4. Propulsion

Propulsion is the subsystem that generates the movement of the pod. The two most promising propulsion mechanisms for the hyperloop, will be introduced and explained. The advantages and disadvantages are listed and the mechanism will be assessed on design criteria. After assessing all mechanisms, a trade-off will be made to determine the best propulsion system. Eventually, a recommendation is given by Delft Hyperloop on which propulsion method to use for a hyperloop. The flowchart (see Figure 4.1) represents the structure of this chapter. The top-level system requirements and the environmental boundaries are input values for this chapter. Within these limits, the propulsion systems will be evaluated in Sections 4.1, 4.2 and 4.3. The final section of this chapter gives a recommendation on which propulsion mechanism to use.

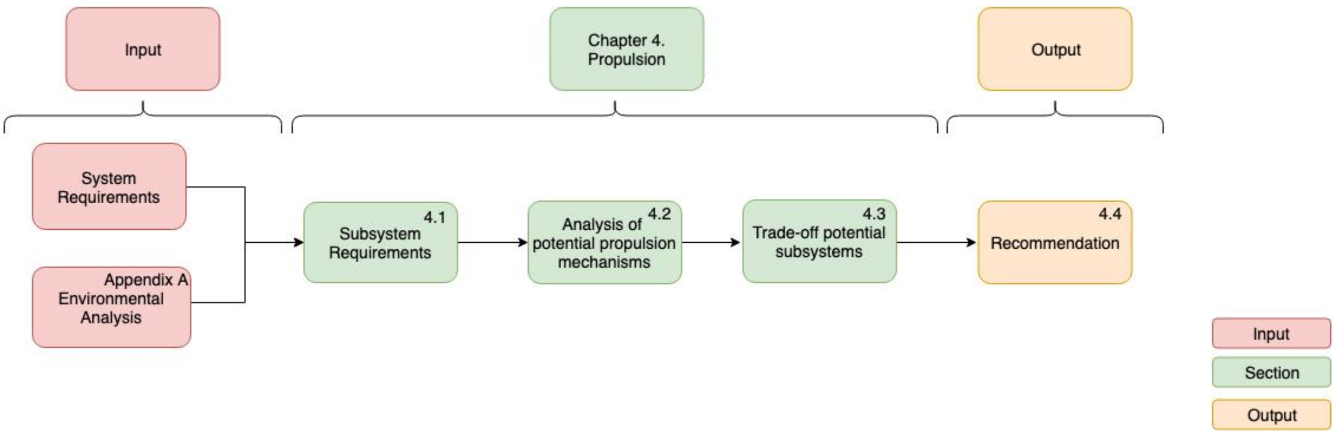

Figure 4.1: Flowchart representing the structure of this chapter.

4.1 Subsystem Requirements

The propulsion mechanism has to be capable of accelerating the pod to the cruising speed and to maintain this speed. Because the pod levitates, the propulsion has to function without any contact. A complete subsystem analysis of the propulsion subsystem is given in this section. Two mechanisms will be introduced; Linear Induction Motor (LIM) and Linear Synchronous Motor (LSM). In the next section they are discussed in more detail and a trade-off is made to determine the most feasible options. The subsystem requirements are determined based on the top-level system requirements and an environmental analysis (Appendix A). The latter determines the limits of the environment in which the system should be able to operate.
The vehicle will levitate in order to be as energy efficient as possible, as was discussed in Chapter 3. Therefore, no propulsion mechanisms can be used that operates on wheels. The Linear Induction Motor (LIM) and Linear Synchronous Motor (LSM) produce a propulsion force electromagnetically and work in combination with levitation. The subsystem requirements for the propulsion are given by the list below.

The subsystem shall:

- be able to accelerate the vehicle to cruising speed (assumed to be 1080 km/h).
- be able to maintain cruising speed (assumed to be 1080 km/h).
- be able to reach high accelerations (compared to accelerations limited by passenger comfort) for goods transportation.
- have the ability to brake.
- transform kinetic energy to electrical energy while braking (regenerative braking).
- The magnetic fields in the passenger compartment should not exceed the values indicated by human safety in magnetic field guidelines [Kircher et al., 2018].
- gather data on temperatures, velocities, acceleration and power consumption [Kaye & Masada, 2004].
- be able to function within the limits given by the environmental analysis (see Appendix A).

The design criteria on which the potential subsystems will be assessed are listed below. More information about these design criteria is given in Appendix B.

- *Reliability*
- *Power consumption*
- *Cost*
- *Safety*
- *Complexity*

The TRL[1] of the technology is important to take into account as well. For more information, see Appendix D.

4.2 Analysis of Potential Propulsion Mechanisms

In this section, two propulsion methods are elaborated further upon. For each mechanism, the current situation and TRL is stated, after which the advantages and disadvantages are given. Succeeding, the propulsion mechanism is briefly summarised and will be assessed according to the design criteria. With this information, a trade-off will be made in the next section. The mechanisms that will be discussed are respectively Linear Induction Motors (LIM) and Linear Synchronous Motors (LSM). The structure of this section is depicted in Figure 4.2.

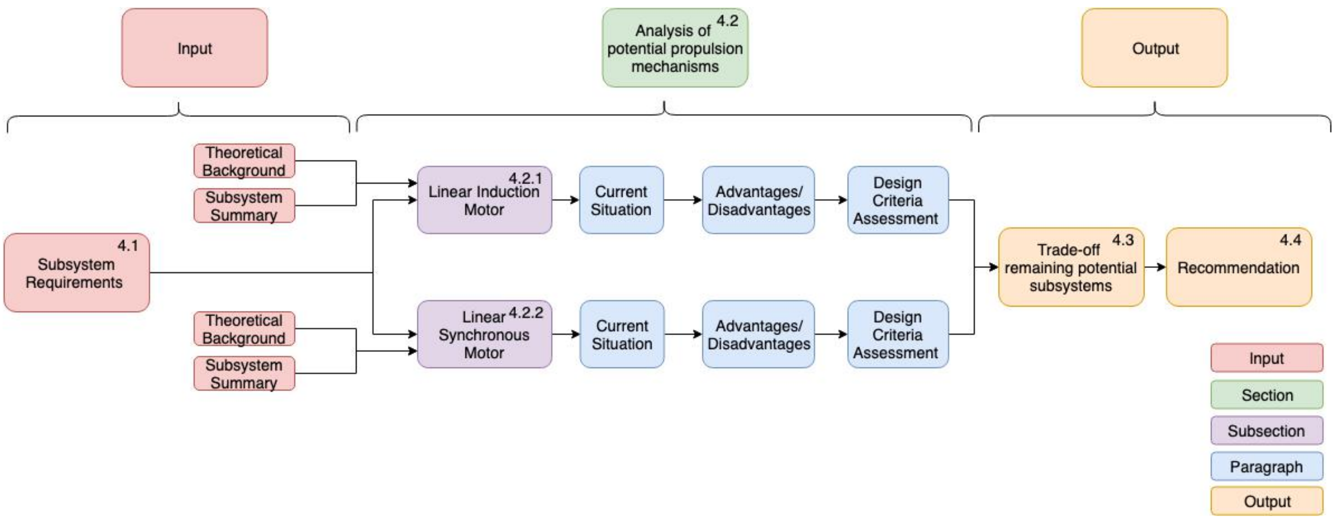

Figure 4.2: Flowchart of the propulsion mechanism analysis.

4.2.1 Linear Induction Motor (LIM)

A Linear Induction Motor originates from a rotary motor and works in a similar way. A rotary motor consists of a stator and a rotor. However, the rotor is cut open and laid out flat. The stator and rotor are respectively called primary and secondary in the linear motor.

The function of the primary part is to generate a varying magnetic field across the air gap, this is called the stator. The magnetic field induces an electromotive force in the secondary part of the LIM, a conductor. This electromotive force creates eddy currents which interacts with the magnetic field of the primary, thereby creating a propulsion force.

Two variants of LIM exist: short primary (SP) and long primary (LP). The stator is always the primary and the conductor is always the secondary.

- Short primary: stator is on-board of the pod and the conductor is in the guideway.

- Long primary: stator is in the guideway and the conductor in on-board of the pod.

Current Situation

A few examples that use LIM for propulsion are listed below. Note that they all of them operate on relatively low speeds. All examples use Short Primary LIM as propulsion mechanism.

1. HSST (Japan): High Speed Surface Transport, maximum speed of 100 km/h [Cassat & Bourquin, 2011] and it uses electromagnetic suspension to levitate.

[1]Technology Readiness Level: a level indicating the development of a certain technology, originally invented at NASA [Mankins, 1995]

2. Korean Hyundai Rotem (South Korea), maximum speed of 110 km/h. The used technology is similar to the HSST technology. [Cassat & Bourquin, 2011]
3. Changsha (China): maximum speed of 100 km/h [Yang et al., 2018].

The TRL of LIM is 9 because it has been researched, developed and implemented in multiple projects already.

Advantages and Disadvantages
The advantages and disadvantages of a Short Primary LIM are represented in Table 4.1.

Table 4.1: LIM Short Primary - Advantages and Disadvantages

Advantages	Disadvantages
• Proven its operation for Maglev [Cassat & Bourquin, 2011][Yang et al., 2018][Thornton, 1993]. • Implemented in applications besides transportation (e.g. cranes, pumps, actuators, conveyor systems and accelerators). Because of its many applications, the system has been researched many times which results in a higher reliability. • Relatively cheap guideway because no active parts and power supply have to be installed (a conducting sheet is sufficient). • No gears required (no mechanical rotary to linear converter).	• A reduced energy efficiency because of end effects. Moreover, the energy efficiency is reduced because the air-gap flux is inductively created. The leakage inductance for the LIM is inherently large and gets worse with an increased air-gap. • Heat generation in the short primary (pod). • Because of the large air gap of EDS, LIM is not efficient in combination with EDS.

The advantages and disadvantages of a Long Primary LIM are represented in Table 4.2.

Table 4.2: LIM Long Primary - Advantages and Disadvantages

Advantages	Disadvantages
• Implemented in high speed Maglev. • No gears required (no mechanical rotary to linear converter). • Relatively high acceleration and deceleration is achievable since the active parts are in the guideway and therefore no heavy batteries are required on-board, reducing the mass to be accelerated. • Able to reach high speeds and do this more efficient than a SP LIM. • Flexibility to respond to variable or uncertain demand, number and size of pods can be adjusted without problems [Kaye & Masada, 2004].	• Air-gap flux is inductively created, the leakage inductance for the LIM is inherently large and gets worse with an increased air-gap, therefore it has a low energy efficiency. • Increased guideway cost because all the active parts of the LIM have to be positioned in the guideway. • Heat generation in the guideway. • Because of the large air gap of EDS, LIM is not efficient in combination with EDS.

Design Criteria Assessment
- *Reliability:* Linear Induction Motors are being used in several applications with a high rate of success. However, the LP LIM has not been in operation for high speed transportation.
- *Power consumption:* energy efficiency of the LIM is low because of end effects [Yang et al., 2018][Liu et al., 2015]. The larger the database with information about LIM performance (e.g. data of LIM drives in steel-wheel transit systems), the higher the reliability of the system will be [Kaye & Masada, 2004].

- *Cost:* in case of an LP LIM, guideway cost will rise significantly because the guideway has to be active and installed with coils. The guideway cost of an SP LIM are lower.
- *Safety:* the system has not been implemented in high speed passenger transport, therefore it should be tested thoroughly to guarantee the safety. The magnetic fields created by the LIM will not be dangerous for passengers located in the passenger compartment. At low speeds, the HSST has proven to be safe.
- *Complexity:* electrical complexity of the LIM is high, maintenance has to be performed regularly.

These characteristics will be used in a trade-off, summarised in Table 4.4.

4.2.2 Linear Synchronous Motor (LSM)

The Linear Synchronous Motor is a propulsion mechanism in which the mechanical motion is synchronous with the magnetic field. The thrust force is not created by an induced magnetic field, but the magnetic field is created by windings. For this it is necessary to know exactly at what position the vehicle is and at what speed it is travelling.

Current Situation
The LSM propulsion has been implemented in multiple Maglev projects already. Examples are listed below:

- The German Transrapid (TR07) uses LSM propulsion in combination with EMS levitation. The top design speed is 482 km/h [Lever, 1998].
- Japanese MLX01 currently holds the world Maglev speed record (581 km/h) while using LSM for propulsion and EDS with null-flux coils to provide lift and guidance.
- Bechtel, this project was started but eventually the US government stopped its funding [Lever, 1998], the design cruising speed was 482 km/h.
- Grumman, this project was started but eventually the US government stopped its funding, the design cruising speed was 482 km/h [Lever, 1998].

The TRL of LSM is 9 because it has been researched, developed and implemented in multiple projects already.

Advantages and Disadvantages
The advantages and disadvantages of a LSM are represented in Table 4.3.

Table 4.3: LSM - Advantages and Disadvantages

Advantages	Disadvantages
• Already in operation in the Transrapid Maglev Cassat & Bourquin [2011]. • The energy efficiency is high (0.8-0.9) compared to that of a LIM. • Ability to reach high speeds (e.g. the Japanese MLX: 581 km/h). Almost all high-speed Maglev designs use a LSM for the propulsion [Han & Kim, 2016]). • Energy does not have to be transferred to the pod since the primary can be in the track [Kaye & Masada, 2004]. • High accelerations can be reached, this could be useful for transporting cargo. However, for passenger transport, the acceleration is limited by safety requirements and passenger comfort [Kaye & Masada, 2004].	• Higher cost compared to LIM because the LIM only requires one active part (in the pod or in the guideway). • LSM lacks the flexibility to easily change with system capacity and operational modes. Moreover, the system needs to be designed for the highest expected demand. If the demand is lower than expected, the system turns out to be over-designed [Kaye & Masada, 2004]. • Requires data for the exact position of the on-board magnets to ensure that the vehicle is synchronous with the traveling wave generated by the stator winding in the guideway [Kaye & Masada, 2004].

Design Criteria Assessment
- *Reliability:* by placing various sensors the reliability enlarged. It is important to know the position and velocity of the pod at all times to ensure the reliability [Kaye & Masada, 2004]. The reliability of active guideways and switches must be established with tests.
- *Power consumption:* the energy efficiency on high speeds around 300 km/h is above 80% and can be even higher at higher speeds.[Kaye & Masada, 2004].

- *Cost:* high investment cost because the active guideway and power supply installation needs to be designed for the highest expected demand. If the demand is lower than expected, the system turns out to be over-designed [Kaye & Masada, 2004].
- *Safety:* the safety has not been implemented often in high speed passenger transport, therefore it should be tested thoroughly to guarantee the safety. The magnetic fields created by the LSM will not be dangerous for passengers located in the passenger compartment.
- *Complexity:* the system is not complex and has been built before. However, maintenance may be time-intensive. If a segment of stator windings malfunctions, repair and re-qualification testing results in the whole track being out of service [Kaye & Masada, 2004].

These characteristics will be used in a trade-off, summarised in Table 4.4.

4.3 Trade-off

In Table 4.4, the discussed propulsion methods are assessed according to the design criteria. The trade-off in Table 4.4

Table 4.4: Trade-off propulsion mechanisms

	Concept 1 **LSM**	**Concept 3** **LIM SP**	**Concept 4** **LIM LP**
Power consumption	0	- -	-
Cost	0	+	-
Reliability	0	+	+
Safety	0	0	0
Complexity	0	+	-

compares the possible methods for the propulsion of the hyperloop with LSM as the baseline measurement. It can be derived from this trade-off that a LIM with a long primary (active guideway) is the least optimal propulsion mechanism for a hyperloop.

An LSM is the best option if the system is assessed from an energy efficiency point of view. Especially for high speed operations the LSM is preferred because of the low energy efficiency of LIM at high speeds. Moreover, the ability to transfer the high electrical power to the pod is impractical at speeds of the hyperloop [Kaye & Masada, 2004]. However, the reliability and safety of the LSM system is less than the LIM because the LIM has been put into practice many times before.

4.4 Recommendation

Two propulsion mechanisms were introduced as potential propulsion subsystems for the hyperloop. Namely, Linear Synchronous Motors and Liniear Induction Motors. For the Linear Induction Motors two types were assessed: LIM with a short primary and LIM with a long primary. The mechanisms were assessed according to the following design criteria: power consumption, cost, reliability, safety and complexity. A trade-off was made to determine the best option.

If it is desired to develop a system that is energy efficient and is able to achieve high velocities (over 1000 km/h), one should opt for LSM. Moreover, LIM is not compatible with EDS levitation and requires non-contact charging of the batteries during the journey. However, the guideway costs and complexity of an LSM propulsion system are higher than those of a LIM.

Since the envisioned hyperloop system of Delft Hyperloop must be energy efficient and requires speeds of approximately 1000 km/h, the LSM is the best option for the propulsion system of a hyperloop. Future research must prove the safety and reliability of a LSM system at high-speeds of 1000 km/h. This should be achieved through extensive testing of the system at a high-speed test facility. Only when safety and reliability are guaranteed, could LSM be a real option for the hyperloop.