraft steering limitations, perfect alignment with the track is not always possible, therefore, the launch bar should be adjustable in lateral direction. The maximum allowed lateral displacement Δy is 0.5m.

The angles γ and θ are preferably small, to minimize F_y and F_z respectively. The longer the length of the launch bar the smaller these angles become since the y and z displacements of the launch bar are constrained. As stated before, the maximal lateral displacement is 0.5m and the maximal height displacement is 1.84m, based on the bottom fuselage height of the A321 [64]. The length of the launch bar will be based on these values and taking the dimensions of the BAe-146-100, one of the smallest aircraft of the aircraft selection, into account. The BAe-146 and the A321 will be used as example aircraft for further elaboration of the design of the launch system. They have been chosen because of their configuration. The wheelbase length of both aircraft varies from 10m for the BAe-146 to 17m for the A321. The A321 has a low wing configuration which means that the landing gear height is large due to clearance for the engines while the BAe-146 has a high wing configuration, which results in a smaller landing gear with a bottom fuselage height of 0.65m. These heights represent the limits in z-direction of the launch system. In Figure 4-9, these two aircraft are shown.

(a) BAe-146 **(b)** A321

Figure 4-9: Aircraft configuration of the BAe-146 and A321 [1]

It has been determined that the maximal length of the launch bar, l_{LB} in Figure 4-8a, for the BAe-146-100 cannot exceed 7m because this is the maximal distance available between the attachment point and the nose gear.

To decouple the aircraft from the shuttle, the aircraft continues travelling along the runway and the shuttle decelerates immediately. As soon as the decoupling has occurred, the shuttle is located underneath the aircraft. It is desired that the height of the launch bar is reduced quickly to omit interference with the aircraft before rotation. Therefore, a minimal angle φ is required to guarantee the height reduction of the launch bar. When selecting the length of the launch bar, this need to be accounted for.

Additionally, the longer the length of the launch bar, the higher the chance of deflection due to its own weight. The weight of the launch bar will also create a moment on the shuttle as the attachment point at the shuttle is located in front of the whole launch bar length.

The launch force F_{launch} given in Figure 4-8b, can be split up in components F_x, F_y, F_z and N going into the launch bar.

$$F_x = F_{\text{launch}} \tag{4-2}$$
$$F_y = F_{\text{launch}} \cdot \tan\gamma \tag{4-3}$$
$$F_z = F_{\text{launch}} \cdot \tan\theta \tag{4-4}$$
$$N = \sqrt{{F_x}^2 + {F_y}^2 + {F_z}^2} \tag{4-5}$$

The larger γ and θ, the larger F_y, F_z and N become. If the launch bar length is chosen to be fixed, this bar should reach a height of 0.65m as well as a height of 1.84m. Therefore the resulting F_z and N for the A321 are relatively larger than these ones for the BAe-146 as θ increases. It can be chosen to extend the launch bar for the A321 height by processing an actuator in the launch bar for extension, and therefore reducing θ. The normal force N in the launch bar is dependent on the length and the angles θ and γ. Its order of magnitude varies between 200kN and 300kN for the A321. This range represents about 30 to 40% of the maximum take-off weight of the A321. Since this actuator needs to guide trough this force, it needs to be able to withstand it. The construction with a launch bar extension actuator would become too heavy, therefore, it is chosen to keep a fixed launch bar length.

In Figure 4-10, the preliminary design of the launcher is given. It can be seen that the proposed shape of the launch bar is currently a tube. The initial diameter of the tube is chosen to be 10cm. A simple stress analysis has been performed to validate the diameter selection. Since the tube is loaded under tension, the equation $\sigma = F/A$ has been used where F represents the normal force N in the tube and A the cross-sectional area. Ferrium 53S, a steel alloy has been assumed as the material used for the tube. The characteristics of this material are given in Table 4-3. This table does not include the degradation of the maximum tensile stress after a number of cycles N to failure. Ferrium 53S has a reduced maximal stress σ after one million cycles (N=10^6) of 1170MPa [65]. A safety factor of 1.5 has been assumed. With a thickness of 4mm and a diameter of 10cm, the tube can handle normal forces up to 1000kN. However, a tension fatigue analysis will not be sufficient to design the launch bar on. A detailed structural analysis will be required which analyses the optimal shape of the launch bar. A different profile can be selected like an I profile, which is more resistant to bending under its own weight. Many parameters define the deflection degree, examples are the material choice, the length of the launch bar and the profile shape. In order to work out the concept, a tube with a diameter of 10cm is considered.

It can be noticed from Figure 4-10 that the launch bar ends at both sides with a ball. At the side of the shuttle, this ball is used as a ball-and-socket joint to facilitate the required movements of the launch bar. At the other side, the ball is used to connect the launch bar to the aircraft. Since the aircraft can only be pulled by the system, a hook-in connection is considered, the ball slides into the attachment from behind (illustrated in Figure 4-15). Both balls have a radius of 10cm. The size of the balls influences the height of the shuttle and of the aircraft attachment. The shuttle design and the aircraft attachment design can be found in Section 4-4-3 and in Section 4-4-4.

The effective angle φ depends on the length of the launch bar, the effective height between the shuttle and the aircraft attachment (the effective launch bar height) and the thickness of the launch bar. A discussion of the launch bar length and other design characteristics will be performed as soon as design details of the shuttle and aircraft attachment are known. First, the preliminary design of the launcher is given and explained in Section 4-4-2. It will give insight on the different part designs.

4-4-2 Preliminary design of the launch system

On the basis of the launch system requirements and launch bar details given in Section 4-4-1, a preliminary concept is proposed, illustrated in Figure 4-10. This concept is not finished and more design details will be added later when more aspects of the different part designs are known.

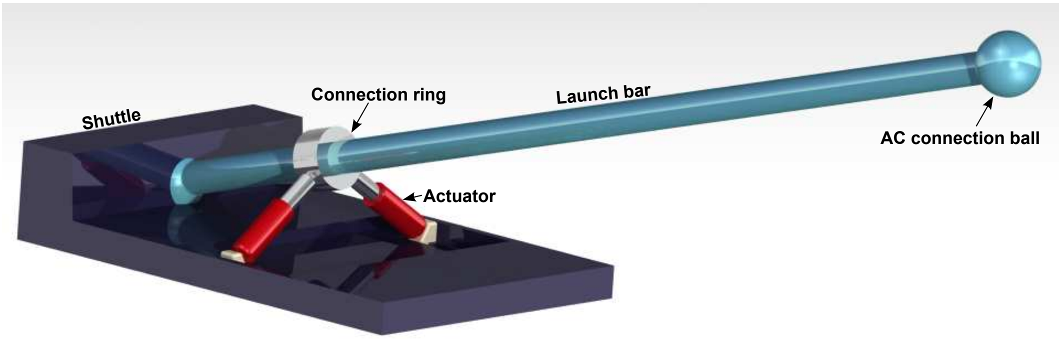


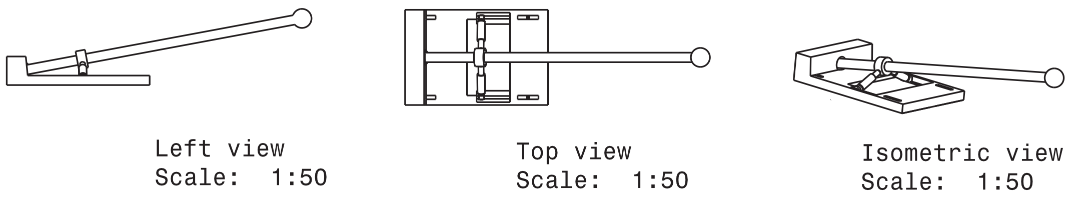
Figure 4-10: Preliminary launcher concept

The autonomous positioning of the launch bar is facilitated by two actuators indicated in Figure 4-10. These actuators are installed on the shuttle and will be able to move the launch bar to the required lateral and longitudinal displacements to connect with the aircraft attachment. The actuators are connected to the launch bar by a connection ring. This ring is fixed on the launch bar. The two actuator connection holes are positioned under an angle of 120 degrees from the origin of the ring.

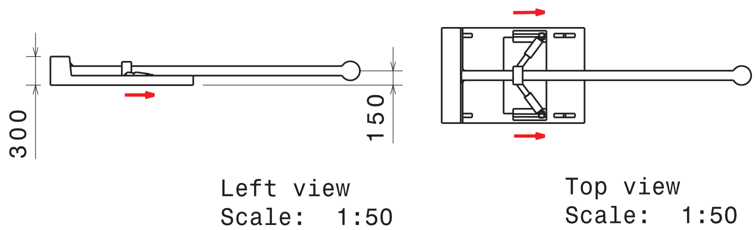
To allow for aircraft rotation at the end of the track, the height of the launch bar needs to be reduced quickly. This is achieved by moving the launch bar positioning actuators away from the origin of the shuttle over a certain distance. The displacement of the positioning actuators is achieved by another actuator installed on the shuttle. This actuator is hidden in the shuttle and is connected to both positioning actuators. Figure 4-11b illustrates the retraction of the launch bar. It can be noticed from Figure 4-11b that the actuator connection ring is kept in place to achieve maximal retraction of the launch bar height.

4-4-3 Shuttle design

The shuttle is present to connect all parts and facilitate propulsion. The upper part, visible from the ground, will store all equipment needed for connection with the aircraft. The lower part, which is hidden in the runway, will enclose all equipment necessary for propulsion. Since the system works on a linear motor, the functions of suspension and guidance will be facilitated by wheels mounted on the shuttle. It is important that the shuttle is firmly connected to the track



(a) Actuator in positioning position



(b) Actuator in retracted position

Figure 4-11: Illustration of retraction of the launch bar

such that it cannot come out while launching aircraft. The dimensions of the shuttle are based on the installed equipment. The magnets define the size of the lower part of the shuttle which is hidden in the runway. The size of the ball-socket joint and the actuator placement define the dimensions of the upper part.

In the unused areas of the shuttle, batteries can be stored for powering the on-board equipment, like the actuators. The total amount of power needed by the batteries is currently unknown. Therefore the size of the batteries cannot be determined. If additional battery storage space is required, the dimensions of the shuttle can be enlarged. The part hidden in the runway can be increased in size or the length of the upper part can be increased. Extending the height of the upper part is limited, since the height of the shuttle is constrained to a maximum of 30cm to allow for aircraft rotation.

The profile of the shuttle depends on the allowed track width, which equals 10cm. This is the maximal allowed width for the transition between the visible part and hidden part of the shuttle, indicated in Figure 4-12. To keep the shuttle fixed in the track, widening of the lower part is needed. The position where the widening of the lower part begins is not defined yet. Two different profiles are positioned next to each other for comparison in Figure 4-12. Widening starts on profile 1 just below the runway. The other profile widens at the bottom. The blue dotted areas indicate optional widening for the excitation magnets in case this is required.

On both profiles, space for wheel placement should be incorporated. Wheels will be put on the upper part of the shuttle and on the widening sections in vertical and lateral direction (see Figure 4-12). The space between the stator and the magnets should be kept as constant as possible for optimal performance of the motor. Resulting side forces exerted on the shuttle should be transferred in the track without affecting the air gap between the track and the magnetic area. The wheels should be positioned on the shuttle, such that resulting forces of the launch bar can be

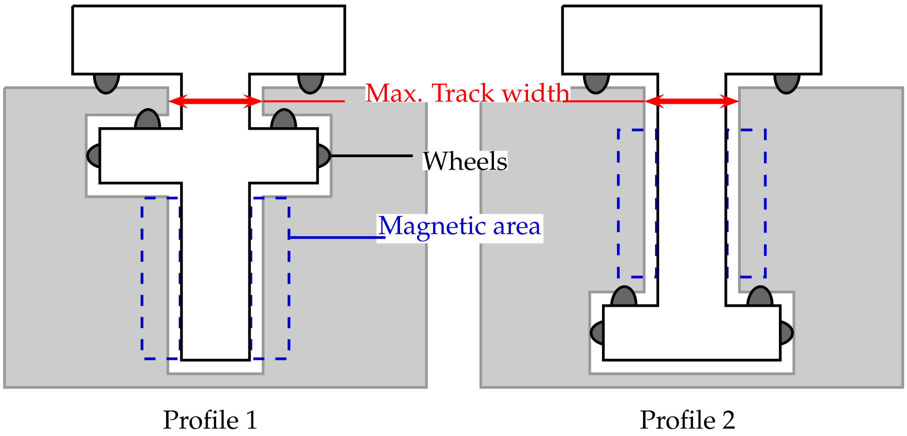


Figure 4-12: Shuttle profiles for track width

transferred in the track. The wheels also constrain the shuttle in the track. When analysing both profiles on the application of a side force, profile 2 is more sensitive to deformation. The vertical distance between the upper part, where the side force is applied, and the location of the horizontal wheels is larger. This vertical distance is smaller in profile 1 which results in smaller torque. The chance of having play at the lower part of profile 1 is larger than for profile 2 since wheels prevent this from happening. However, the excitation field created by the interaction of the magnets with the track reduces the chance of play and the lower part can be made stiff. Therefore, profile 1 has been selected.

The exact positioning of the wheels will be done when the size of the shuttle is determined. First, the selection of the actuators will be discussed and how their positioning drives the upper part design of the shuttle. Then, the lower part of the shuttle is designed by defining the magnetic area.

Actuator selection

The positioning of the launch bar by the actuators should go automatically. Two actuators will be used for the positioning, one at the left and one at the right from the centreline of the shuttle, as shown in Figure 4-10. These actuators need to be able to displace the launch bar weight. During launch, they should be able to move along with the movements of the launch bar, passive mode.

The positioning accuracy of the launch bar, at the aircraft attachment, is determined by the location of the actuators on the shuttle and their end play allowance. The further the actuators are positioned in longitudinal direction from the origin of the launch bar, the more accurate the end positioning of the launch bar and the longer the actuator extension length, become. The required launch bar end positioning accuracy equals 2 cm. This is important when selecting an actuator.

Since the actuators need to be active for positioning of the launch bar but passive once the launch bar is connected, hydraulic actuators are chosen. Electric actuators are not an option because they cannot be unloaded once connected. During positioning, it is required for the actuators to act fast and accurate. Once the launch bar is positioned and connected to the attachment, the load on the actuators should be released such that the launch bar is able to move along with the movements of the aircraft and is able to centre itself with the centreline of the track. The actuators should function as dampers. Once the aircraft is released, another actuator is activated to reduce the launch bar height, as explained in Section 4-4-2 (Figure 4-11b). It is unknown to the author which actuator can perform the functions explained in this section and if they can be applied to this concept. If this operation can be achieved by electro-hydraulic actuators, an actuator like the Parker Compact EHA is proposed. It has an operating speed of 84mm/s and can apply loads up to 16kN [66]. The only uncertainty is the accuracy of this actuator. There is a possibility that the launcher design requires custom designed actuators. It will be assumed that the actuators have a maximum end play of 2mm, similar to the end play of the Linak LA36 actuator [67].

The positioning actuators should facilitate the launch bar to reach heights ranging from 0.65m to 1.84m, for the BAe-146 and the A321 respectively, with a maximal sidewards displacement of 0.5m. The smallest displacements of the actuators are found for the BAe-146. When the launch bar needs to be displaced 0.5m to the left, the left actuator needs to reduce its length while the right actuator needs to increase its length. These movements have been illustrated by Figure 4-13, front view. The smallest actuator length, in this figure the $l_{A,left}$, is based on a launch bar lateral displacement of 0.5m for the BAe-146. The longest actuator length ($l_{A,right}$) is based on the length of the opposite actuator with a lateral displacement of 0.5m for the A321. These examples for the BAe-146 and the A321 have been illustrated in Figure 4-14. The variation in actuator lengths determines the size of the actuators and at which y-position the actuators need to be put. The longitudinal positioning of the actuators on the shuttle determines the end accuracy of the launch bar. The further away from the origin of the launch bar, the more accurate the end positioning becomes. As soon as the length of the launch bar has been determined, the positioning of the actuators can be defined.

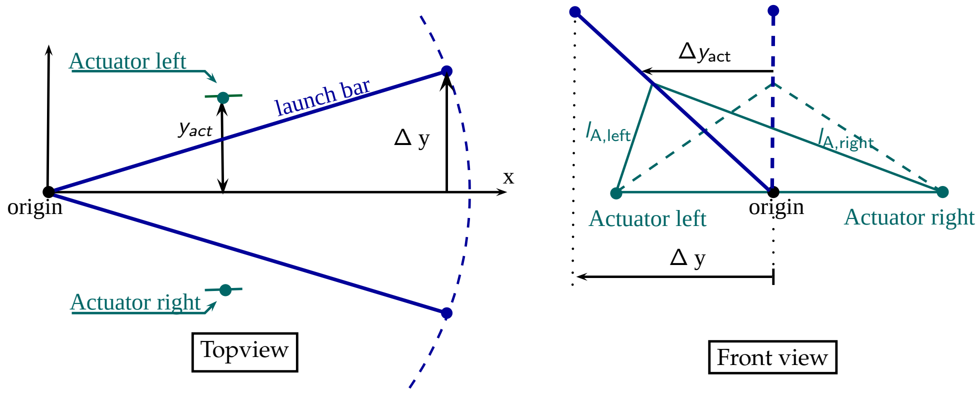
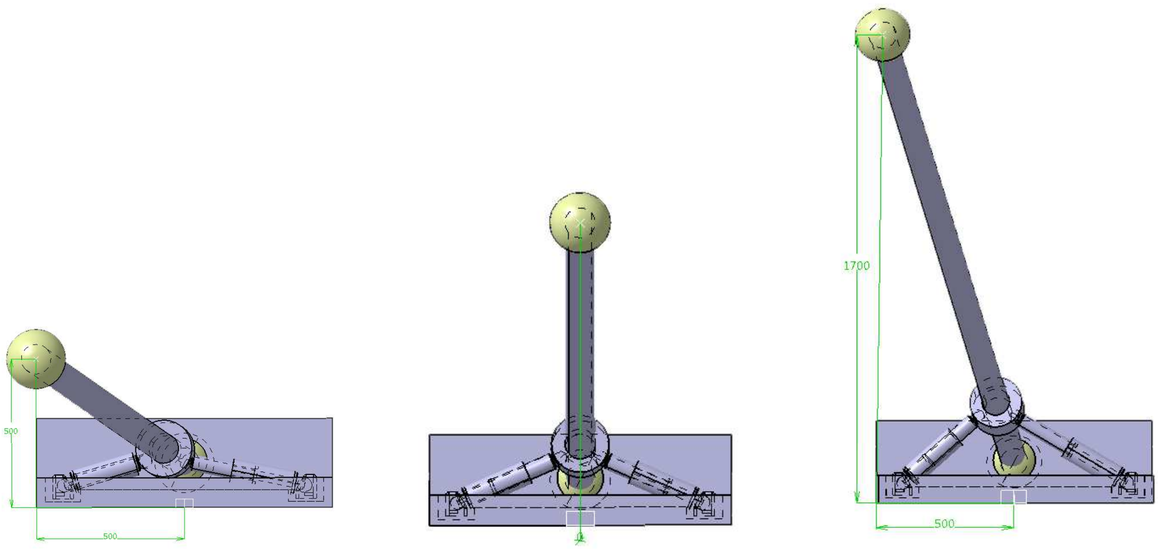


Figure 4-13: Actuator movement allowances

The actuators are driven by a linear motor which need to be energized by batteries on the shuttle. Space for battery placement on the shuttle needs to provided. However, currently there is no weight estimation of the launch bar and it is not known which type of actuator that is used. Therefore, it is difficult to predict the volume needed for the batteries on the shuttle.

The sliding distance as well as the positioning and the dimensions of the actuators are defined in Section 4-5-1. As long as the size of the launch bar is not determined yet, details on the actuators cannot be specified. The above ground shuttle design is mainly driven by the positioning of the actuators. Therefore, the dimensioning of the shuttle is discussed in Section 4-5-1 as well.



(a) Actuator deflection BAe-146, y_{LB}=0.5m

(b) Actuator deflection, y_{LB}=0m

(c) Actuator deflection A321, y_{LB}=0.5m

Figure 4-14: Actuator movements

Electric layout

In this section the hidden part of the shuttle (in the track/runway) is discussed. This part of the shuttle will mainly consist of electric equipment needed for propulsion of the launcher along the track. A new estimation will be given on the magnetic area requirements on the shuttle to achieve the required launch forces.

Since the accelerations for the launches are reduced, the magnetic area on the shuttle, determined in Section 3-2 for different accelerations, reduces as well. The magnetic area is given for electromagnets (EM's) and permanent magnets (PM's) in Table 4-5. Recalling that permanent magnets generate a force half the strength per square meter as created by electromagnets, the required PM area doubles compared to the EM area. The shuttle will operate in a blade shuttle configuration, as explained in Section 3-2-1 and illustrated in Figure 3-14. The disadvantage of PM's compared to EM's are: PM's are heavier, sensitive to demagnetization, more expensive and create a smaller thrust force. The problem of demagnetization is manageable when carefully creating the electric design of the system. Care should be taken of the air gap size, the current going through the magnets, and other design criteria [37]. When choosing for the use of PM's, the shuttle structure is simple as only PM's need to be installed. EM's need to be charged by electricity. This electricity needs to be transferred to the shuttle by using either sliding contacts or inductive power transfer (IPT) systems [23]. This latter is a contactless power supply system which has been applied on the Transrapid as well [40]. By providing current directly to the shuttle, on-board power storage devices are not required for magnetic excitation. When applying electromagnets on the shuttle, more heat dissipation, due to losses in the coils, is created compared to a permanent magnet configuration. These losses might create the need for active cooling, dependent on the time duration of the launch and the amount of heat dissipated. More research into cooling is required when developing this system further. According to [37], the PM configuration results in simpler power electronics system and a heavier overall system compared to the EM configuration.

Table 4-5: The required shuttle magnetic area, based on launch forces of A321

Acceleration	F [kN]	EM area [m^2]	PM area [m^2]
0.2g	183.18	0.46	0.92
0.24g	226.66	0.57	1.14

In any case, more research is required in developing the detailed electric layout of the system. Different aspects need to be researched more in detail such as cooling, costs, weight, power electronics, control systems, redundancy systems, magnetic shielding and other relevant parameters. Currently, preference is given to an electromagnetic configuration since a larger thrust force can be delivered with a smaller installed area on the shuttle. A total magnetic area of 0.57m^2 is required. A double-sided configuration is used. This implies that 0.29 m^2 of electromagnets needs to be installed on each side of the shuttle facing the track. When the shuttle length equals 1m, a depth of 0.29m is required. The same launch forces, as given in Table 4-1 for acceleration of the aircraft and shuttle, can be used for braking of the shuttle at the end of the track. The shuttle is brought to a standstill within 170m with a deceleration of nearly 4g. The placement of the electromagnets is shown in the final design, Figure 4-23.

In the next section, the design of the aircraft attachment object is explained.

4-4-4 Aircraft attachment design

The aircraft attachment is designed to guide trough the launch force of the shuttle to the aircraft. A hook-in concept is considered such that only forces in the launch direction can act on the structure and as soon as the forces are reversed, decoupling occurs. The launch bar hooks in from the rear to the front and positions itself for attachment. This action is illustrated in Figure 4-15. The outer sphere of the attachment is designed to allow an end positioning accuracy of the launch bar of 2cm. The inner sphere fits the launch bar connection. Since the connection ball of the launch bar has a radius of 10cm, the outer radius of the attachment equals 12cm. When including the plate thickness mounted on top of the attachment object for connection to the aircraft, the origin of the launch bar connection ball, find itself at a distance of 15 cm underneath the aircraft.

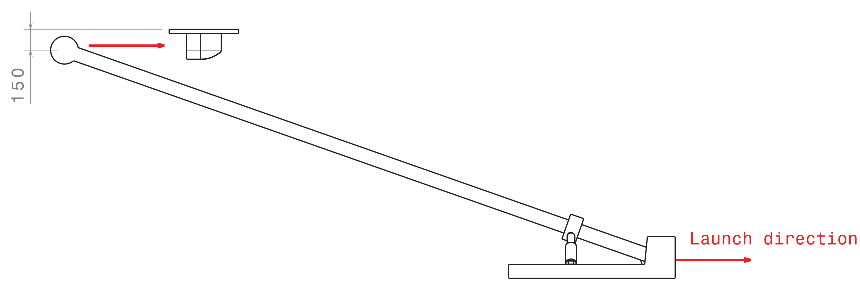


Figure 4-15: Launch bar hook in movement

Another important requirement that influences the attachment design is the required lateral displacement of 0.5m to the left or to the right. The attachment should allow for the launch bar to hook in when it is displaced at 0.5m from the track centreline. The resulting aircraft attachment is illustrated in Figure 4-16. The size of the cut-out area of the attachment depends on the sidewards and vertical inclination angle of the launch bar with the attachment. The longer the length of the launch bar, the larger the frontal cut-out area becomes for small aircraft, as the vertical inclination angle φ is small. From Figure 4-16, it can be noticed that the frontal cut-out area is quite large due to the required Y- and Z-movements of the launch bar. Less than half of the launch bar ball frontal area is comprised by the attachment. A larger area is required for the attachment to effectively transfer the launch force in the airframe. Now the chance exists for the shuttle to pop out of the attachment during launch. The design of the launch bar will be influenced by this.

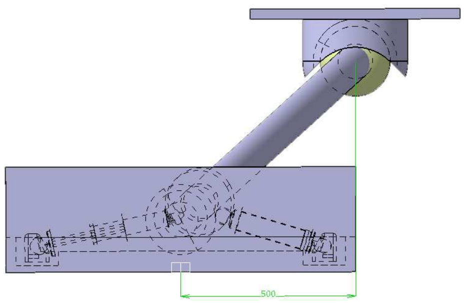


Figure 4-16: Attachment with launch bar visualization, front view

The final shape and size of the attachment are dependent on the shape and the dimensions of the launch bar. The height of the launch bar is restricted by the available volume underneath the fuselage defined by the smallest aircraft, the BAe-146.

Minimizing the excrescence drag resulting from the aircraft attachment

The attachment has cut-out areas for the launch bar to fit in, as can be seen from Figure 4-16. Due to the presence of this frontal cut-out area and since the size of the attachment is not negligible, an increase in drag during flight results. Therefore, fairings can be mounted on the attachment or on the aircraft, to smooth the flow over the attachment when the aircraft is airborne. In Appendix B, a 2-D drawing is given of a demo aircraft in flight, with the attachment mounted on it. Since the attachment is mounted on the keel beam of the aircraft, it will not be feasible to retract the construction without performing a structural analysis on the keel beam. Therefore fairings can be chosen to minimize the excrescence drag resulting from the attachment. Fairings will lead to little aircraft adaptations. Aerodynamic tests will have to be performed to define the shape and positioning of the fairing(s).

4-5 Final launcher design

In the previous section, an introduction on the design requirements and preliminary designs on the different launcher parts are proposed. In this section, the final launcher design will be presented.

Before an assembly of the final launcher design is possible, an update on the different part designs is given.

4-5-1 Update of the different part designs

Launch bar

Since the attachment part comprised less than half of the frontal area of the launch bar connection ball for the smallest height requirement (see Figure 4-16), the end position of the connection ball on the launch bar has been adapted. The origin of the ball is moved upwards from the centreline of the launch bar, as illustrated in Figure 4-17. This puts the connection ball higher such that more area of the ball can be enclosed under a small inclination angle between the shuttle and the launch bar. In the next section, changes to the shape of the attachment will be explained as a result of the displacement of connection ball on the launch bar.

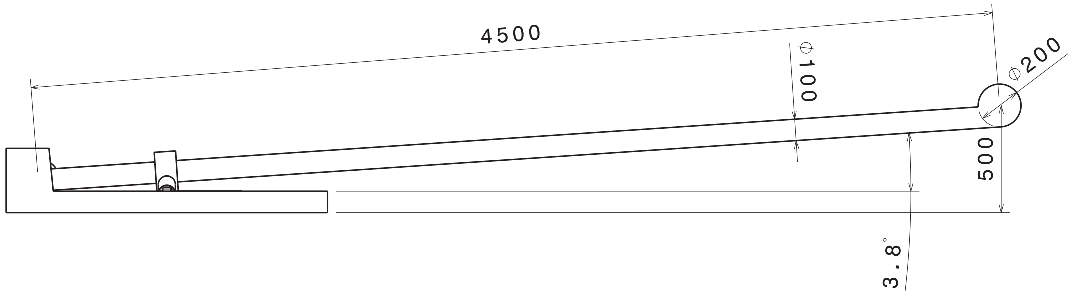


Figure 4-17: Launch bar dimensions, expressed in mm

The launch bar is mounted on the shuttle and the centre point of the ball-and-socket joint (diameter of 20cm) finds itself at 150mm above the ground. The centre point of the attachment connection ball is also located at a vertical distance of 15cm underneath the fuselage. The effective height the launch bar should achieve, is reduced by at least 30cm. Because the aircraft connection ball is moved upwards from the centreline of the launch bar, the launch bar effective height reduces to 30cm, for the BAe-146, and to 150cm for the A321. Table 4-6 gives the changes of angles γ and φ (defined in Figure 4-8b) for these different heights and a lateral displacement of 0.5m. The resulting forces F_y, F_z and N are compared to the maximum take-off weight of the regarding aircraft, F_x is constant for each specific aircraft and equals the launch force.

As stated before, the smaller angles γ and φ, the smaller the resulting forces F_y, F_z and N (see Figure 4-8b). Since the effective height is determined, a launch bar length can be selected. Before, the length is selected, a minimum inclination angle φ or launch bar height should be defined for launch bar retraction. The launch bar height is reduced by sliding the positioning actuators away from the launch bar origin on the shuttle (see Figure 4-11). This sliding distance is limited by the dimensions of the shuttle. In order to work effectively, the angle φ can not be too small, in order to reduce the height sufficiently. However, large inclination angles increase the resulting forces acting on the aircraft and shuttle. Therefore, both aspects have to be considered. It has been decided that the ratios F_y/W_{TO} and F_z/W_{TO} cannot exceed 10% for all aircraft, a launch bar

Table 4-6: Angles and resulting forces of launch bar with a lateral displacement of 0.5m

(a) BAe-146

l_{LB} [m]	γ [°]	φ [°]	F_y/W_{TO}	F_z/W_{TO}	N/W_{TO}
3.0	9.6	5.8	5%	3%	29%
3.5	8.2	5.0	4%	2%	29%
4.0	7.2	4.4	4%	2%	28%
4.5	6.4	3.8	3%	2%	28%
5.0	5.8	3.5	3%	2%	28%
5.5	5.2	3.2	3%	2%	28%

(b) A321

l_{LB} [m]	γ [°]	φ [°]	F_y/W_{TO}	F_z/W_{TO}	N/W_{TO}
3.0	11.1	29.8	5%	15%	30%
3.5	9.1	25.2	4%	12%	29%
4.0	7.7	21.9	4%	10%	28%
4.5	6.8	19.3	3%	9%	28%
5.0	6.0	17.3	3%	8%	27%
5.5	5.4	15.7	2%	7%	27%

length of 4.5 m has been selected from Table 4-6. The inclination angle φ equals 4 degrees for the BAe-146. When adding the connections to the launch bar, its total length becomes 4.7m.

Aircraft attachment

The changed position of the connection ball on the launch bar influences the shape of the attachment. The frontal cut-out area is reduced, the new dimensions for the attachment part are given in Figure 4-18.

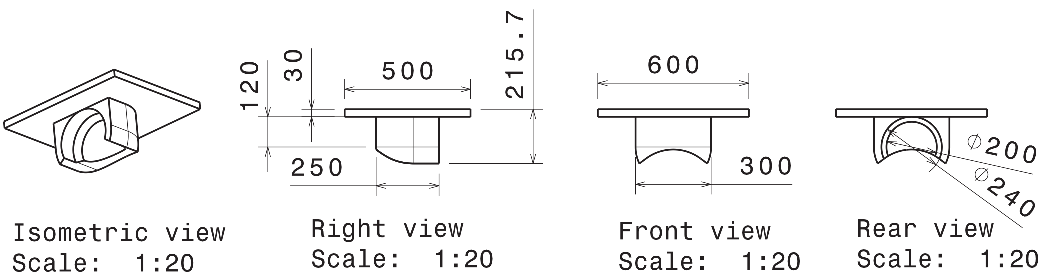
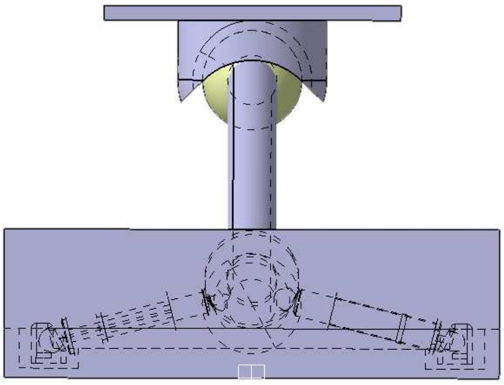
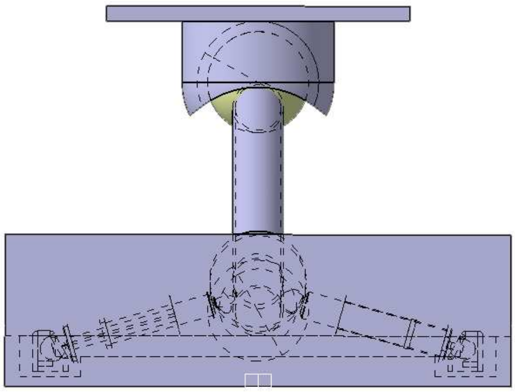


Figure 4-18: Aircraft attachment dimensions, expressed in mm

The shape of the previous attachment and the new attachment can be compared in Figure 4-19. It can be noticed that more than half of the frontal area of the connection ball is covered by the redesigned attachment object. The edges left and right are designed such that a lateral displacement of 0.5m is reached. The design of the attachment is driven by the required displacements of the launch bar for the BAe-146, since it has the smallest effective height. For the A321, the frontal cut-out area of the attachment is less constraint as the inclination angle of the launch bar is larger. The shape of the newly designed attachment, given in Figure 4-18, can be mounted on all aircraft of the aircraft selection.



(a) Previous attachment



(b) Attachment with updated dimensions

Figure 4-19: Attachment comparison

Shuttle

The shuttle design can now be completed as the size of the launch bar has been determined. The minimum and maximum stroke length of the actuators can be determined as well as the lateral and longitudinal positioning of the actuators. The criteria defining the stroke length are mentioned in Section 4-4-3. The minimum and maximum actuator stroke lengths are illustrated in Figure 4-13 and have been determined for the BAe-146 and A321. The actuator dimensions are dependent on their longitudinal and lateral position on the shuttle. At a distance of 60cm in longitudinal direction from the origin of the launch bar and at 41cm in lateral direction, all the required launch bar movements are achieved within the required the launch bar end accuracy. The dimensions of the actuator are given in Figure 4-20. The housing is indicated in the section view in red. It is possible to put the actuators at an increased longitudinal distance from the origin of the launch bar (>60cm). As a consequence, the shuttle dimensions have to increase in longitudinal and lateral direction and the actuators lengths should increase. Since 60cm, offers the required movements of the launch bar within the accuracy constraint, this position has been chosen. In Figure 4-23 the positioning of the actuators on the shuttle is illustrated.

The stroke length travelled on the shuttle for launch bar retraction can be defined (see Figure 4-11). The original position of the actuators is 60cm in longitudinal direction from the origin of the launch bar. When sliding the actuators forward, as illustrated by Figure 4-21, a zero inclination angle of the launch bar is achieved, the launch bar rests on the shuttle as illustrated in Figure 4-21. The launch bar connection ball is located at a height of 20cm. The launch bar deflection should be avoided, therefore the launch bar should be rigid enough.

The dimensioning of the shuttle's upper part is driven by the actuator positioning and the wheel placement. The maximum width of the shuttle can be defined yet and equals 1m. In longitudinal

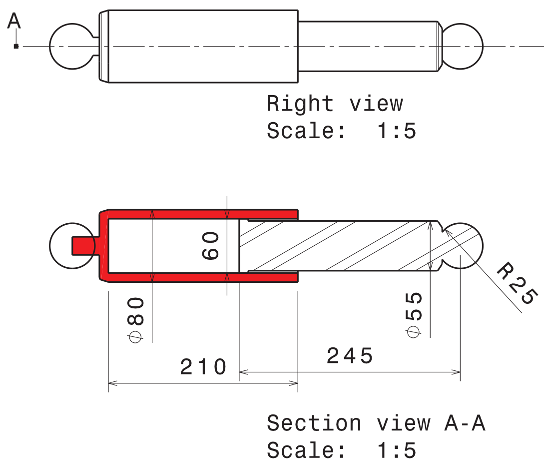


Figure 4-20: Actuator dimensions, expressed in mm

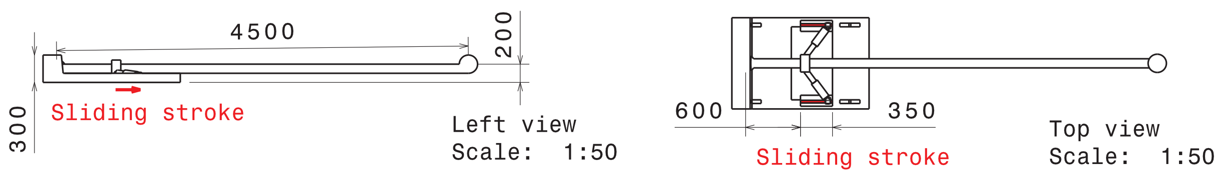


Figure 4-21: Launch bar retraction, expressed in mm

direction, the placement of the wheels will define the shuttle length. As been explained in Section 4-4-3, wheels are put in the front and the rear on the shuttle. The placement of the wheels will be discussed in the next section.

Wheel placement

Wheels are needed for suspension and guidance of the shuttle. They need to transfer the forces exerted on the shuttle to the runway in longitudinal, lateral and vertical direction. Four wheels are placed on the upper part of the shuttle. They are used for support and drive in a predefined track on the runway. On the lower part of the shuttle, hidden in the track, four wheels in longitudinal and lateral direction are positioned. The set of longitudinal wheels keeps the shuttle in the track and the set of lateral wheels opposes side forces exerted on the shuttle. In Figure 4-22 the wheel positioning is displayed. The lower part of the shuttle is extended in longitudinal direction such that the opposing moment created by the wheels is larger when a vertical force is applied at the origin of the launch bar. However, the centre of gravity of the shuttle should be determined in order to make an accurate wheel positioning. Dynamic and static analysis are required to achieve good insight on forces acting on the shuttle and on the wheel placement.

In this design, wheels similar to train wheels have been used. These wheels operate in a predefined track, which is illustrated in the track design, see Section 4-5-2. Advantages iron wheels have over rubber wheels are: the lower rolling friction coefficient, higher operating velocities and the non-existence of flat tires. Heat production of the wheels is an important design criterion, especially

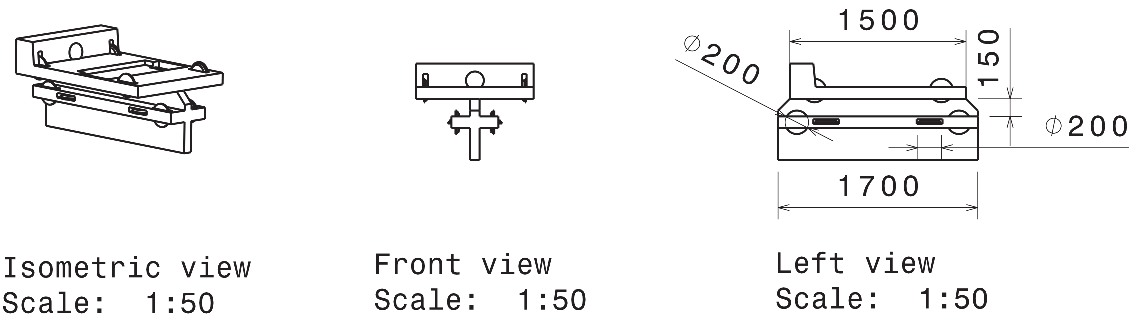


Figure 4-22: Wheel placement on the shuttle, expressed in mm

when high velocities need to be achieved. The maximal diameter currently chosen yields 20cm. However, it has not been investigated if these wheels can achieve velocities beyond 100m/s. Therefore an additional analysis is required for wheels design and selection.

The shuttle dimensions have been determined and can be observed in Figure 4-22. The upper part has a width of 1m with a length of 1.5m. Since all parts of the shuttle have been determined. An assembly of all these parts results in the final launcher assembly, illustrated in Figure 4-23. The aircraft attachment part, in yellow, is included as well. The launch bar is illustrated in light blue, the actuator housings are red and the magnetic area is indicated in green on the lower part of the shuttle. The wheels driving in the track are also shown in Figure 4-23.

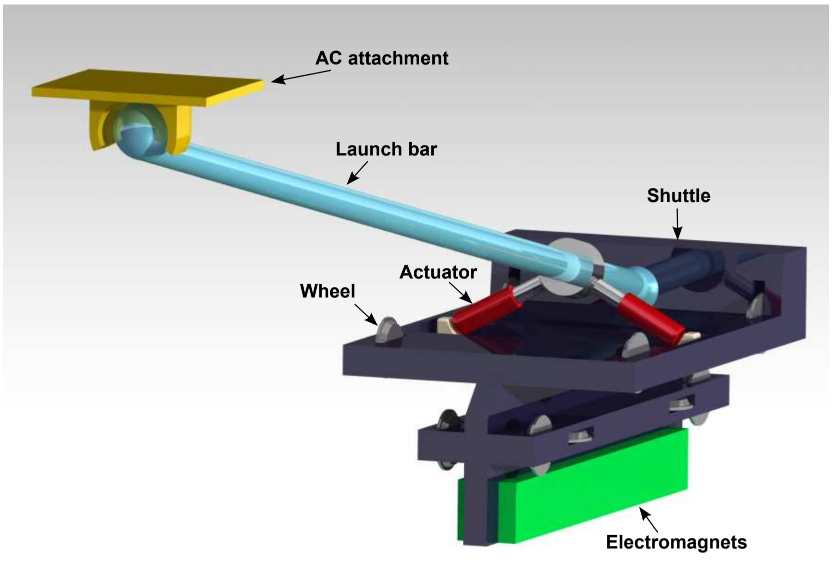
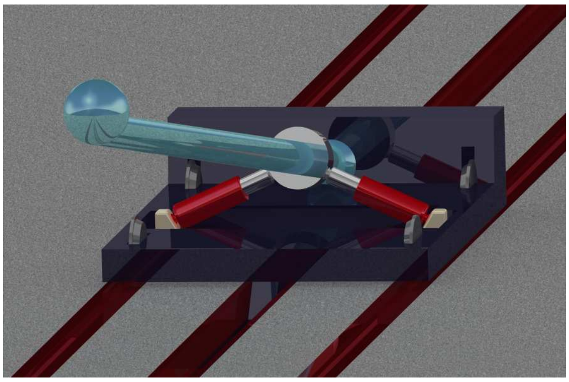


Figure 4-23: Final launcher assembly

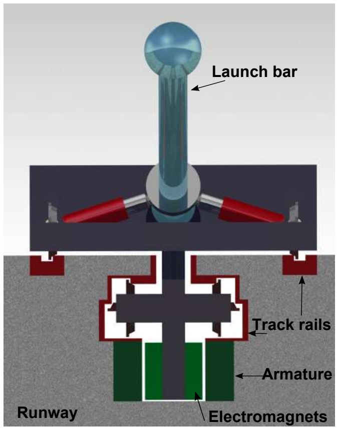
In Appendix B, drawings on the shuttle dimensions and the final assembly with a demo aircraft can be found. The next goal is to implement this launcher in the track and mount the attachment to an aircraft. A track design is proposed in the next section.

4-5-2 Track design

The track is installed at the centre of the runway and its layout is mainly defined by the shape of the shuttle. The shuttle has been designed to firmly fit in the track, as a result the track design is adapted to the shuttle's profile. The track trough is limited by a maximum width of 10 cm, based on the assumption that this width cannot hinder aircraft wheels while driving over it. As an example, the BAe-146, one of the smallest aircraft in the selection, has a nose wheel width of 20cm [47]. The shuttle width in the trough equals 8cm, which gives 1cm play at both sides of the track. In Figure 4-24a, the upper part of shuttle sliding in the track is shown. Figure 4-24b shows a front view of the shuttle - track combination. From this figure, can be noticed how the track layout is adapted to the shape of the shuttle. Two wheel tracks are assimilated in the track runway surface to give guidance to the shuttle wheels. Wheel tracks are also provided in the lower track area which can be noticed from Figure 4-24b. The track width under the runway surface is



(a) Visible part



(b) Front view

Figure 4-24: Shuttle in track

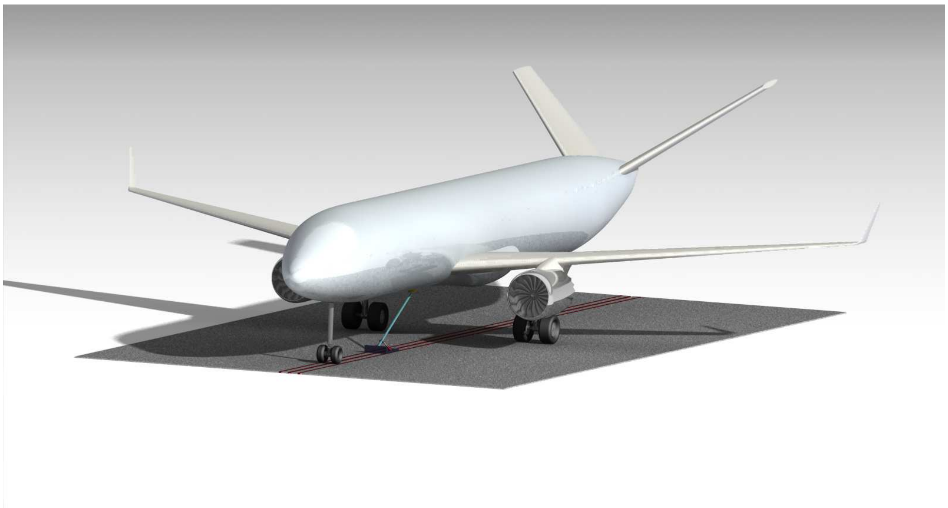
defined by the equipment of the linear motor. In Figure 4-24a, the green extensions on the shuttle represent the magnets mounted on the shuttle. At the same height on the track, the armature of the linear motor is installed. High-current power cables need to be assimilated in the runway to power the track. These cables depart from the energy storage location to the track where the power is fed to the armature. A control system will drive the different sections to achieve the desired velocity in each section.

Figure 4-25 illustrates how the aircraft is connected to the launcher, installed on the track. The track processed in the runway is indicated in burgundy. More detailed drawings can be found in Appendix B.

4-6 Launch system operations

The launcher design is defined, but the system is not operable yet. In this section will be explained how the system is made operable. Aspects to be considered are communication and control.

(a) Launcher connected to demo aircraft



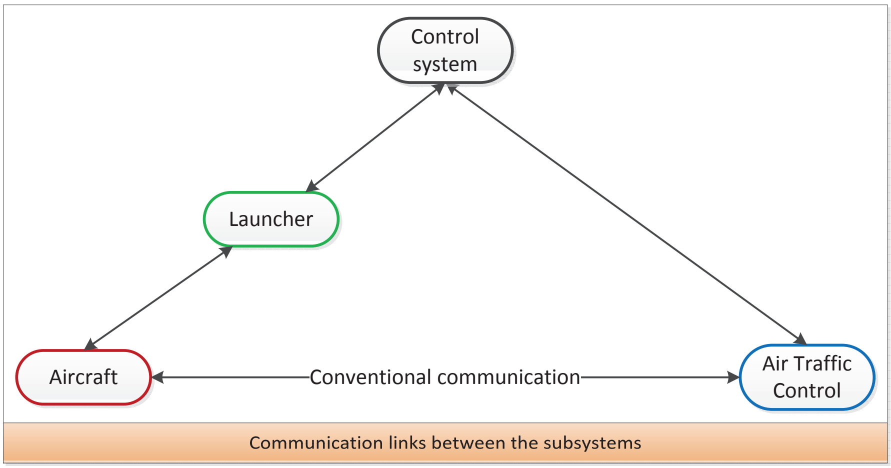
(b) Launcher connected to demo aircraft

Figure 4-25: Shuttle in track

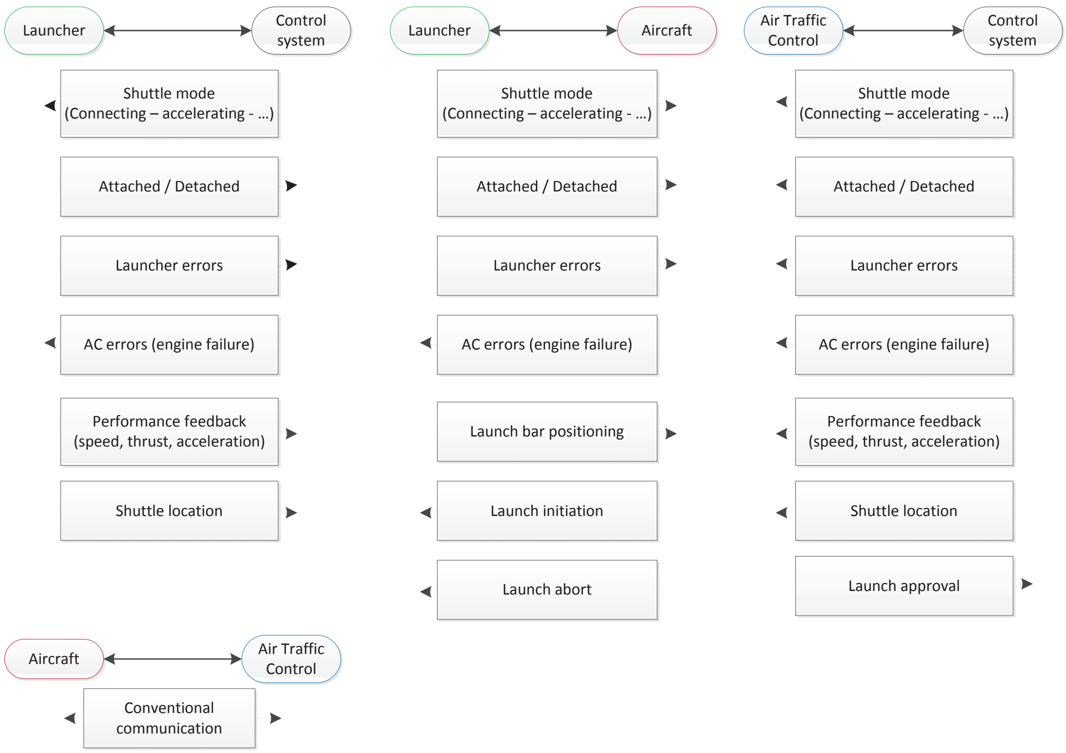
4-6-1 Communication links

To make the launcher operable, different systems need to be able to communicate with each other and the performance of the launch system should be traceable and controlled. The communication links required between the different systems are shown in Figure 4-26a. A control system will be used as the main communication link between the launcher, the aircraft and air traffic control. The control system is an external device installed on the airport which controls all actions of the shuttle. It defines the shuttle operating mode, it follows the performance of the shuttle (the velocity, the track location, the acceleration, the direction, etc.) and it drives the armature in the track (by controlling the frequency, the voltage and the current). However, direct communication between the launcher and the aircraft is needed, to position the launch bar and confirm attachment of the aircraft to the launcher.

The communication functions between different subsystems are illustrated by Figure 4-26b. It



(a) Communication links of the launch system



(b) Communication functions between the subsystems

Figure 4-26: Communication links of the launch system

indicates which information is sent from one subsystem to another.

The launch system will operate under different operating modes and each mode defines which tasks the system needs to perform. The different modes are stated below with a short explanation.

Aircraft seeking and connecting mode: In this mode, with the aid of sender and receiver devices, the shuttle displaces itself along the track to seek the aircraft. The shuttle needs to be able to standstill and perform forward and backward movements at low speed in order to find the aircraft attachment point. The shuttle will move forward and backward along the track with respect to the attachment location. If the longitudinal position of the shuttle is ready for connection, the actuators can start by moving the launch bar in the vertical and the lateral direction. Once the launch bar fits in the aircraft attachment, a signal is sent to the control centre and the pilot. The launch can be initiated.

Launch mode: will accelerate the aircraft to the launch velocity. As soon as this velocity is reached, the system will switch to:

Shuttle deceleration mode: The shuttle decelerates at the end of the track to a standstill over a maximum distance of 400m. During this procedure, the aircraft is released. The actuators on the shuttle are activated to reduce the launch bar height.

Launch location return mode: is entered when a standstill is reached by the shuttle at the end of the track. The shuttle is sent back to the launch location to pick up new aircraft.

Abort assisted take-off mode: This mode is activated when an error occurs severe enough to abort the take-off during the launch. The control centre sends a signal to the launcher to abort the take-off. Scenarios under which this mode can occur are discussed in Section 4-1-1. During this mode, the shuttle is decelerated immediately to a standstill and the aircraft is released. The pilot can decide, depending on the severity of the problem, what his action will be, either continue the take-off or abort the take-off.

Additional equipment for the subsystems

Besides the structural launcher equipment, additional equipment is needed for the operations of the system. Different communication equipment needs to be installed in the cockpit, at air traffic control, at the shuttle and at the aircraft attachment. A short description on additional equipment for each topic will be handled briefly.

Cockpit equipment: A cockpit device needs to be designed and installed. On the nose wheel of the A320, a camera is installed to give the pilot visuals of the runway. This camera can be used to enhance the positioning accuracy of the aircraft at the launcher pick-up point. Since the aircraft needs to be positioned at a maximum of 0.5m lateral displacement of the track centreline. The nose wheel camera can be installed on other aircraft in case it is not installed yet. Assuming that this camera is present on all aircraft of the aircraft selection, the additional information to be sent to the cockpit is limited to the performance feedback from the shuttle. This feedback includes information on the shuttle operation mode, the status of the system connection and launcher errors.
In case of aircraft engine failure during launch and the pilot decides to abort the launch, a sensor needs to be installed at the brake pedals in the cockpit. As soon as the brakes are hit by the pilot, a signal is sent to halt the shuttle. This sensor can only be active when the launch is initiated since the brakes are used prior to launch to keep the aircraft in position while the aircraft engines are delivering thrust yet.
A launch button to initiate the launch is installed on the device. This button is activated

when air traffic control has approved the launch. The pilot is the only one to initiate the launch. Figure 4-27 illustrates a possible cockpit display.

Figure 4-27: Cockpit launcher display

Air traffic control: should be able to know at all times where the shuttle is situated. Therefore a small interface, which will look similar like the one given in Figure 4-28, will display constantly the position of the shuttle on the launch track. This interface can be added to the conventional monitor display. Errors with the launch system should be reported automatically to air traffic control (ATC). The mode in which the shuttle operates needs to be traceable by air traffic control. Another responsibility of ATC is to approve the launch prior to launch, without this confirmation, the pilot cannot initiate the launch. They will send a signal to the control system to approve the launch.

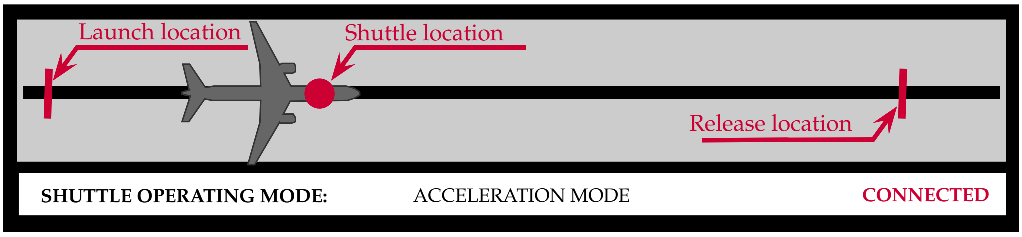


Figure 4-28: Air traffic control launcher display

Aircraft connection point equipment: A sender/receiver is put at the attachment point which can communicate with its counter part mounted on the shuttle. This ensures autonomous connection between the aircraft and the shuttle. When the aircraft is connected, information on the limitations of the aircraft is sent to the shuttle, for example, the maximum launch velocity. A push-sensor is put in the attachment housing to inform the pilot and launcher if the system is connected or not.

Shuttle equipment: On the shuttle a sender/receiver is put to connect autonomously to the aircraft. The signals send by this device are used to drive the actuators for positioning of the launch bar. When connection is completed, a signal is sent to the aircraft and air traffic control. The other sensor in the attachment housing takes over and gives continuous feedback to the pilot and ATC on the system connection during the launch. A sensor in the launch bar can be installed to monitor the normal forces in the launch bar and if any forces in x, y or z direction are beyond the maximum allowed forces. In case one of these forces exceeds the allowed values, the shuttle decelerates and decouples.

Runway / track equipment: A sensor implemented in the track traces the performance of the shuttle, this information is processed by the control centre. The necessary information on the shuttle location and performance is given to air traffic control.
Marks on the runway indicate the path the pilot needs to follow to achieve good alignment

and where to park the aircraft prior to launch (Figure 4-29). Additionally, the pilot has a camera mounted on the nose wheel for enhanced steering visuals.

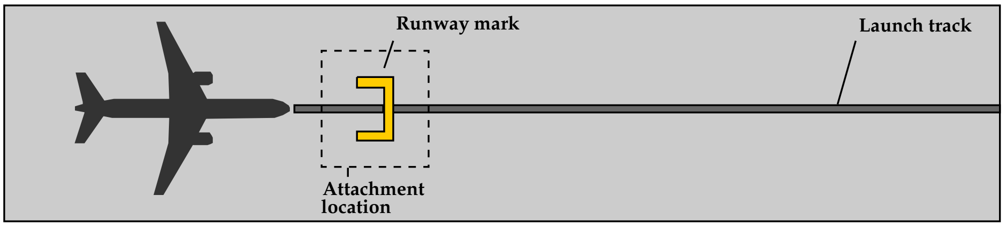


Figure 4-29: Runway layout with positioning marks

When an aircraft is being positioned by the pilot for launch on the runway, the shuttle should find itself at all times behind the aircraft. Otherwise, there is a chance that the nosewheel interferes the track. The shuttle will not be able to connect with the aircraft. It is important that the shuttle has returned to the launch position before the aircraft is positioned on the runway.

Chapter 5

Conclusions

In this thesis a design of a launcher is proposed to assist commercial aircraft during take-off. First, the conclusions resulting from the concept exploration are discussed. Next, the research question, as defined in Chapter 1, will be answered by the final design.

5-1 Concept Exploration

Two different concepts have been explored. The first one uses Magnetic levitation technology. In this concept, the aircraft is installed on a moving, levitating platform which is accelerated along the track to the launch velocity. The second concept does not use magnetic levitation, only a linear motor is used for propulsion. A shuttle connects with the aircraft and accelerates along the track. Unlike the previous concept, the aircraft rests on its landing gear as with a conventional take-off while accelerating.

A trade-off is performed between both concepts on performance, energy consumption, electric equipment, runway modifications and airport modifications. Concept 2 has been selected for further elaboration as the final concept due to the following reasons:

- Concept 2 consumes up to 30% less energy. A total amount of 14GWh per year of electricity is consumed compared to a consumption of 20GWh per year by Concept 1, for launches to a take-off velocity of 120m/s. These numbers are equivalent to the annual energy demand of 2674 and 3761 Dutch five person households.
- A smaller amount of electromagnetic area is required, 1.4m^2 (Concept 2) versus 5.24m^2 (Concept 1). The smaller magnetic area requirement is due to the absence of levitation and the reduced thrust force (559kN vs. 786kN).
- The control system is less complex compared to Concept 1 since guidance and suspension systems are substituted by wheels, the control system is restricted to propulsion operations.
- Concept 1 requires more electric equipment as suspension and guidance are facilitated by the maglev system, in Concept 2 wheels are used for suspension and guidance of the cart. Due to the increased energy consumption of Concept 1, a larger amount of electricity for launches needs to be generated and stored at the airport.

The main advantage Concept 1 has over Concept 2 is that it does not require modifications for the main gear attachment while Concept 2 requires aircraft attachment modifications, either at the nose wheel or at the keel beam.

5-2 Final concept

The final concept developed during the course of this thesis will answer the research question, stated as:

> *"Can a system be designed that utilizes magnetic assisted take-off of conventional passenger aircraft from a conventional airport?"*

and the accompanying sub-questions:

1. How would such a system function?
2. What aircraft modifications are required?
3. What airport modifications are required?
4. What are the system's power/energy consumptions?

All sub-questions will be answered in the next paragraphs.

1. *How would such a system function?*
   The final functional requirements and performance requirements for the launcher are given in Figure 4-7a and Figure 4-7b. To summarize the performance requirements, the launcher should reach a maximum launch velocity of 113m/s over a launch stroke of 2900m and a maximal mean acceleration of 0.24g is used.

   In the final design, the launcher is connected to the keel beam. This beam is located where the lower part of the fuselage is cut up by the wheel wells (see Figure 4-5) and is the most reinforced part of the fuselage. The attachment at the keel beam is located between the main gear and the nose gear, in front of the most forward centre of gravity, to increase the directional stability.

   The operation of the system goes as follows: the aircraft taxies to the runway, once arrived, it goes to the launch track located on the runway. There, the pilot positions the aircraft and the shuttle drives in from the rear of the aircraft to connect the launcher to the aircraft. Once the shuttle is attached, the pilot communicates with air traffic control and initiates the launch. Aircraft and shuttle accelerate to the launch velocity. At the end of the track when the launch velocity is achieved, the shuttle detaches and decelerates to a standstill. The aircraft rotates and initiates the climb. The shuttle returns to the aircraft pick-up point.

   A linear synchronous motor is used to propel aircraft. The stator of the LSM is processed in the track on the runway and the shuttle, the moving part of the motor, is equipped with electromagnets. These electromagnets are installed on the lower part of shuttle, hidden in the track. Through excitation of the magnets, a magnetic thrust force is generated to accelerate the shuttle along the track. Electromagnets are chosen over permanent magnets because they are able to generate a thrust force per square meter twice as large as can be generated by permanent magnets. This reduces the size of the magnetic area on the shuttle. A total electromagnetic area of $0.57m^2$ is installed on the shuttle. The stator in the track is divided in sections for optimal energy efficiency of the linear motor as each section can be energized individually.

In order to connect the shuttle to the aircraft, an autonomous positioning system is required. A launch bar is installed on the shuttle and is positioned by two actuators to the aircraft attachment part. These actuators are positioned at the left and at the right side of the launch bar on the shuttle, at 60cm of the origin of the launch bar in longitudinal direction and 41cm in lateral direction. The positioning of the actuators allows an accuracy of the launch bar positioning within 2cm. The launch bar has an overall length of 4.7m. The aircraft attachment is designed such that only forces in the launch direction can be applied, otherwise the system decouples. The movements of the launch bar are restricted in height by 1.84m and in lateral direction 0.5m from the centreline of the track. The shuttle has a length of 1.5m, a width of 1m and a maximum height of 30cm. The final launcher design connected to a demo aircraft is shown in Figure 5-1.

A control system is installed at the airport to facilitate the communication between the launcher, air traffic control and the aircraft. This control system also controls the movements of the launcher and monitors the performance; acceleration, speed, thrust and power consumption. Each track section is controlled and powered by the control system.

2. *What aircraft modifications are required?*
   The major aircraft modifications resulting from installation of the system imply, mounting the attachment object to the exterior of the fuselage at the keel beam and installing a cockpit device, which gives information on the status of connection and the shuttle operating mode (aircraft docking, accelerating, etc.) to the pilot.

3. *What airport modifications are required?*
   The track needs to be installed at the centre of the runway with a maximum track trough width of 10cm. Marks for aircraft positioning at the runway are required.

   A control system needs to be installed at the airport for motion control of the shuttle and to facilitate the communication between the launcher, the aircraft and air traffic control.

   Power storage and power generation systems are required, to provide the needed amount of energy per launch. High-current power cables are used to transfer the electricity to the launch track.

   A display needs to be installed at air traffic control to monitor the actions of the shuttle (aircraft docking, accelerating, etc.) and track the location of the shuttle

4. *What is the system's energy consumption?*
   The system is designed to launch aircraft with maximum take-off weight up to 90,000kg. At Schiphol airport 80% of all daily departures can be facilitated by the launch system. Two accelerations have been used for the launcher energy calculations, 0.2g and 0.24g. The launch stroke equals 2900m. On an annual basis, Schiphol Airport will approximately consume 6,703MWh of electricity for launching aircraft, with a mean acceleration of 0.2g and 8,295MWh with a mean acceleration of 0.24g. These numbers correspond to the annual energy demand of 1269 and 1570 Dutch five person households, respectively.

To answer the main research question, it is possible to design a system that utilizes magnetic assisted take-off of conventional passenger aircraft from a conventional airport, however, more research is required and this will be discussed in Chapter 6.

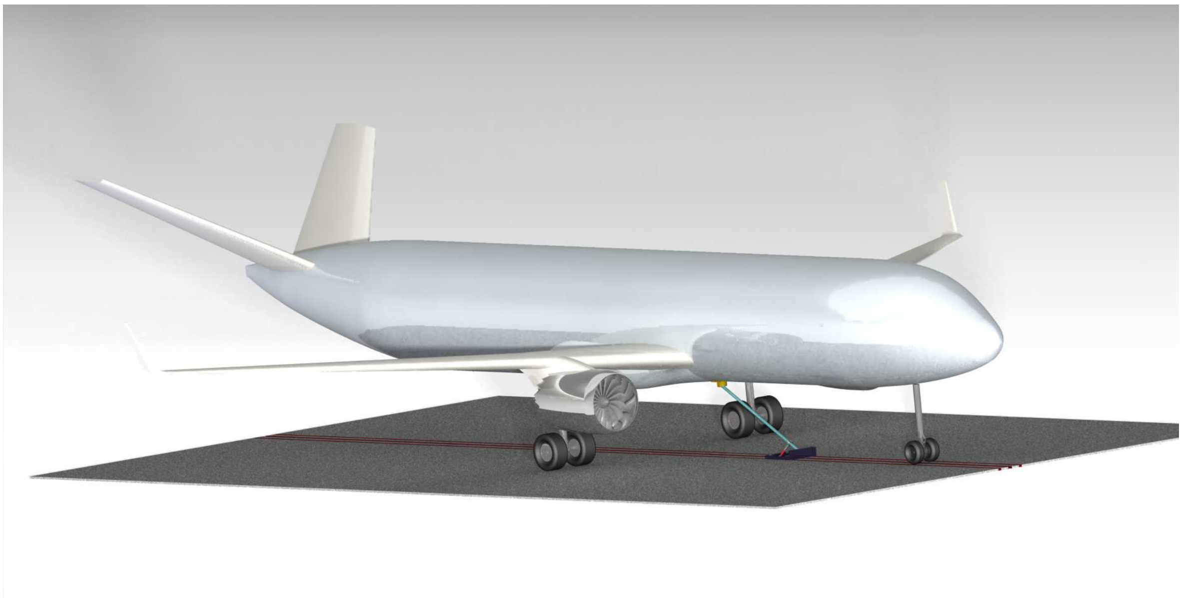


Figure 5-1: Final launcher attached to a demo aircraft

Chapter 6

Recommendations

This thesis has put the focus on the technical feasibility in the development of a launcher designed to assist aircraft during take-off. A conceptual design for a launcher is proposed but other aspects need to be investigated as well. Before this system can be made operable, research is required in the field of operations, control, regulations, aerodynamics, economics, noise and electric motor design. Before research is started in the above mentioned fields, it is important to find out first what the possible noise benefit is in the vicinity of airports resulting from the implementation of the launch system. The achievement of a possible noise benefit was the primary objective for the design of a magnetic assisted take-off system. Therefore, it is recommended to start upcoming research in this area.

6-1 Further research suggestions

To make the proposed concept operable, further research to be performed in different areas is discussed. A distinction can be made between two categories, topics that require more in depth research and topics have not been researched and should be investigated.

6-1-1 Topics to be elaborated more in depth

Structural part analysis: A structural analysis of different part design for the shuttle, the track, the aircraft attachment and the launch bar need to be performed and redesigned if needed. Different materials have to be selected for the different parts. During the launch bar design, attention should be put to minimize the flexibility when choosing the material and defining the structural layout of the launch bar. When the parts are designed structurally, a refined weight estimation of the shuttle can be established. Additional research is required regarding the placement of the attachment point on aircraft. If it is possible to move the attachment point more forward than what is currently possible, the directional stability of the system during launch will increase. The effects of attachment at the keel beam should be investigated. It could be possible that the attachment location needs additional reinforcements due to increased stress concentration areas.

Electric motor design: The electric configuration of the linear motor has been investigated briefly. A proper motor design however should be proposed with design specifications on the pole pitch, the current, the voltage and other characteristics. The main performance requirement of the motor is to accelerate the shuttle over the length of the track. Therefore, the motor should be designed to achieve optimal acceleration in each section of the track. Each section can be adapted in the design to achieve this goal. An analysis on optimal motor layout for each section is desired. Different lengths per section can be established based on the output velocity per section. This also requires research in motor excitation magnets and thermal properties of the motor. There is a chance that active cooling is required.

Launch simulations: Simulations of launches with different aircraft should be performed. These simulations can give insight on the optimal thrust settings for the aircraft, the flap settings, the flight trajectory to be followed, the optimal launch speed for different specifications, like minimal noise spread. These simulations are likely to result in a change of aircraft operations. Different trajectories can be developed with the aid of the system. The resulting forces acting on the shuttle and the aircraft can be simulated during a launch and analysed. Effects of the attachment location on the directional stability of the aircraft can be analysed.

Control system development: The control system needs to be designed.All actions and movements of the shuttle are controlled by this system and communicated to the aircraft and air traffic control. Feedback on the launcher performance (speed, acceleration, thrust, power consumption) should be communicated with air traffic control.

Airport integration: How the system will fit in the airport has been investigated. Though, more research in this topic is important. New ground operating procedures have to be elaborated. Where the airport will get its electricity from, how it will be transported to the launch track. The influence of the application of the launch system on the current airport operations should be investigated. For example the influence on the amount of departures, and many other topics related to airport integration.

Safety: The aspect of safety has been discussed in the worst-case scenarios but more considerations towards safety are required. What is the effect of taking off with low thrust settings? What happens when the aircraft does not align with the track any more? Does the application of the system increase safety? What is the effect on the safety of the passengers and the airport while using this system?

Avionics and air traffic equipment: The additional equipment resulting from the application of the launcher for the cockpit and ATC is suggested. How it will eventually be installed has not been investigated. How easily can it be installed in the cockpit and how can implemented for ATC? To what extend are avionics influenced by the magnetic field created by the linear motor? What measures can be taken to prevent this?

Aerodynamic drag: It should be investigated for airborne aircraft to what extend drag increase results from the aircraft attachment and how it can be prevented, by placing for example fairings.

Launch velocity: Currently, the maximum launch velocity considered does not go beyond the maximum allowed landing gear extension speed. This velocity exceeds the maximum tire velocity. More research in achievable launch velocities is required.

6-1-2 Topics not yet researched

Costs: An analysis of the costs for the installation and the exploitation of the system in the airport should be done.

Regulations: Changes in regulations need to be investigated and new regulations need to be proposed such that implementation of the system is possible.

Certification: It should be investigating to what extend the system needs to be certified and how the system can meet certification requirements.

Weather resistance: It has not been investigated how the system behaves during precipitation or cross wind. This system might create opportunities for launches with tail wind, as it accelerates aircraft to a higher velocity. These factors can affect the operability of the system. Research in this topic is necessary.

Operations: The resulting changes in operations of aircraft should be examined. New trajectories and procedures can be established. The departure rate can be altered. If substantial reductions in noise reductions are achieved, the evening and early morning departures, having more strict noise allowances, can be increased.

Noise and fuel emissions: As mentioned earlier, research in noise and fuel emissions resulting from operations of the system need to be investigated and analysed. Since noise reductions in the vicinity of airports were the primary objectives in the design of a launch system, it is essential to research possible noise and fuel emission reductions. Launch simulations can be created for different aircraft to analyse the noise and fuel emissions.

Suggestions for research have been proposed and it can be concluded that a lot more research is required to achieve an operable system. However, hopefully, this thesis gives some insight in the design of the launcher and can be the first step in achieving a fully operable system, to be installed on airports within a few decades.

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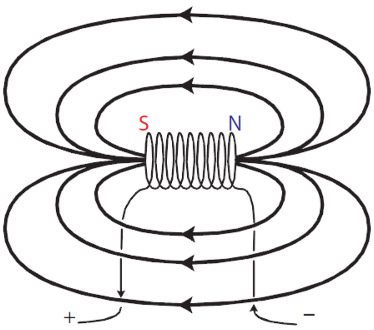
Appendix A

Electromagnetism

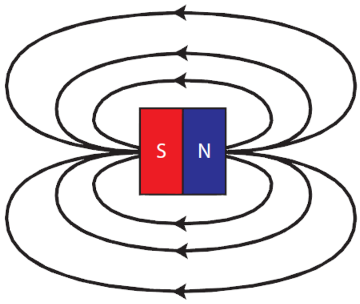
A-1 Permanent Magnets/ Electromagnets

Permanent Magnets are able to produce magnetic flux in an airgap without excitation of windings or dissipation of electric power. It consists of ferromagnetic material and a similar name to permanent magnets is hard magnetic materials. Rocks can contain ferromagnetic material and are abundantly present on Earth. PMs are well known in daily life, think at refrigerator magnets, and are used in many applications.

An electromagnet is the opposite to a permanent magnet. It does not have the natural ability of a permanent magnet to create a magnetic flux, only through the excitation of windings or dissipation of electric power, it is able to generate a magnetic field. In Figure A-1 both types of magnets are shown for comparison. Note that the magnetic field lines are going from North to South.



(a) Electromagnet [3]



(b) Permanent Magnet [3]

Figure A-1: Electromagnet and Permanent Magnet

A-2 Halbach Arrays

Halbach arrays are named after the physicist Klaus Halbach. It is an array of permanent magnets which are placed in certain manor with a certain orientation such that the flux densities are combined on one side and on the other side are cancelled [31]. It makes optimal efficient use of permanent magnets for creating a periodic magnetic field near the lower surface of the array. This result is accomplished by cancelling the field above the array, while producing a nearly purely sinusoidally varying periodic magnetic field below the array. This magnetic field falls off exponentially with distance away from the lower side of the array.

They are applied in the Inductrack concept which involves two main components: a special array of PMs mounted on the vehicle and a track embedded with close-packed coils. When the Halbach arrays are mounted on the bottom of the vehicle, a magnetic field is generated by the arrays that induces currents in the track coils and as a consequence lifting the vehicle by several centimetres and stably centring it [68]. Figure A-2 gives a representation of the arrangements of the permanent magnets of the Halbach array.

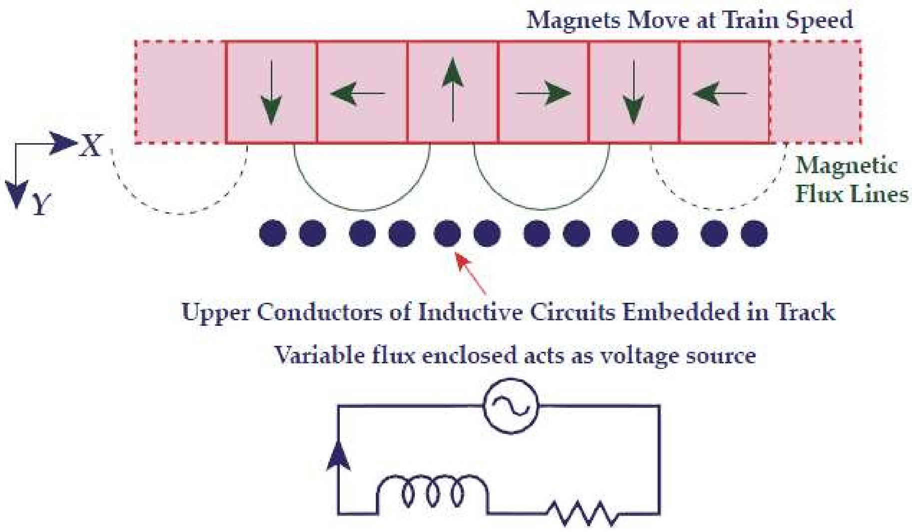


Figure A-2: Schematic diagram of Inductrack concept

A-3 Superconductivity

Superconductivity is a state at which almost no electric resistance exists in some metals. This state occurs at temperatures close to the absolute minimum 0 K. This phenomenon was discovered in 1911 by H. Kammerlingh-Onnes when trying to liquefy Helium as Helium only liquefies at temperatures this low [23].

Superconductors are able to carry a large direct current without any resistance and to exclude a static magnetic flux from its interior. This latter is known as the *Meissner effect* and distinguishes a superconductor from a conductor. A conductor conserves the magnetic flux in its interior. The critical temperature T_C is the temperature at which a material becomes a superconductor, dependant on the material, the critical temperature can range from 1K to 130K [23]. Today, a lot of research is conducted to achieve the superconductive state at room temperature because cooling to temperatures this low also cost a lot of energy. If a permanent magnet (PM) is placed on top of a superconductor and the superconductor is above its critical temperature, and is cooled below its critical temperature, the magnetic field of the permanent magnet is excluded by the superconductor. The PM is repelled and if the weight of the PM is lower than the repulsion force, the PM levitates above the superconductor.

Besides the critical temperature, two other critical quantities need to be considered, the critical magnetic flux density B_C and the critical current density J_C. These critcal values are dependent on each other and must not be exceeded at any case. When they are exceeded, the material loses its superconductivity and generates the electrical resistance (*quench effect*). In synchronous machines superconducting windings are used as D.C. excitation windings. The excitation system does not have any ferromagnetic core because the magnetic flux density exceeds the saturation magnetic flux density. This explains why the Japanese MLX system uses air-cored superconductors.

Superconductivity is used in electrical machines and reduces excitation losses, increases magnetic flux density, eliminates ferromagnetic cores, and reduces the synchronous reactance in synchronous machines.

Appendix B

Drawings

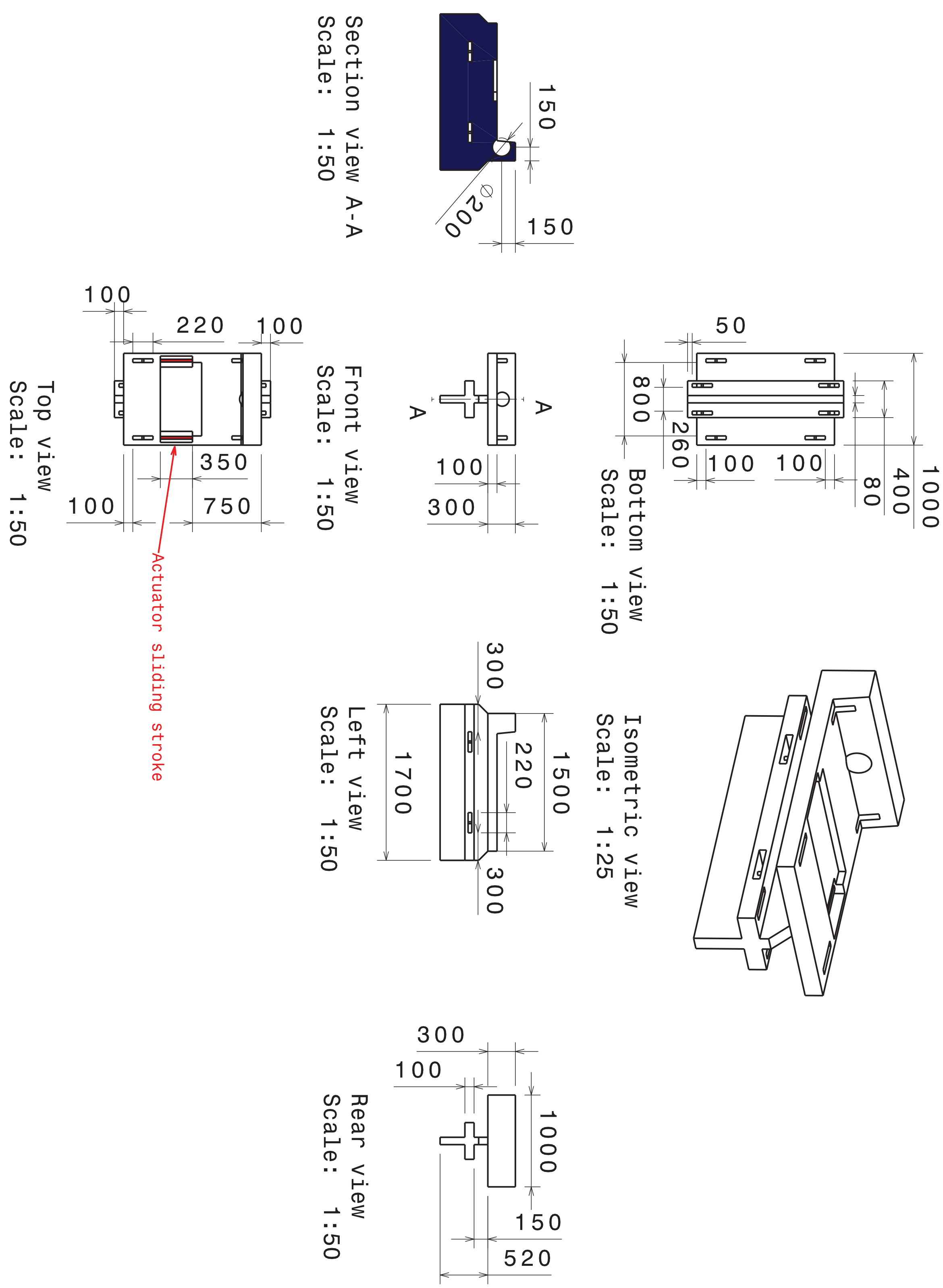


Figure B-1: Shuttle 2D drawing, dimensions expressed in mm

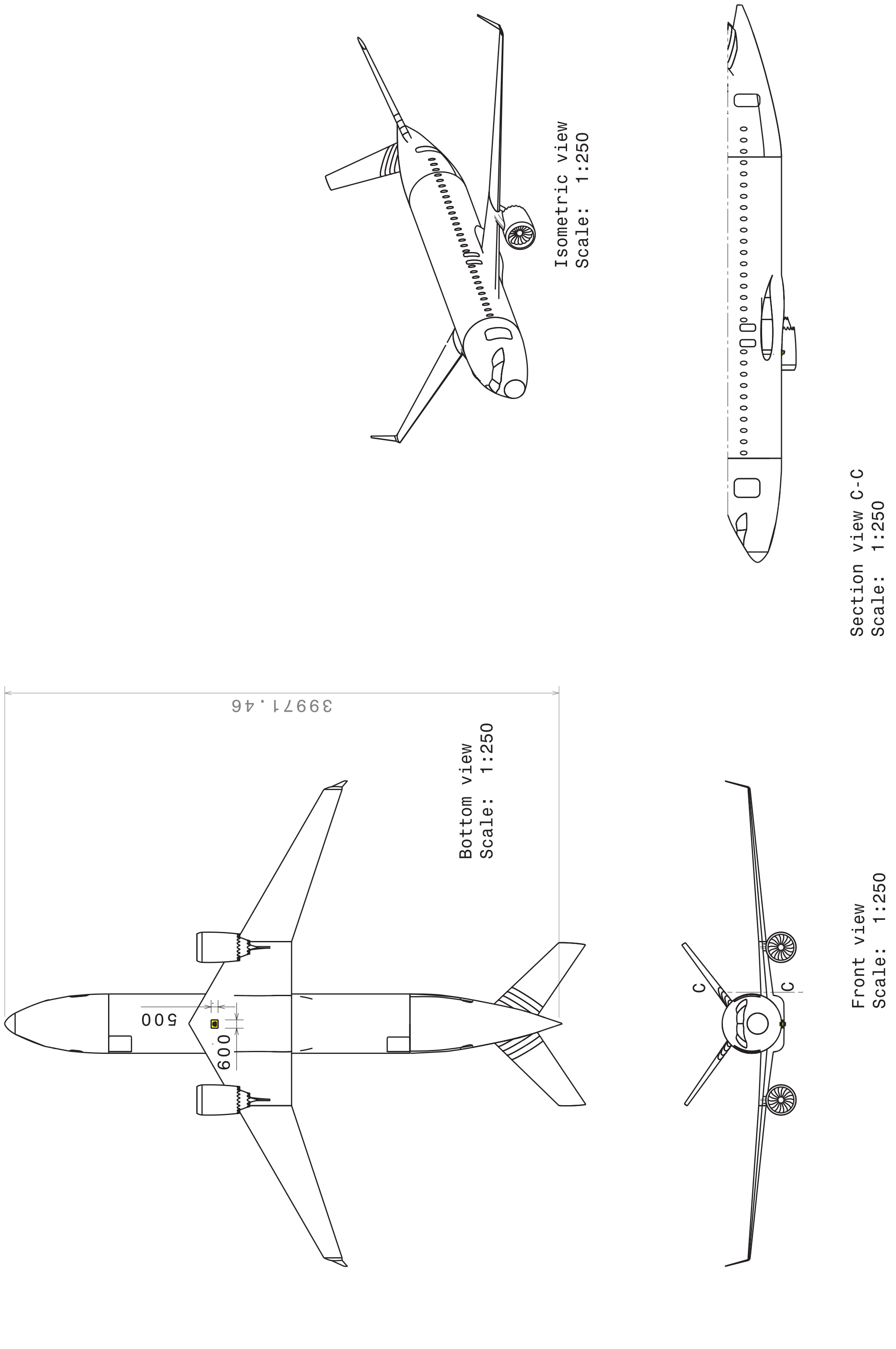


Figure B-2: Aircraft in flight with attachment mounted on it

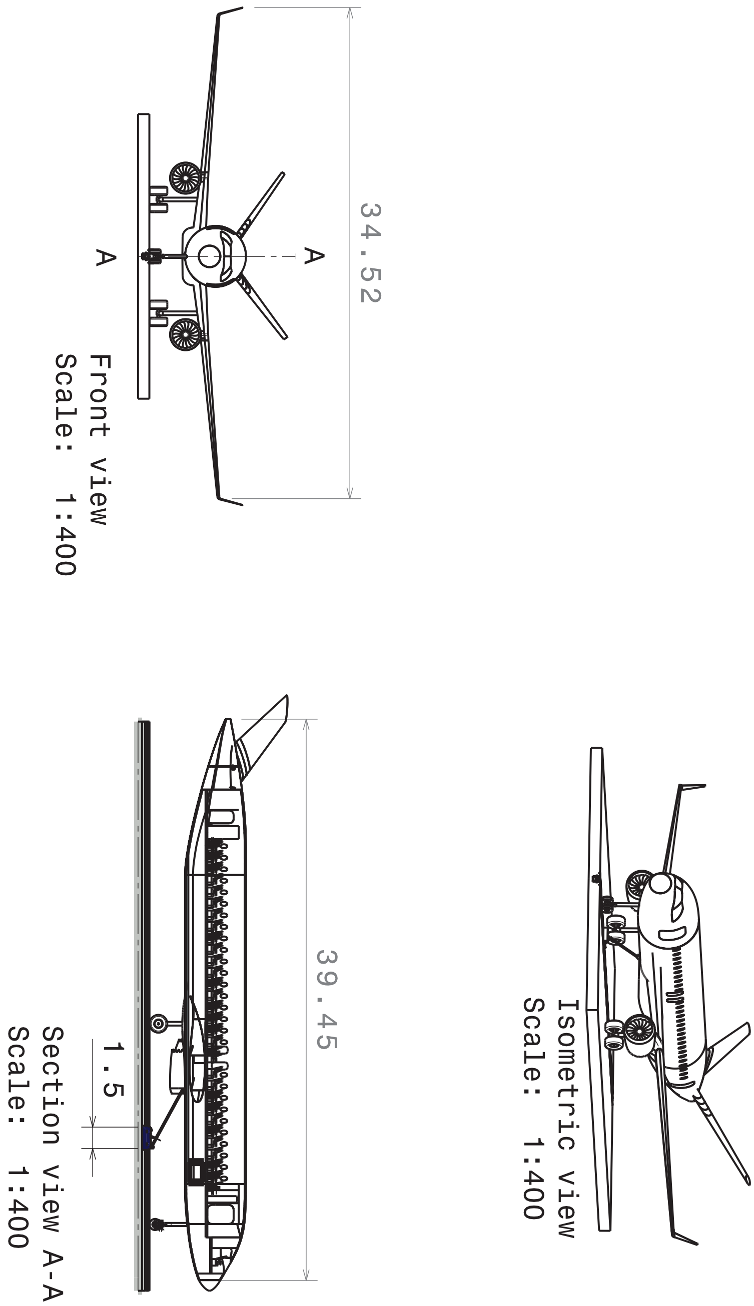


Figure B-3: Demo aircraft attached to the shuttle on the runway, expressed in m

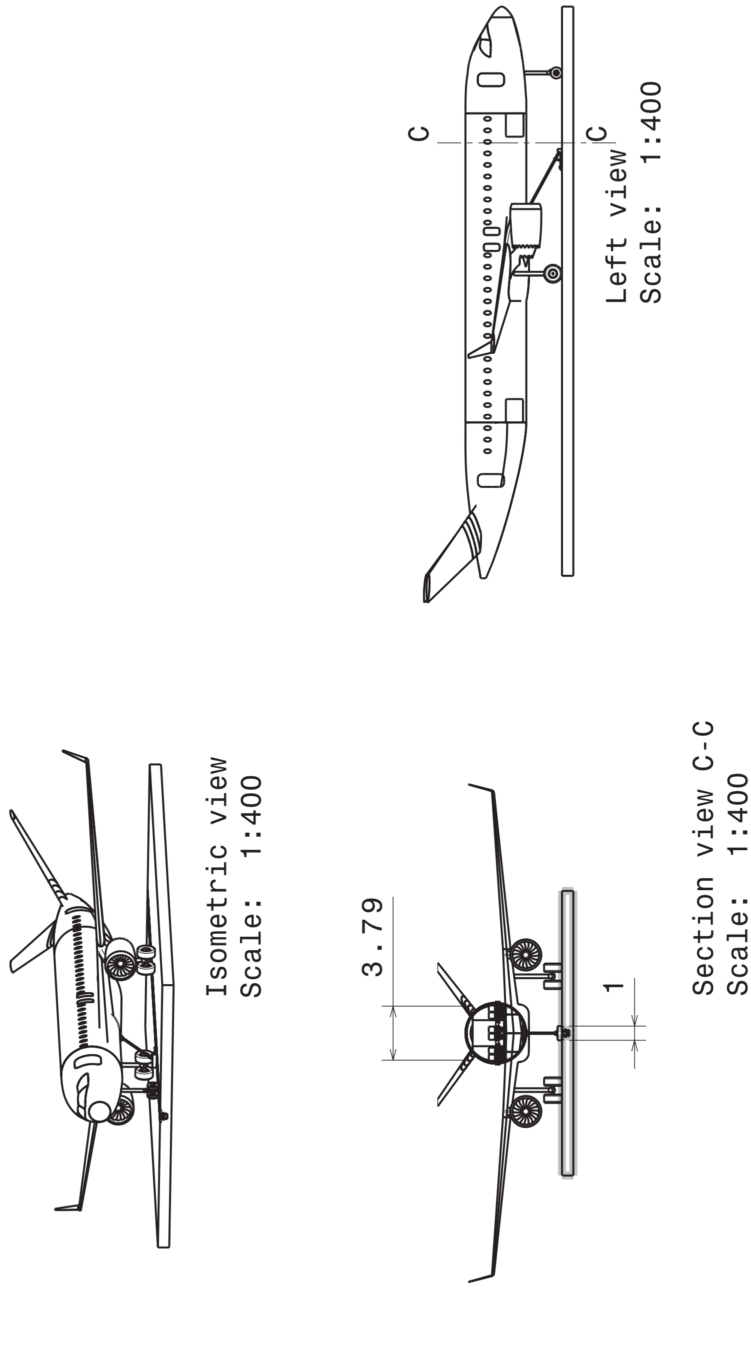


Figure B-4: Demo aircraft attached to the shuttle on the runway, expressed in m