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Development Paths of Multi-Car Elevators

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology

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Abstract

While the world's population moves to cities and the height of the building base rises, the limitations of elevator technology become more significant. The greatest problem of the modern elevator is the required space. Related to this is the majority of the hoistway volume, which is not in active use on a traditional single-car elevator. This inefficiency results in a large loss of usable floor space, especially in high-rise buildings.

This thesis discusses attempts to solve the inefficiency problem by installing multiple elevator cars into a single hoistway. The elevators with multiple cars have existed since the 19th century, and various development paths have been present, but currently only one product is commercially available. The thesis presents design challenges and solutions that are characteristic for multi-car elevator concepts.

While the current elevators move only vertically, horizontal car movement can be considered to be a mandatory feature to achieve the expected capacity of a future multi-car elevator. The horizontal movement is required to enable possibility for cars to pass each other. Most patents on multi-car elevator concepts are based on conventional roped hoisting equipment. However, linear electric motors are considered to be a promising technology that could provide propulsion more easily in all directions.

In theory, a "vertical train" –like elevator concept could have a flexible number of cars in the same hoistway. The additional cars would reduce the number of hoistways and enhance the usability of the system in different installation heights. Still today, only a few of the self-propelled elevator concepts have survived beyond the prototype stage. Three common challenges with the concepts include power-transfer, safety, and costs.

Keywords multi-car, elevator, lift, self-propelled, circulating, multi-path, hoistway

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Tiivistelmä

Maailman väestön muuttaessa kaupunkeihin ja rakennuskannan kohotessa yhä korkeammaksi, ovat hissitekniikan rajoitukset käyneet entistä merkittävämmiksi. Nykyaikaisen hissin suurin ongelma on sen vaatima tila. Tilantarve on seurausta siitä, että tavanomaisessa köysihissikonstruktiossa vain pieni osa hissikuilun kokonaistilavuudesta on aktiivisessa käytössä. Erityisesti korkeissa kiinteistöissä mainittu tehottomuus aiheuttaa merkittäviä menetyksiä hyödynnettävässä lattiapinta-alassa.

Tämä diplomityö käsittelee keinoja ratkaista edellä mainittu hissien tilankäytön tehottomuus asentamalla useita hissikoreja samaan hissikuiluun. Tällaisia hissejä on ollut olemassa jo 1800-luvulta lähtien, ja sen seurauksena on havaittavissa useita monikoriseen hissiin johtavia kehityspolkuja, mutta silti nykyisin saatavilla on vain yksi useampaa koria samassa kuilussa hyödyntävä kaupallinen tuote. Työ esittelee monikorisille hisseille ominaisia suunnittelun haasteita ja ratkaisuja.

Siinä missä perinteinen hissi liikuttaa koria vain pystysuorasti, voidaan vaakasuuntaista liikkumista pitää lähes välttämättömänä ominaisuutena monikoriselle hissille halutun tehokkuuden saavuttamiseksi. Vaakaliike tarvitaan hissikorien keskinäisen ohittamisen mahdollistamiseksi. Suurin osa monikorisia hissejä käsittelevistä patenteista perustuu tavanomaisiin köydellisiin nostolaitteisiin, mutta siitä huolimatta lineaarinen sähkömoottori voidaan nähdä lupaavampana käyttölaitetekniikkana joka tarjoaisi yksinkertaisemmilla ratkaisulla työntövoimaa kaikkiin suuntiin.

Teoriassa ”pystysuuntainen juna” –tyyppinen hissikonsepti voisi johtaa ratkaisuihin joissa hissikoreja saataisiin kuiluun tarpeen mukainen määrä. Lisätyt korit voisivat vähentää hissikuilujen lukumäärää ja parantaa järjestelmän käytettävyyttä erikorkuisissa rakennuksissa. Tähän asti vain muutama itsestään kulkeva hissikonsepti on selvinnyt prototyyppiastetta pidemmälle. Konseptien kolme yleisintä haastetta liittyvät energiansiirtoon, turvallisuuteen ja kustannuksiin.

Avainsanat monikorinen, hissi, kiipeävä, kiertävä, lineaarikäyttö, hissikuilu

Foreword

The research presented was carried out due to KONE's interest in multi-car elevators.

I would like to express my gratitude for Ville Lähteinen, the instructor of this work. His insights and guidance were valuable for every aspect of my thesis. I also thank Research Director Harri Hakala, Professor Kalevi Ekman, and co-workers in the patent department who have offered assistance if required. In addition, Mikko Pajunen, who worked on his thesis on linear electric motors at the same time, has been an excellent support.

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Abbreviations

IMCE	Independent multi-car circular elevator
LSM	Linear synchronous motor
LSRM	Linear switched reluctance motor
MR	Machine room
MRL	Machine room-less
PEEK	Polyetheretherketone
PESSRAL	Programmable electronic systems in safety related applications for lifts
PMLSM	Permanent magnet linear synchronous motor
TLIM	Tubular linear induction motor

1 Introduction

More than half the world's population is already concentrated in the urban areas. Nevertheless, the wave of migration to cities is not diminishing (United Nations 2010). Since available building space is limited and land prices are increasing, mid- to high-rise construction has proved to be the most economically and environmentally viable solution to provide adequate living space. While occupying less soil; taller constructions allow to preserve remaining greenery and centralize intelligent control of energy, even in high-density areas. (Ridder 2014a)

While the demand for high-rise building has continuously grown, some technical elements of construction engineering have changed greatly. In the 1950s, the strongest concrete available could withstand stress of 21 MPa, limiting all-concrete buildings to twenty odd stories. With modern supplements, the new concrete grades can reach compression strength beyond 200 MPa. Due to these advanced materials, walls and internal skeletons of the buildings can be built thinner to support the structural loads. Slimmer structures cut weight, construction costs, and free up interior space. (Jones 2007)

Similarly to improvements achieved in building materials, the development of elevator technology is a necessity. Construction of higher buildings naturally increases the volume of traffic in the elevators. The primary traffic increase occurs on the lower floors because all of the passengers have to move through them. The increased demand for conveyor capacity leads to a situation, where the space reserved by elevators becomes more and more critical factor. It is argued that currently, the available elevator technology limits the height of a building. (Brown 2014)

In this thesis, the word *hoistway* designates opening required by a car when it travels the height of elevator. Currently, almost all the elevators operate only one car per hoistway. The space requirement of the elevator could be minimized by installing multiple elevator cars into a same hoistway, while keeping wait times within an acceptable level. One proposed solution is a double-deck elevator, but this method has disadvantages (Barker et al. 1997). Instead, a multi-car elevator could be the next major step to solve the aforementioned capacity issue. The multi-car elevator could offer a new flexibility to elevator installations. Not only by saving the precious floor area for more productive purposes, but also by allowing a more appropriate spread of the elevator capacity inside the building.

Although the multi-car elevators have not revolutionized the people transportation yet, all the major companies in the industry have continuously developed the multi-car technology for decades. The motivation of this thesis is to distinguish development paths of multi-car elevators, and recognize the maturity levels of the technologies and concepts.

Even though there are many unanswered questions regarding modern hoisting systems and power transfer technologies, this study mainly concentrates on system-level concepts and inventions related to mechanical engineering. Therefore, detail level traffic calculations, comparisons of propulsion system technologies, and legal restrictions, like the safety codes and standards of the industry, are not in the scope of this study, despite their importance in elevator system design.

1.1 Research questions

In this thesis, patents and literature related to multi-car elevators are studied in order to distinguish the development paths of the multi-car elevators. Additionally, the commercial maturity of technologies and concepts is evaluated. The research questions that should be answered are:

i. What kind of multi-car elevator concepts occur in patents and literature?

ii. What are the challenges of the multi-car elevator? How the problems are proposed to be solved in the patents and literature?

iii. How the discovered concepts compare?

iv. What kinds of paths exist in the development of the multi-car elevators?

1.2 Research approach and material

The main task of this thesis is to find, review, and sort a large number of relevant patent publications. The previous studies of the thesis subject are neither known nor publicly available. The source material includes patents, studies, articles, and a few textbooks related to the elevator technology.

The main source of data in this thesis is patent publications. The patent research led to the discovery of 170 patent families that relate to the subject. A closer look to the material is taken in Section 6.2. Since the number of patents is vast and the valuation of the found concepts is challenging, the finding are categorized into six comparable groups.

1.3 Thesis structure

The chapters are organized as follows:

Chapter 2 introduces the background of the multi-car elevator technology. The chapter also presents elevator types, defines the term “multi-car”, and lists the advantages and possible applications of the multi-car elevators.

Chapter 3 presents technological characteristics and challenges of the multi-car elevators. These challenges form the basis for later discussion.

Chapter 4 collects the outcome of the patent research. The focus of this chapter is mainly on finding the most important multi-car elevator concepts. The chapter also reviews the history of the public multi-car elevator projects.

Chapter 5 is a comparison between different concepts previewed in the previous chapter. This chapter raises some promising multi-car elevator and evaluates benefits and weaknesses of the systems.

Chapter 6 presents the discussion of development paths of the multi-car elevators and inspects statistics of relevant patents.

Chapter 7 draws up the a comprehensive conclusion about the master`s thesis work. The chapter also features author’s recommendations on how to proceed with the topic in the future.

2 Background

In this chapter, the technical background of the multi-car elevators will be introduced. The chapter introduces and defines elevator types, which are relevant for this thesis. In addition, the advantages and applications of the multi-car elevator technology are discussed.

2.1 Definitions of elevator types

2.1.1 Single-car elevator

Figure 1 illustrates the crucial parts of the single-car elevator. The basic parts of the elevator include a hoisting machine, a car, a counterweight, and a rope that connects other parts. The rope runs over the traction sheave, which is a grooved wheel rotated by the motor. The weight difference of the car and the counterweight usually rests on the friction between the sheave and the rope. Traditional round ropes can also be replaced with belts and in some rare situations with chains. (Strakosch & Caporale 2010)

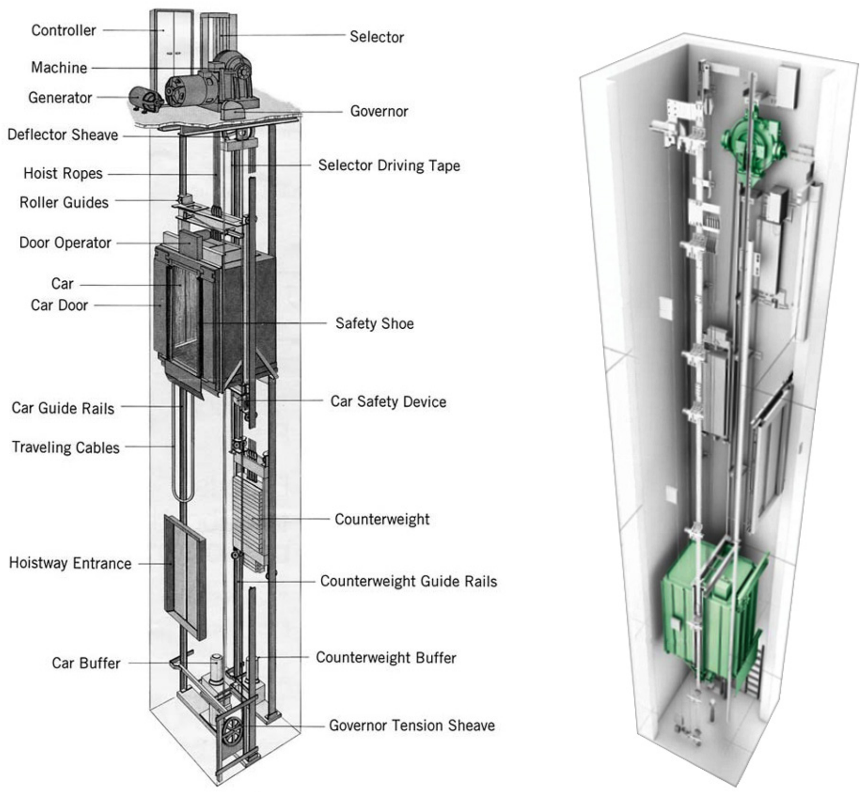


Figure 1 On the left is a conventional single-car elevator installation with a gearless hoisting machine. On the right is a machine room-less gearless elevator installation. (Strakosch & Caporale 2010, p.6)

Fundamentally, the implementation of the elevator is well established. The vast majority of the modern elevators utilize a traction machine (Section 3.1.1) that is not as height limited as the drum-type or hydraulic devices. In practice, the travel height of the traction elevator is restricted by the weight of the rope itself, and the load capacity of the sheave shaft and its bearings. Conventional rope materials limit the maximum travel height to about 500 meters, but new carbon fiber ropes enable elevators to travel 1 km in theory. (Strakosch & Caporale 2010, p.8; KONE 2013)

The traction elevators can be categorized by the drive system to geared and gearless elevators. Additionally, it is common to categorize systems to elevators that include the machine room (MR) and to machine room-less (MRL) elevators that fit all the equipment inside the hoistway. Both elevator types are present in Figure 1. The machine room is a space that accommodates a hoist machine, a lift controller, a power controller, a motor generator set, an overspeed governor, and a circuit breaker. The room usually situates above the hoistway. (Strakosch & Caporale 2010)

In order to hold the tension of the ropes, the common elevator system includes a counterweight. This pile of stacked metal slabs or a piece of concrete also improves the elevator’s power efficiency by compensating the force of gravity on the car. The mass of counterweight is equivalent to the weight of the elevator car with additional 45–50 % of the weight of the full load of the car (Janovský 1999, p.207). In addition to the counterweight, the elevator may also include compensation ropes to negate the moving weight of the hoisting ropes. Wire ropes or chains form the compensation with one end fastened to the counterweight and other end to underneath of the elevator car.

The hoistway is equipped with guide rails, landing doors, and buffers or bumpers in the pit. Guide rails align the elevator car and counterweight horizontally preventing unwanted movement and noises inside the car. Usually, spring-loaded roller guides are used between the car and the rails. The buffer is a safety device that locates at the end of the hoistway to stop a car or counterweight beyond its normal limit of travel. It is designed to absorb and dissipate the kinetic energy that occurs at a rated speed of the elevator. (Janovský 1999, p.3)

2.1.2 Paternoster

The first paternoster (i.e. continuous elevator) installation appeared in England in the 1860s. However, the first system was essentially a refined version of the German man-engine elevator used in mines. As illustrated in Figure 2, the paternoster cars are in constant motion along a circular track in two parallel hoistways. The one hoistway is dedicated for upward and the other for downward transportation. Due to this arrangement, interaction between cars is not required. The elevator consists of two identical rope loops; in front and back of the car. The loops are horizontally offset thus they do not block the access openings. The rope connection points, marked in Figure 3, are placed diagonally at two corners of the car so that the car always maintains its balance.

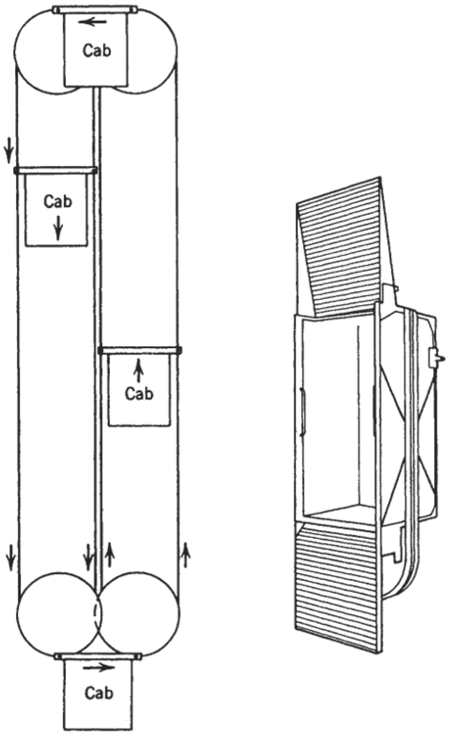


Figure 2 Paternoster elevator schematics and an individual car. (Strakosch & Caporale 2010, p.99)

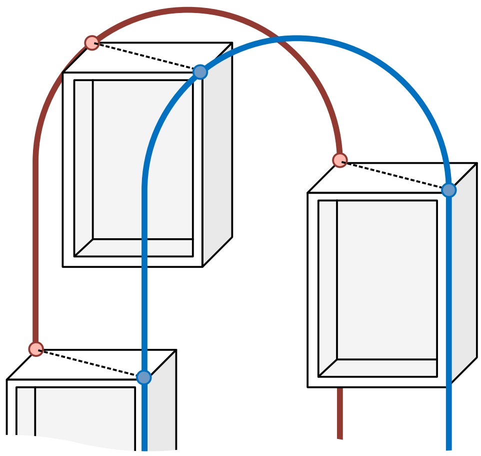


Figure 3 Most common roping arrangement of a paternoster elevator. The blue rope runs in front and the red rope behind the car.

The paternoster could be considered as the world's first "multi-car elevator", satisfying the most of the requirements presented in Section 2.1.4. However, unlike in real multi-car elevators, in a paternoster the cars always move simultaneously with constant spacing. Although the cars do not operate as separate units, the number of the cars can be changed to fit requirements of the installation location. (Gray 2005)

An average speed of 0.3 m/s allows passengers to enter and leave the paternoster car during the movement. The travel speed is slow, but because the cars are in a constant motion, the paternoster achieves beneficial transportation capacity. In addition, the passenger's wait for service remains short compared to conventional elevators. However, a human element exists in each instance of the use of paternoster, since passengers must leap in and out of the moving car. Due to this major safety concern, the system is currently considered unsuitable for people transportation, but some old installations are still in operation in Europe. One of the installations locates in Parliament House in Helsinki, Finland. (Strakosch & Caporale 2010, p.100)

2.1.3 Double-deck elevator

In all its simplicity, a double-deck elevator is a lifting device with two cars attached together in a single hoistway. The double-deck system is not a multi-car elevator in terms of the definition in Section 2.1.4, but because double-deck elevators are commonly used in high-rise buildings, they will be discussed for comparison purposes.

The double-deck elevator requires dedicated loading and unloading areas, where the both cars can be accessed simultaneously. This arrangement is particularly important for the shuttle operation, but also for the elevators that operate all the floors. Passengers have to select the correct car-deck to travel to either even or odd floors. The loading floors are usually connected by escalators. (Tschuppert 2013)

Normally the cars in the double-deck elevator are fixed to each other, which restricts the design freedom of the architect. However, some double-deck elevators do have the ability to adjust to moderate changes in floor heights. Figure 4 presents Westinghouse Elevator Company's vision of such a device from early 20th century. The elevator had two cars sharing common hoisting ropes in a large frame. The lower car had the ability to move inside this frame, which helped the elevator to adjust height differences between various floors. Currently, fundamentally similar double-deck elevators are sold by Otis and Toshiba, for example. (James & Boozer 1930; Russett 2007)

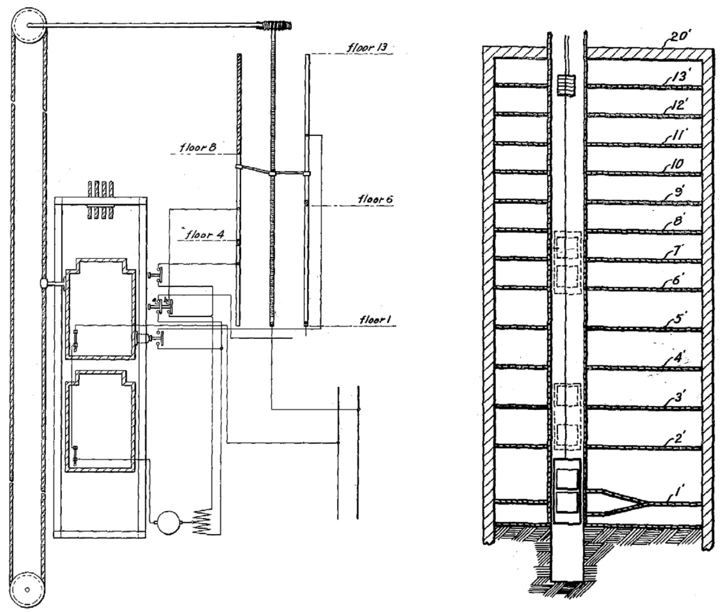


Figure 4 Illustration of Westinghouse's double-deck elevator as presented in US Patent 1914128. (modified from James & Boozer 1930)

In addition to challenges in passenger flow, weak power efficiency is also a typical drawback of the double-deck elevators. The entire double-deck car has to be transported even in situations where only a small amount of conveying capacity is required (Tschuppert 2013). Thus, triple-deck elevators, which consist of three level elevator cars, do not exist on the market.

Despite the disadvantages, the double-deck elevators offer a valid solution to move passengers to sky lobbies in high-rise buildings. In an optimal situation, the required building core space can be reduced to half compared to a single-car elevator. In 2007, around 650 double-deck installations operated in 50 buildings in the world. This is relatively minute number compared to millions of operational single-car devices. The first buildings to have only double-deck elevators were the Petronas Towers in Kuala Lumpur, completed in 1997. (Barker et al. 1997; Russett 2007)

2.1.4 Multi-car elevator

In this thesis, the following definition is used for *a multi-car elevator*: In a multi-car elevator, at least two separate cars per hoistway operate simultaneously. Furthermore, the system can consist of additional hoistways, overtaking lanes, and other spaces reserved to store elevator cars. Unlike a relatively common double-deck elevator, a multi-car elevator does not have one car fixed to another. The freedom to operate cars independently creates a group of new mechanical and operational control problems. The challenges of a multi-car elevator are discussed in Chapter 3. (Strakosch & Caporale 2010, p.176)

In the field of multi-car elevators, no specific form factors or technical solutions can be defined as superior when compared to others. Many of the concepts are not even intended to compete with each other because they fulfill different requirements of different applications. For example, the feasible installation heights, traffic density, and hoistway requirements may vary. Some of the concepts are meant to operate as shuttle elevators where others are designed to serve all the floors.

2.2 Advantages of multi-car elevator

The main motivation for multi-car elevator development is to provide a transportation system efficient in terms of building core space and overall costs (Barker 1997). According to Mitsubishi, almost 30% of the total floor space in a 100-floor skyscraper must be dedicated to elevator systems necessary, including the loading lobbies (Fortune 1998, p.66). The multi-car elevator increases the handling capacity of the elevator system relative to the reserved floor space and, therefore, the higher initial expenses can be paid back through rents gained on the saved space. (Brown 2014)

In tall elevators, the utilization of the hoistway space can be enhanced by increasing the car speed. The faster car is capable to complete more trips than its slower counterpart. However, the slower movement requires shorter acceleration and braking distances. It also helps to avoid pressure problems, which cause ear discomfort for many passengers of the high-speed elevators. A multi-car elevator can achieve the beneficial transportation capacity with a slower operating speed than single-car elevators. (Barker 1997, p.56-57)

In skyscrapers exceeding 100 floors, the problem of the limited practical length of elevator hoistways has been solved by coupling the hoistways together. Traditionally this arrangement creates demand for sky lobbies. Many of the multi-car elevator concepts aim to reduce the need for car changes because loading and unloading of the passengers take considerable amount of time. In an advanced system, a passenger could simply enter one car, which would navigate through the building all the way to the desired destination. (Salmon et al. 1998; Barker et al. 1997)

Since a multi-car elevator system reduces the number of hoistways, the system also requires fewer entrances. The remaining hoistway doors can be used more efficiently than in a single-car system. The multi-car elevator system could provide architects with increased architectural freedom because lobbies could be built smaller. Some multi-car elevator concepts also enable horizontal transportation that could dramatically change the building layouts. (Löksy 2006)

Fewer hoistways also improve energy efficiency of the building because a smaller volume must be heated or cooled down. The energy losses due to the mandatory ventilation of the hoistway are clearly lower. Depending on the hoisting system, some multi-car elevators also save energy in low traffic situations because only a required amount of car capacity needs to be moved. (Thumm 2012, p.9-10)

2.3 Applications of multi-car elevator

In this section, various applications proposed in literature and patents are introduced. As mentioned in the previous sections, the multi-car elevators aim to savings in required building core space in relation to transport capacity. However, in this study, we discuss vastly divergent multi-car elevator types that have their very own characteristics. Since the feasible applications for concepts vary greatly, the entire list does not apply to any particular concept.

- Megatall buildings, over 600 m – In megatall buildings the limitations of the conventional elevators systems culminate causing an economical barrier to build higher. As the building height increases, an increasing amount of core space is needed by hoistways. A tall building also requires higher hoistways, which have more unoccupied volume. Currently, the problem is managed with transportation zones, but the multi-car elevator could reduce the need for them.

- Shuttle elevator to sky lobby – Especially a ropeless multi-car elevator suits transferring people between two platforms far from each other extremely well. In this case, the cars can drive with longer spacing that decreases the car management and safety issues of multi-car elevators. Moreover, the individual cars can move at comparatively high speeds. The existing roped dual-car elevators discussed in Section 4.1.1.1 also have these benefits in shuttle installations (Kocher 2014).

- Office buildings – The required elevator capacity varies during the day because people tend to arrive and leave the workplace about the same time. Many multi-car elevator concepts adapt effectively to the requirements of the rush-hour transportation. Especially the self-propelled elevator solutions can work adaptively if they have the ability to store spare cars in reserve.

- Replacement of an escalator or a travelator – Escalators and especially inclined travelators require a lot of space. These machines impact the design choices of the architect because they determine the placement of walkway paths and interfere with other uses of the floor space (Löksy 2006). Some multi-car elevator concepts provide a more compact solution for transferring people between two floors. For example, in a subway station a multi-car elevator could save space by replacing escalators, but also conventional elevators required to offer barrier-free access.

- Modernization – A single hoistway multi-car elevator enables a possibility to enhance the capacity of an existing hoistway significantly. ThyssenKrupp advertises its TWIN system (Section 4.1.1.1) as appropriate for this type of modernization purposes. If the extra capacity is not needed, the emptied hoistway can be dedicated to other uses, for example for cables and pipes. (Oberwelland 2012)

3 Challenges in multi-car development

As mentioned previously, multi-car elevators have been in development for decades. Corporations have exhibited some prototypes a few times, but unfortunately cost or technical hiccups have eventually buried the projects. The state of the existing hoisting technology can be considered as the main obstacle between innovation and market success. However, in practice the problems of the multi-car elevators are much more diverse.

In this chapter, the most crucial technical challenges hindering in the progress of the development of a multi-car elevator are discussed.

3.1 Hoisting system types

The development of a cost, power, and energy efficient multi-car elevator depends greatly on the hoisting system. Theoretically, a direct linear drive enables the most versatile possibilities, but so far, the technology has not been ready for elevator applications. On the other hand, the conventional roped systems can provide a much better-known foundation for multi-car elevator development. In this study, roped (i.e. traction sheave elevators) and self-propelled elevator systems are examined equally. In addition, the terms *linear motor* and *linear drive* are restricted to designate electric linear motors.

3.1.1 Traction machine

Indirect-hoisting is the most utilized hoisting method at the moment. In case of a traction elevator, a driving sheave transmits the motor power to elevator ropes attached to the elevator car. The traction force is initiated by friction between the ropes and the sheave surface.

Even though the traction machines are common, they are problematic in multi-car elevator installations. Ropes reserve a significant portion of the hoistway volume. Moreover, traction machines do not allow as adaptive multi-car elevator designs and scalability as self-propelled solutions. Despite the challenges, the traction machines are widely used in multi-car elevator patents.

The roping forms an important feature of the traction elevator. Apart from the location of the machinery, the roping also depends upon the rated load and speed of the car. The design should also maximize the lifespan of the ropes and minimize the power consumption of the system. To meet these requirements, the number of sheaves should be low as possible and the possibility to reverse bends should be avoided. Conventional rope materials limit the maximum travel height to about 500 meters as mentioned earlier in Section 2.1.1. (Janovský 1999, p.61)

3.1.2 Linear motor

In a rotary electric motor, a magnetic field moves rotor and stator relative to each other causing a drive shaft to rotate. In a figurative sense, a linear motor rolls out the conventional motor parts to form a planar surface. This flat motor can be installed directly between the car and the hoistway. As demonstrated in Figure 5, the rotor (i.e. primary) and the stator (i.e. secondary) are straightened to run relatively to each other. In an elevator installation, the car would directly hang on the magnetic field. Simple in theory, but in practice the development of the linear motors relies largely on experience, trial-and-error and empirical design of experiment. (Toliyat & Kliman 2004, p.46-50)

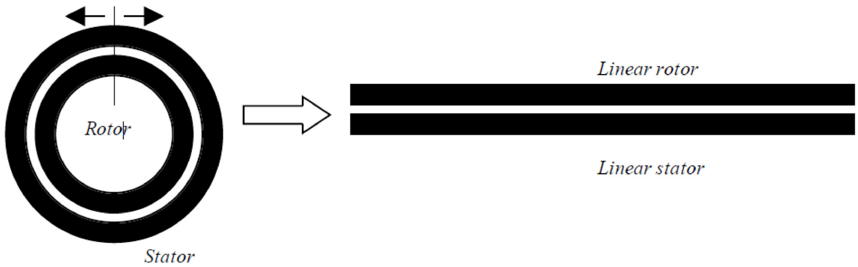


Figure 5 Principle of linear motor (So et al. 2014)

The distance between the rotor and stator plays a large role in the feasibility of the linear motor technology. This so-called air gap should remain as small as possible to maintain the desired functionality because the elements running too far from each other decrease energy efficiency and power of the motor. On the other hand, if the elements run too close to each other, a possibility of contact and wear exists. It is expensive to manufacture long accurate guide rails, and therefore the linear motor constructions easily cause too tight tolerances to be applied on the scale of elevators. It is also difficult to install the rails straight and parallel onto a hoistway wall. The problem is even greater if motors are required at multiple sides of the elevator car.

In addition to the wanted drive force, a linear motor also generates enormous attractive forces between the rotor and the stator. These forces lead to two problems according to Tibbits (1995, cited in Onat et al. 2010):

- The size of the gap varies which leads to changes in performance and speed.
- The attractive forces stress the support structures and tend to loosen the fixing bolts.

In case of the flat motor, guide rollers running directly on the reaction plate could facilitate the air gap problem. Then the motor should be constrained in a flexible way to the car. If the motor element on the car could move independently in the horizontal degrees of freedom, it could follow exactly the surface of the stationary element.

In order to compensate attractive forces, most of the existing linear motor elevator prototypes have linear motors on two sides of the car. However, such an arrangement may be impractical in a multi-car elevator implementation. Otis designed their linear motored elevator around a tubular linear induction motor, TLIM (Section 4.2.1.1). In spite of other characteristic challenges, TLIM maintains the air gap by itself, and it does not have problems with attractive forces. (Janovský 1999, p.5)

The most basic question related to linear motors is; which side of the motor forms the track and which one acts as the mover. Due the material costs, usually the electrified driving element, stator, is installed on the car. This decision causes that significant amount of the power needs to be transferred into the car. In the multi-car elevator installation, a power cable to the car is not necessarily an option. Therefore, it is advisable to find a method to decrease the material cost of the stator and install it stationary to the hoistway.

Figure 6 illustrates a cross section of a linear motor solution that places the entire motor on a single side of the car. In this case, attractive forces are compensated with closed stator construction that mounts on the car. The windings (80) locate on the track, and the secondary mover (permanent magnets 66) runs on two sides of the stationary primary. The presented motor could be utilized in a circular multi-car elevator, for example.

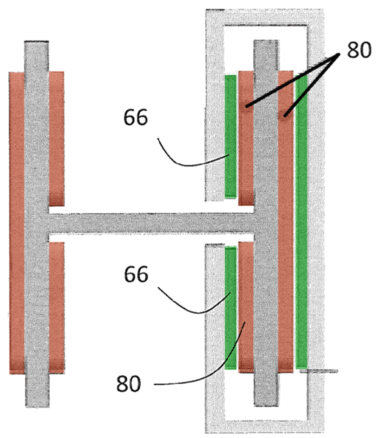


Figure 6 Cross sections of the linear motor proposal (redrawn from Piech 2014)

The most adaptive multi-car elevator concepts include self-propelled cars with linear motors to provide the propulsion. Linear motors introduce saving in ropes, counterweights, and balance’s guides. Nevertheless, self-propelled applications tend to be expensive because a linear motor has to be as long as a hoistway. Linear motors also have difficulties with energy efficiency. For example, a linear induction motor (LIM) may consume four to eight times the power of an equivalent traction system because the linear motor has to lift the whole payload, the car, and the moving element of the motor. However, also the linear motored elevator could involve counterweights but that is in most cases impractical. (Fortune 1998)

To improve energy efficiency of the elevator, the linear motors can be used to assist braking. Thus, kinetic energy is converted into electrical energy. In the case of a multi-car elevator, a downward moving car could directly power an upward moving car. This motor braking could also act as a safety feature that reduces the speed of a falling car in case of power failure (So et al. 2014, p.53).

In the past, the LIMs have been popular in elevator development. However, at the moment, it seems that linear synchronous motors (LSMs) are more suitable for elevator application than LIMs. For example, a linear switched reluctance motor (LSRM) or a permanent-magnet linear synchronous motor (PMLSM) could be used instead. This is not a novel approach to the motor development since Mitsubishi had a linear PMLSM in elevator prototype already in the early 1990s. (Onat et al. 2010; Wang et al. 2012)

3.1.3 Other hoisting methods

Traction machines are not the only indirect hoisting method. Belts and chains can also be used in a similar fashion. The first elevator to utilize a V-belt drive was installed in Germany in 1954. Later, the popularity of toothed belts has increased. The advantages of the belt driven machines are the small diameters of the traction sheave and diverting pulleys, high energy efficiency, low moment of inertia of rotational masses, quiet operation, and low maintenance cost since belt does not require lubrication. However, elongation of the belt may cause be problems while loading or unloading a car. (Janovský 1999, p.142-145; Weinberger 2013)

Hydraulic elevators have retained popularity against traction devices due their low initial costs and safety. However, hydraulic elevators are mostly suitable for low-rise applications, which reduce their usability in multi-car elevator installations. Some later discussed patents propose the use of hydraulic cylinders as auxiliary devices, for example, to move a car horizontally. (Çelik & Korbahti 2006)

In addition to various linear motor technologies, also other techniques can be used to build self-propelled elevators. For example, a rack-and-pinion drive resembles a straightforward mechanical solution to provide propulsion for a self-propelled car. Therefore, this drive system is commonly used in temporary elevators seen in construction sites. However, the rack-and-pinion elevators are too brutal for commercial purposes because they are low and noisy compared to many other elevator types. Additionally, the durability of the teeth can be a problem.

3.2 Horizontal movement

While a conventional elevator moves only up and down, many multi-car elevator concepts permit some degree of horizontal movement that introduces new design issues. A conventional vertically moving elevator car, for example, does not need to offer any visual signal of the upcoming behavior. However, all the unexpected horizontal movement decreases passenger safety and comfort.

Currently, it is unclear how much horizontal acceleration is accepted by the passengers, but most likely the acceleration must remain as slow as possible (Dünser et al. 2002). The acceleration restriction creates the question: Should the system be designed in the manner that the car is emptied before the horizontal transition? This approach would allow much faster transition speed, but it would also increase a demand for additional stops to unload and load the car. Any additional stop sequence naturally requires time.

If passengers can travel horizontal routes, the car has to be equipped with at least handrails and stanchions. For longer horizontal trips foldable seats should be considered, even though when used, the seat would limit the capacity of the car significantly. More cars would be needed because seated passengers require more space than standing people. Additional cars increase traffic and therefore journey times would extend. Moreover, the seats in an elevator can also be considered strange by the passengers because an elevator trip is usually relatively short. However, sitting may be the only practical and comfortable manner to experience fast horizontal accelerations.

Otis pondered the problem of horizontal movement in the Odyssey project (Section 4.1.3.1). They considered installing windows that allow visibility to outside the car because it is easier for a passenger to maintain balance when movement can be sensed visually. However, windows cannot be installed in every elevator because most elevators locate in the building core. A view to the hoistway structures would not be the most elegant solution. Therefore, Otis planned to utilize smart glass windows that allow the view only when the car travels outside the hoistway. Inside the hoistway, the smart glass would block the view, and the passenger would be informed with voice announcements and direction displays about the unconventional car movement. (Barker 1997, p.74-75)

3.3 Car guidance

A guidance system of a sort is required, to allow a steady and safe travel of an elevator car. Guides keep the car on its designed path and guarantee the safety in case of operation malfunction (Strakosch & Caporale 2010, p.181). In the most of linear drive concepts reviewed in this study, the guidance system also maintains a uniform air gap between stator and rotor. Depending on the technology, gap distances are usually only a few millimeters, and they should remain relatively stable because changes result to alterations in the thrust provided by the motors.

Horizontal movement causes additional challenges to the guidance. There are three basic solutions to transfer cars from a vertical rail to a horizontal rail:

- Curved guide provides continuous angle change between the horizontal and the vertical paths.

- Guide rollers can be detached temporarily while the secondary guidance system supports the car during the horizontal movement.
- Section of the guide rail rotates or moves connecting drive path to alternative route.

The first mentioned solution allows cars to change hoistway without stoppages. However, the drive speed may need to be reduced temporarily. Driving the car through a continuous curve eliminates the time loss that is present in other solutions, but may also be the most challenging one. In case of circular elevator, a changing segment can be built as a fixed corner element. If the horizontal movement occurs in the middle of the hoistway (Figure 7), a controlled turn track section becomes unavoidable.

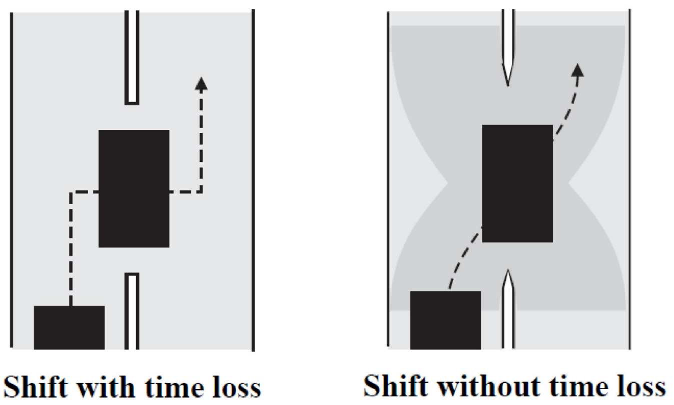


Figure 7 Two manners to handle car movement to adjacent hoistway (Dünser et al. 2002)

The other two solutions require the full stoppage of the car, but horizontal shifting requires smaller section of the hoistway. Moreover, mechanical factors in the two later mentioned solutions should be simpler compared to mechanics of the continuous guide rail. For example, in case of a linear motor, the motor elements do not have to be short and flexible to bend trough varying track shapes.

3.4 Brakes and Emergency systems

Safety is a major concern in many multi-car elevator projects. While a single-car elevator is relatively safe in terms of possible collision, the multi-car elevator increases the risk factor significantly. An elevator system with multiple cars in the common hoistway must be equipped with one or more collision-prevention systems to ensure the safe operation.

Elevator brakes have two functions. They stop and hold a car stationary during every operation cycle of the elevator. Brakes are also required as a safety gear in case of a power outage or other unexpected malfunction. The brakes have to able to stop the car traveling its rated speed with 25% overload. (Janovský 1999, p.187)

Usually, a traction sheave elevator is equipped with a so-called machine brake, which is a drum or disc brake fixed directly on the drive sheave. Normally, the brake is spring-loaded, so in case of power outage brake pads are pressed against the brake sheave. An electromagnet can be used to reload the springs because such a brake construction includes small mechanical tolerances; therefore, an air gap between the friction surfaces can be only a tenth of a millimeter. Additionally, because the friction characteristics of the connecting surfaces are well known, the braking force can be defined accurately. (Weinberger 2013)

A machine brake cannot be utilized in a self-propelled elevator. Therefore, a car brake becomes necessary (i.e. a brake that is fixed on the car and acts on the guide rails or other static structures). The car brake reduces the system's complexity, as it stands directly on the elevator component it should hold or stop. Unfortunately, the car brake is more challenging to realize than a classical machine brake. Due to the tolerances in rail manufacturing and installation, the car brakes tend to have larger air gaps than machine brakes. In order to compensate the large closing and opening distance, the system must include a fast actuator with a sufficient reach. (Weinberger 2013)

The guide rail forms more unpredictable braking surface than a brake sheave or a brake disc. Especially oil affects to the friction coefficients significantly. Therefore, the car brakes normally exercise higher normal forces than machine brakes. In order to achieve smooth operation, the braking system has to be able to evaluate a pre-torque. Thus, the load measurement equipment has to be integrated into a brake itself. (Weinberger 2013)

There are two clear triggers for emergency braking in elevators. The braking is done if:

- the cars are located too close to each other, or the end of the hoistway or
- the car exceeds a rated travel speed. (Seki et al. 2005)

In case of a straight one hoistway system, the emergency brakes trigger can be placed on a push rod. The rod is a long vertical beam fixed on top and bottom of the elevator car. Therefore, it also increases the total height of the car unit, which is a significant disadvantage in a multi-car elevator. The alignment of the rod is in many cases impossible to maintain parallel to the direction of the motion, especially on a curved drive path; thus, such a device is not suitable for a circular elevator, for example. (Seki et al. 2005)

An overspeed governor is a typical emergency system in a conventional elevator. If a car exceeds the safe traveling speed, the overspeed governor mechanically triggers safety jaws to grip the guide rails. Since the overspeed governor is a roped device itself, it is unlikely that it could be installed onto a self-propelled elevator system.

Travel speed has a major impact on the braking distance. Therefore, the design of the multi-car elevator has to balance between speed and safety clearance between cars. Cases where the cars are driving toward each other are particularly problematic. Many multi-car concepts have become possible only because use of PESSRAL (Programmable Electronic Systems in Safety Related Applications for Lifts) related electronic safety devices. PESSRAL is also applied in current commercial multi-car elevator, ThyssenKrupp’s TWIN. (Gómez et al. 2008)

3.5 Passenger guidance

A user interface of a single-car elevator is extremely simple for the passenger. In the simplest case, one button summons the elevator car. Moreover, the buttons inside the car represent each floor of the building. On the contrary, elevator groups (i.e. combinations of multiple elevators) may contain more complex destination operating panels and guidance applications that could be modified for multi-car elevators. However, the multi-car elevators create unique requirements for passenger guidance, especially inside the car.

Outside the elevator car, the multi-car reminds conventional elevators. A beneficial passenger guidance system tells the passenger the estimated time to the car arrival and location where the car can be entered. In case of the multi-car elevator, it is also crucial to indicate whether the arrived car is the one that the passenger is waiting for. Additionally, the progress of the journey should be well informed to passengers because the average travel times in a multi-car elevator are expected to be longer than in a single-car elevator. On the other hand, the multi-car elevator could also be designed to run stream of cars between to landings without any input of the passenger. (Hikita 2008)

It is obvious that the passenger have to be informed when the car arrives to desired destination. However, in some cases, the removing the passenger from the car is not only recommended but also mandatory. Some cars may drive to route sections where the passengers are not allowed to be on board. The reasons for such restriction are:

- the system is designed to drive empty when car moves horizontally,
- the car enters storage space,
- the car requires maintenance,
- the car heads to the destination that passenger does not have permission to enter.

Visual or audible indicators could be included to empty the car. For example, an audio recording could recommend the passenger to leave the car (SikShin et al. 2010). The effect could be supported with messages on display screens and changes in lighting. The same systems could also provide indication of upcoming horizontal movement of the car, as discussed in Section 3.2.

Some multi-car elevators may have to stop during normal operation as the railway trains stop to wait for a free track. However, inside the closed elevator car the passengers can grow unnecessary alarmed if the reason for the stop is not explained to them. A usual reason for stopping is another car too close on the pathway. The car may also wait doors open at the departure floor if the route is not clear. In both cases, the passenger must be provided with the adequate information. (Terry et al. 2008)

3.6 Hoistway shape

A usual hoistway structure has the shape of the rectangular prism. It is a hollow column formed by four supporting wall surfaces. The interior surfaces should provide a robust mounting base for elevator equipment. All the walls do not equally carry the load; at least one wall is usually reserved for doors, and lighter structures can be designed for example between two adjacent hoistways.

A multi-car elevator sets new requirements for hoistways. Short horizontal pathways may fit inside the conventional hoistways, but new kind of structures are needed if the elevator is intended to offer horizontal transportation. The horizontal structures must be supported and isolated so that they do not disturb the space utilization in the surrounding area. Some multi-car elevator concepts also require widenings, storage spaces, and other unusual hoistway shapes. The new features increase the technical challenges of construction.

The dimensions and shape of the multi-car elevators should remain simple to offer easily approachable products for architects. Allowing the cars to pass only in certain sections of the system decreases the theoretical volume of the multi-car elevator system because the most of the hoistway needs only one drive path. However, the required wide passing sections (Figure 12 on page 35) prevent the two hoistways to be located side by side, or otherwise impractical empty space is left between elevators.

3.7 Control

Control logic of a small single-car elevator system can be relatively simple. The passenger can summon a car and set the desired destination floor. The controller responds to calls, for example, in the order they were given. The control logic becomes notably more complicated if the building consists of several elevators and dozens of floors. Despite the fact that in this case, the elevator cars do not physically affect to each other.

The most important goal of the multi-car elevators is to save space. In other words, the conventional elevator group is compressed into a smaller package. Besides being responsible for the efficiency of passenger transfer, the control system also manages relations between the multiple cars. Handling cars in this compressed space requires considerable amount of computing power to find the most optimal flow of the cars. In the case of a multi-car elevator, each elevator car affects to another.

To operate smoothly, a multi-car elevator has to know in advance the destination of the passenger. Thus, the cars can be managed in the manner that they interfere with each other's performance as little as possible. The controller should also consider the expected passenger numbers. For example, in office building the cars can be arranged to lower levels to wait passenger in the morning, and to upper levels in the afternoon. The service should be maintained with a minimum number of operational cars to save energy. Thus, some multi-car elevators even offer possibility store cars outside the hoistway. (Sansevero & Terry 2007; Dünser & Deplazes 2003)

Safety restrictions and technical solutions set the limits within which the elevator system can operate. For example, the cars should always remain a safe distance from each other without decreasing the passenger comfort. In some cases, the motor control of self-propelled elevators can also provide additional limitations to calculations. Either way, the destination control is key element of efficiency in any multi-car elevator. (Thumm 2012)

4 Multi-car concepts in literature study

Elevator systems consisting of multiple cars have existed since the end of the 19th century. However, the old continuously moving circular multi-car concepts are generally considered unsafe and unsuitable in our modern time era, even though the transportation capacity of these devices would still be efficient. The industry has had difficult times finding a multi-car elevator solution that could truly compete with single-car elevators in price, power efficiency, and safety.

Still today, common roped hoisting systems are the most mature technology to build a multi-car elevator, although a self-propelled elevator has been fantasized to be the eventual solution to revolutionize the industry. Self-propelled multi-car elevators have been developed for decades, but the necessary technology to concretize the theory has not been available.

In the early 1990s, many elevator manufacturers invested in the development of LIM powered elevators. Otis and Mitsubishi were the two largest competitors in the race. Otis' vision was to eliminate the rotating drive motor and sheave by installing the primary mover of the LIM on the counterweight. Alternatively, Mitsubishi tried get rid of all the ropes by installing the primary mover directly on the car. The fact that Mitsubishi proposed a ropeless elevator design already over two decades ago, still without success, underlines the challenges of the linear motor driven elevators. (So et al. 2014)

In this chapter, the findings of the literature study are presented. In addition, some existing multi-car elevators are discussed in more detail. These chosen concepts "exist", in regard that their public appearances are not limited to patent publications. These elevators have already turned into products, or the companies have at least taken advantage of them in effort to create marketing excitement and hype.

Because the multi-car concepts differ greatly from each other, the reviewed concepts are divided into six categories to simplify the comparison. At first, all the multi-car elevator concepts are identified by type of the hoisting system. In this instance, the categories for the hoisting systems are:

- Roped – elevators where an indirect device moves the elevator car.
- Self-propelled – elevators with the autonomous elevator car.

In following sections both of these two groups are further divided into three subgroups according to the expected layout of the system. The full categorization is presented in Appendix 1.

4.1 Roped elevators

In this thesis, the word *roped* is used to designate an elevator that utilizes ropes, or similar machine elements, to drive and suspension purposes. In most conventional elevator construction, the rope passes over a drive sheave, which is rotated by a motor, and the ends of the rope connect to a car and a counterweight. The cars of a roped elevator can work as individuals or be grouped mechanically together to a common drive system. The challenges of the roped hoisting equipment were discussed in Section 3.1.1.

The following sections examine the patent publications that cover roped multi-car elevator systems. Findings are categorized into three groups:

- **Type Ro-Si:** Roped Single hoistway multi-car elevator consists of one main hoistway,

- **Type Ro-Ci:** Roped Circular multi-car elevator consists of at least two hoistways that form a circular drive path,

- **Type Ro-Mu:** Roped Multi-path elevator consists of multiple hoistways, and is capable to provide horizontal transportation.

The categorization reflects on how the concept handles the elevator cars. The categories are not necessarily competing because they differ regarding the feasible size and the capacity of the systems. Chapter 5 discusses in more detail how these unique features influence to the potential usage of the present concepts.

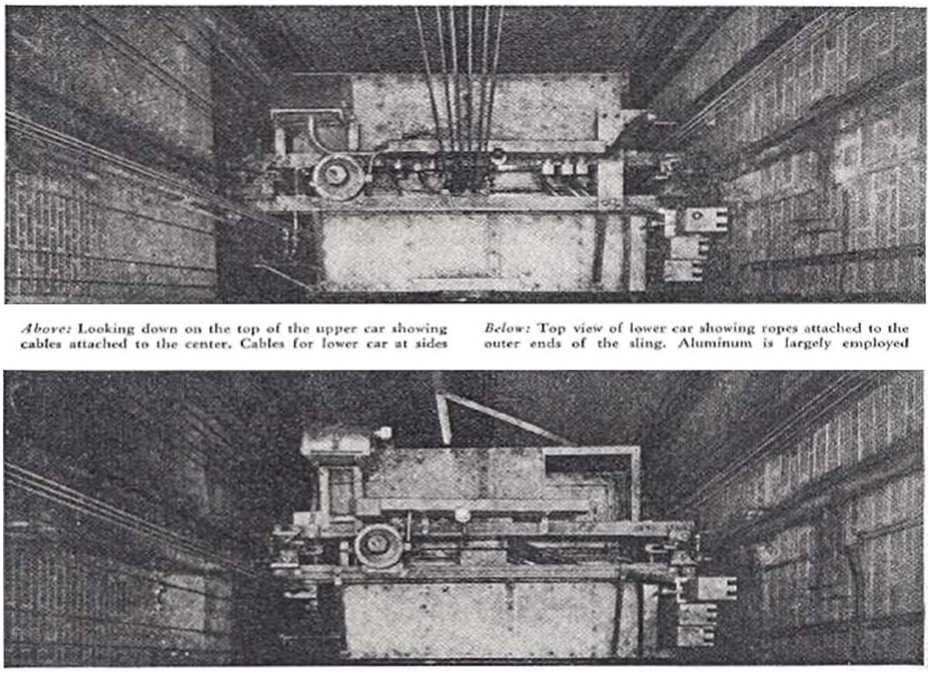
4.1.1 Type Ro-Si: Roped single hoistway

A multi-car elevator consisting of several cars in a single hoistway is most likely the simplest possible design to fulfill the definition of a multi-car elevator introduced in Section 2.1.4. ThyssenKrupp's TWIN elevator represents a typical member of this category, and it also remains the most commercially successful instance of a multi-car elevator. A common drawback of the roped single hoistway elevators is the low optimal number of cars. Moreover, the management of the cars is challenging because in many designs the individual cars cannot pass each other.

4.1.1.1 TWIN

The concept of two elevator cars inside a single hoistway has been around for a long time. In 1907, Clair Foster patented an elevator that had two independently moving cars positioned one above the other. The upper car was hoisted by a traction machine and the lower car by a drum machine. Otis patented a similar concept but with two traction machines in 1931. (Foster 1907; Anderson 1931)

The world's first multi-car elevator installation, other than paternoster, took place in the 1930s. Westinghouse Electric & Manufacturing Company prototyped a multi-car elevator in an 11-story office building in Pittsburgh, USA. As shown in Figure 8, the device bears a resemblance to the modern TWIN elevators. The system consisted of two independent traction elevators that shared the same hoistway, but also guide rails and landing doors. The ropes of the upper car ran in the middle of the hoistway, whereas the ropes of the lower car were divided to sides to pass the upper car. The lower car served the first through the ninth floor, and the upper car served the third through the 11th floors. The prototype remained the only installation because economical and technical problems aborted the development of the concept. After that, the elevator type fell into oblivion for almost 70 years. (Gray 2006; Strakosch & Caporale 2010, p.176)



Above: Looking down on the top of the upper car showing cables attached to the center. Cables for lower car at sides

Below: Top view of lower car showing ropes attached to the outer ends of the sling. Aluminum is largely employed

Figure 8 Test installation of Westinghouse's multi-car elevator presented in Scientific American. (James 1931)

In 2003, the ThyssenKrupp TWIN elevator system made its world debut with a pilot installation in the University of Stuttgart, Germany (Strakosch & Caporale 2010, p.177). As shown in Figure 9, TWIN elevator fits two independent elevator cars (12, 14) into a single hoistway. The cars are driven by two gearless synchronous traction machines (28, 44) that locate in a machine room above the hoistway. The upper car is connected to a counterweight (20) using a single rope strand portion (18), which runs over a traction sheave (22) and a deflecting sheave (24). The lower car, located directly underneath the upper car, hangs on two ropes (30, 31) being divided on two different sides of the car and running laterally outside the upper car. The cars could be roped 1:1, but in the current installations both cars utilize a 2:1 roping, which means that the car and the counterweight travel at half the speed of the rope. (Reuter 2010)

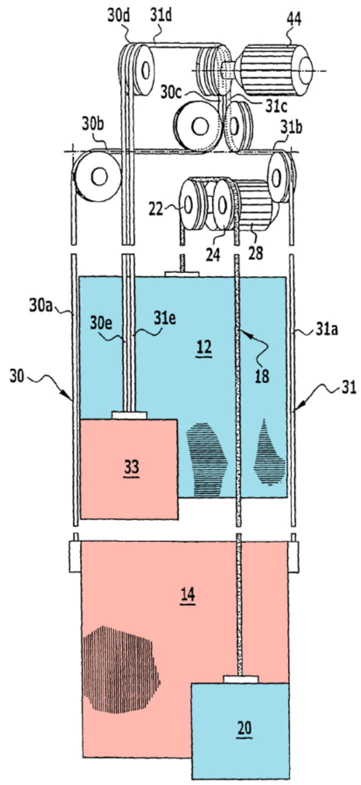


Figure 9 Illustration of the TWIN system as presented in US Patent 7753174 (modified from Reuter 2010)

The TWIN is designed for buildings more than 50 m high, and its potential travel height is 250 m (Thumm 2012). The elevator is approved for speeds up to 8 m/s. The TWIN has a lower total mass to move than a double-deck elevator, and the TWIN elevator also offers the ability to turn off one of the cars in the situations when traffic is light. Among other things, the TWIN offers 30% energy savings compared to double-deck in non-shuttle applications. The elevator does not include a buffer between cars, but the call allocation maintains a minimum clearance of one empty landing between cars. However, the two lowest floors can be accessed simultaneously. (Oberwelland 2012)

The most of ThyssenKrupp’s rivals have done research on similar concepts as TWIN. Mitsubishi, Otis, and Schindler have various patents of their competitive solutions, some of which have been applied before the announcement of TWIN. The basic properties of these product concepts have been collected to Table 1. The table is compiled of the most recent publications.

Table 1 Properties of the dual-car elevators

	ThyssenKrupp	Schindler 1)	Mitsubishi 2)	Otis 3)
Number of hoistways	1	1	1	1
Number of cars	2	2 (or more)	2	2 (or more)
Number of counterweights	2	1-2	2	2 (or more)
Counterweight	Adjacent to the other on same hoistway wall	Adjacent to the other on same hoistway wall	On opposite hoistway side walls	Adjacent/On top to the other
Roping arrangement	Both cars 2:1	-	Both cars 1:1	Both cars 2:1 / Upper 1:1 and Lower 2:1
Suspension body	Rope	Belt	Rope	Rope / Belt
Machine room or Machine roomless	MR	MR / MRL	MRL	MRL
Number of motors	2	2-3	2	2

1) References: US2008149426A1
2) References: US2011108366A1, EP1564177B1, JP4311590B2, JP2002362849A, US6062344A
3) References: US2012006626A1, US8087497B2, EP2662323A1, WO2006127004A1

Schindler has been the most active to patent inventions related to the dual-car concept. The company's multi-car elevator, as presented in the patents, utilizes belts instead of ropes (Kocher 2014; Allwardt et al. 2010). Weinberger (2013) has hinted that the company has developed car brakes future elevators in mind. It is possible that their dual-car elevator would include a similar system, since it would eliminate elongation problem with the belts while loading and unloading the car.

As can be seen in Table 1, patents do not show obvious direction of where Otis is (or was) going with their dual-car elevator concept. They have left open almost all the fundamental mechanical choices. One of their original ideas has been to install counterweights on the same rail one above the other. In this case, hoisting and compensation ropes would pass through the channels in the weights. Mitsubishi has been more consistent in their publications than Otis has. (Terry et al. 2006)

The most dual-car implementations resemble each other's. For example, the number of cars appears to be two in all concepts, but, of course, the option for additional cars has been left open in many cases. Due the cars in a single hoistway elevator cannot pass each other, the additional car would not necessarily have desired effect to the capacity. However, some elevators also offer concrete will to increase the car count, like the concept in Figure 10.

Despite similarities, also notable differences exist between different Type Ro-Si concepts. Unlike ThyssenKrupp, all the other manufacturers have been interested in machine room-less solutions. The development step to include hoisting devices inside the hoistway seems logical if a company has already made investments in such technology in single-car elevators, even though MRL solutions may not match the installation heights of the MR elevators. The design of the roping is another mechanical aspect that differentiates the proposed concepts. There are various methods to arrange the sheaves, motors, and counterweights.

In addition to the major manufacturers, also other developers have eagerly patented "TWIN-type" elevator concepts. Jacobs (2014) claims that the number of cars could be increased up to six or even higher. Roping of such a device would be relatively complex as can be seen in the design proposal in Figure 10. In the introduced invention, each car has an associated motor, ropes, sheaves, and counterweights. The motors locate at the top of the hoistway. They are not connected to counterweight ropes, but instead the motors run separate closed rope loops with ends attached to the rear wall of the car.

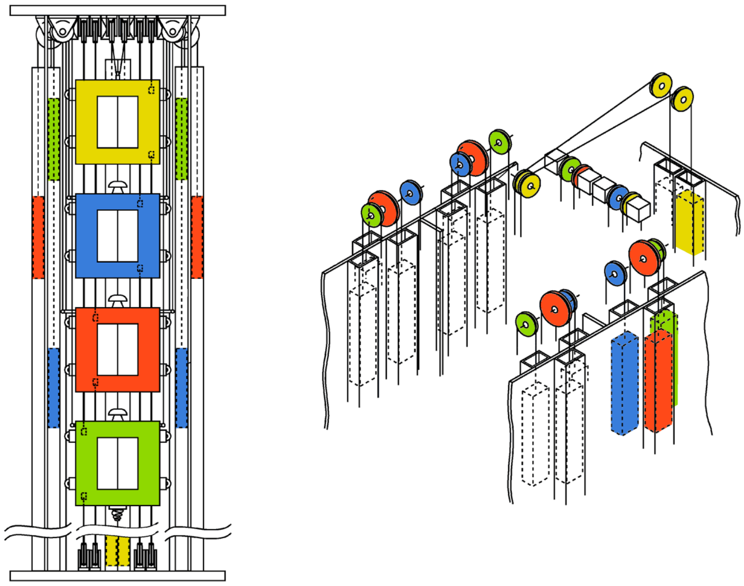


Figure 10 Roping of the four-car elevator (modified from Jacobs 2014)

The uppermost car has a different roping arrangement than the rest of the cars. The counterweight runs at the rear wall of the hoistway, and its rope connects to the center of the uppermost car. The rests of the cars contain the counterweight ropes at each corners of the car, and the weights run on sidewalls. Everything is horizontally offset; thus the machine elements do not hit each other. (Jacobs 2014)

KONE has made simulations how the TWIN elevator compares to single- and multi-deck elevators. They came into a conclusion that TWIN is suitable for low population offices, residential buildings, hotels, and hospitals. However, the system was noted as unsuitable for forming any shuttle group solution. For example, in case of a 45 floors high office building with a population of 1900, the TWIN was considered to have 5% longer waiting times over the single-car solution, and 18% over the double-deck solution. The TWIN system required less floor space than the double-deck elevator system, but slightly more space than the single-car system. (Siikonen et al. 2008)

4.1.1.2 Other Ro-Si concepts

The U.S. patent application No. 5816368 presents a multi-car elevator concept that makes use of both a traction machine and a linear electric motor. The system is designed to meet requirements of the megatall buildings, especially in shuttle elevator use. (Barrett et al. 1998)

The elevator on the patent consists of two cars traveling in a long hoistway. The invention enables cars to pass each others at the middle of the hoistway. Thus, the elevator structure is divided into three parts: upper, middle, and lower section. The upper and lower sections include traction machines and counterweights that are responsible for hoisting. The hoisting ropes are fixed to a coupler device that cars can lock onto. The patent introduces a few proposals for the coupler's operating principle. (Barrett et al. 1998)

The cars are exchanged between couplers in the middle section; that is a 64 meters long enlargement with enough room for cars to pass safely. Figure 11 illustrates the principle of the middle section. At the left-most state the couplers (32, 33) move cars (30, 31) towards each others. Linear motors begin to take control of the elevator movement. At the second state, couplers release cars under the command of the linear motor drive. At the third state cars pass and the couplers have begun acceleration to the opposite direction. At the fourth state, the cars continue moving while the couplers increase speed. At the final state, the couplers are at the position to reattach to the cars. (Barrett et al. 1998)

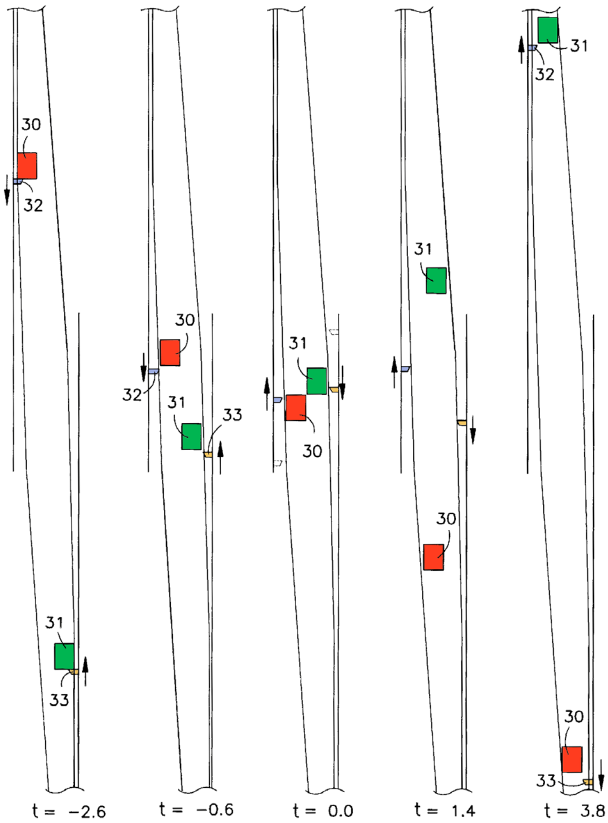


Figure 11 Operating principle of the vertical hoistway switching concept. The drawing illustrates only the middle section of the elevator. (modified from Barrett et al. 1998)

Toshiba has a simpler approach to allow cars pass in a single hoistway. The patent application JP04341479A proposes an elevator hoistway in which two elevator cars move in opposite directions. In the present invention, the cars remain connected to hoisting ropes without interruption that will increase the safety. A linear hoisting device is not necessary, as seen in Figure 12. Somewhere of its length, the hoistway has a widening, which enables the two elevator cars to pass by each other without colliding. (Yutaka 1992)

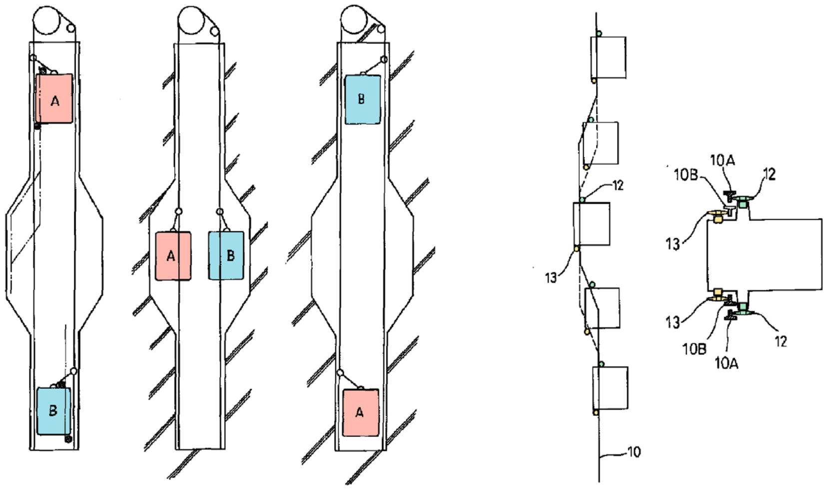


Figure 12 Toshiba's dual-car system that includes a by-pass zone at the middle of the hoistway (modified from Yutaka 1992)

Each car hangs on a rod that connects the center of the car roof to a hoisting rope. The rod is capable to pivot that enables the car to move horizontally approximately the length of its width. The rope remains vertical at all times, but the horizontal movement of the cars occurs due to the shape of the guide rail. For this, two similar imbricate rails are required: the first rail (10A) supports the top guide rollers (12) of the car, and the second rail (10B) supports the rollers (13) in the lower part of the car. (Yutaka 1992)

Mitsubishi has taken a similar approach with Toshiba (Figure 13). In Mitsubishi's concept, two cars are paired with rope that runs over a traction sheave. The rope (4) does not connect directly to the car, but to the frame (19) that allows the car to slide horizontally in relation to a connection point to perform the passing maneuver. Horizontal movement distributes mass unevenly, therefore, the frame travels between two guide rails (15) that hold the car steady and prevent tilting. (Katsunori & Yukiomi 2007)

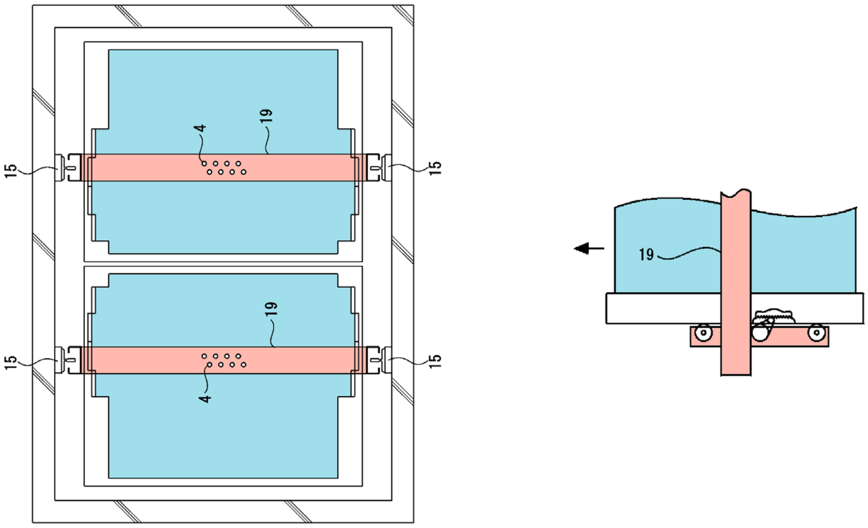


Figure 13 External hoisting frame that allows a car to move horizontally. Rails (15) support vertical travel of the frame. On the right is the sliding mechanism under the car. (modified from Katsunori & Yukiomi 2007)

In addition to TWIN, ThyssenKrupp also has further developed Type Ro-Si concepts. One of them is able to position roped cars in such a manner that they can pass each other. As depicted in Figure 14, the system is built of sections. The ends of the elevator consist of at least two adjacent hoistways, and the middle section consists of one hoistway. The passing areas are at the ends of the hoistway, which creates an advantage over the previously presented concepts. In this elevator, the cars do not have to move synchronously to opposite directions. Therefore, unnecessary trips with empty cars are avoided and waiting times are most likely shortened. (Reuter et al. 2005)

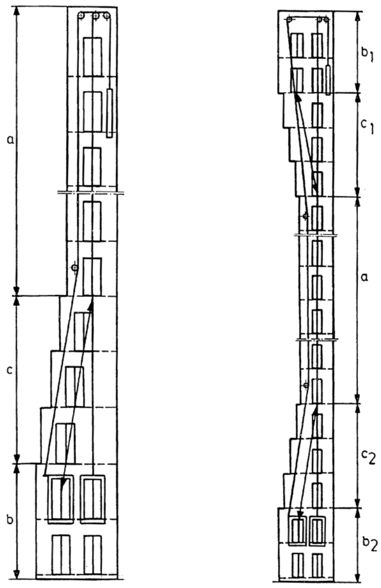


Figure 14 Two variations of the multi-car elevator that consist of separate and common track sections (modified from Reuter et al. 2005)

Both common and separate track sections can be utilized for loading and unloading purposes. The system can be built in the manner that the first car can travel only in a vertical direction, and other cars take horizontal routes. The cars can have dedicated guide rails for the whole hoistway length, or a common rail can be utilized at the shared sections. The described elevator can operate all the floors, but only the first car can access the doors that locate at the horizontal displacement sector (c). However, the cars could operate at different speeds. The first car could be dedicated for fast transportation, or alternatively the other cars could overcome the time lost in horizontal movement with higher vertical speed. (Reuter et al. 2005)

Even though the presented concepts are feasible, they are also disadvantageous because the by-pass zone occupies a relatively large enclosed area in the building structure. Installing multiple hoistways side-by-side would cause great space losses, even if the widenings could be installed on different levels. Furthermore, the demanded enlargements may be unfavorable for construction engineering reasons.

Rajaram Pejavar (2009) has conceptualized a multi-car elevator capable of operating elevator cars as individuals, despite the fact that the cars share the same indirect hoisting equipment. In the concept of Figure 15, every drive assembly includes a motor that runs ropes in endless loops over two sheaves located at opposite end of the hoistway. A car clamps to upward moving ropes to move up, and to downward moving ropes to move down. The ropes do not stop during the normal operation sequence. Rather, the clamps smoothly and gradually increase friction over a few seconds, acting as a clutch, until the elevator car is moving at the same speed as the ropes. The drive assembly also has a stationary segment that car can attach while parking. The clamps situate on long telescopic arms that make possible to reach the ropes horizontally.

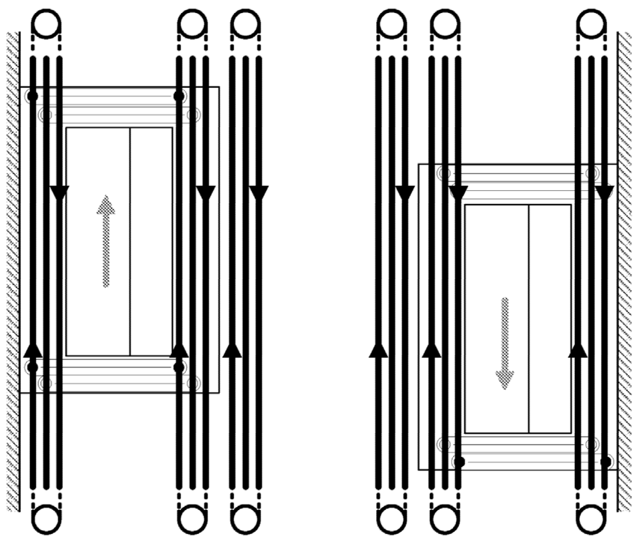


Figure 15 Three elevator hoistways that contain detachable roped hoisting device (modified from Pejavar 2009)

The example case presented in Figure 15 has four similar drive assemblies in the hoistway, one for each corner (only two are visible in Figure 15). A smaller number of drives would also be possible, but the greater number of drive systems even outs lifting forces on the car. (Pejavar 2009)

Figure 16 shows Mitsubishi's Type Ro-Si concept. The system consists of two hoistways that both accommodate a car frame. Each frame has two cars. The upper car (20) can move to a secondary position, which allows the lower car (19) to access the upper part of the frame. A screw-type hoisting device (22) handles the vertical movement inside the frame. The frames can move past each other when the upper and lower cars locate at the primary positions, one on top the other. Doors are located at opposite sides of the double hoistway. Furthermore, the counterweights run inside the rear wall. (Honda 2009)

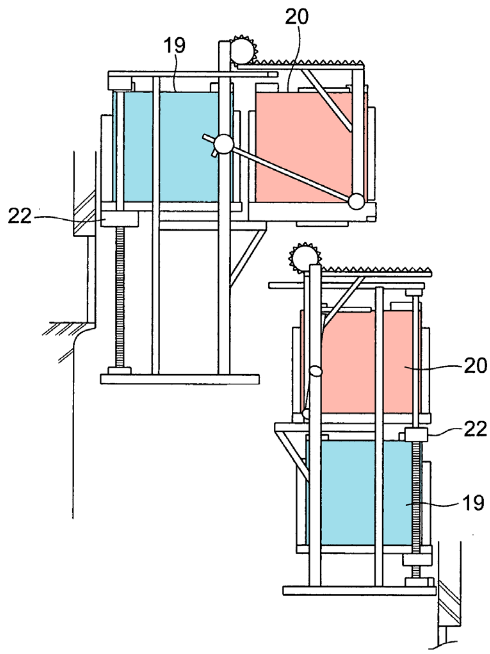


Figure 16 Double-deck elevator that can displace the upper car of the frame horizontally (modified from Honda 2009)

It is difficult to see how the elevator in Figure 16 would be more beneficial than two adjacent double-deck elevators. Both require space of two hoistways and are capable of operating the volume of four cars.

4.1.2 Type Ro-Ci: Roped circular

Roped circular elevators form the oldest group of the multi-car elevators. The traditional paternoster discussed in Section 2.1.2 (page 12) is the main inspirer of this multi-car elevator type. Type Ro-Ci elevators consist of two adjacent hoistways that are occupied by circulating elevators cars. Each hoistway is dedicated to either ascending or descending traffic. Especially Hitachi has been interested of Type Ro-Ci elevators, and they have even introduced some research results. Hitachi's prototypes and other circular roped elevators are discussed in this section.

4.1.2.1 Hitachi’s Circulating Multi-Car Elevator

Hitachi’s *circulating multi-car elevator* shares similarities with the traditional paternoster, but unlike its predecessor, Hitachi’s elevator includes doors on cars and landings. The elevator has two connected hoistways, one up and other down, to cycle cars on the circular track. Because the cars can travel close together in a continuous chain, the system achieves relatively high capacity. In Hitachi’s estimates, two hoistways could thus accommodate traffic equivalent to five hoistways in a traditional single-car configuration. (Koroluk 2015)

The Hitachi’s elevator includes multiple parallel hoisting rope loops, as shown in Figure 17. At least two elevator cars are installed on one rope and the cars attached to the same rope act as mutual virtual counterweights. Therefore. They also position simultaneously. The arrangement of the paired cars is similar to double-deck elevators, but in this case, the cars locate distant from each other. A linear motor provides the thrust to compensate the weight difference between the paired cars and to circulate the cars along the track (Shunichi et al. 1996)

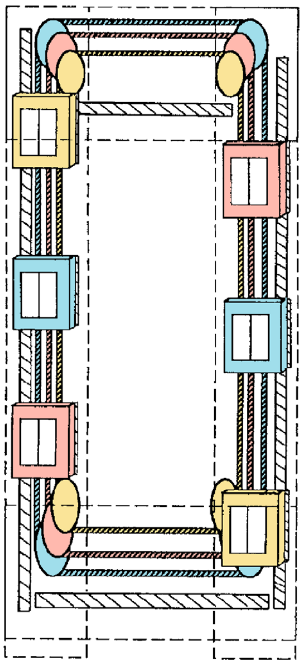


Figure 17 Illustration of the Hitachi’s linear drive multi-car concept as presented in the patent JP08059139. (modified from Shunichi et al. 1996)

In another patent, Hitachi presents a concept for an elevator that circulates double-deck cars. Both hoistways and horizontal sections include linear motor stators (53) to couple with primary mover (54) on the car. Each car runs between rope lines and connects to them through a bearing supported horizontal beam. The cars have dedicated ropes, so in case of Figure 18, the six cars can be circulated at the same time. (Masanobu et al. 1996)

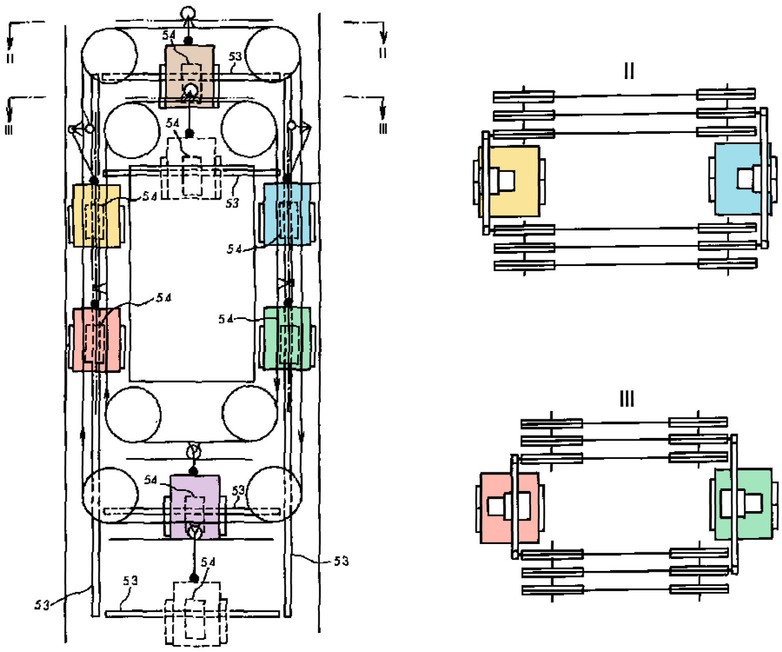


Figure 18 Circulating multi-car elevator that consists of six independent cars (modified from Masanobu et al. 1996)

Besides linear driven elevators, Hitachi has also considered the use of a rotating motor and a drive wheel that would be mounted directy on the car, as in Figure 19. Also in this version, the drive device would attach to another car rought a rope loop to negate the weight of the empty car. (Hagiwara et al. 2005)

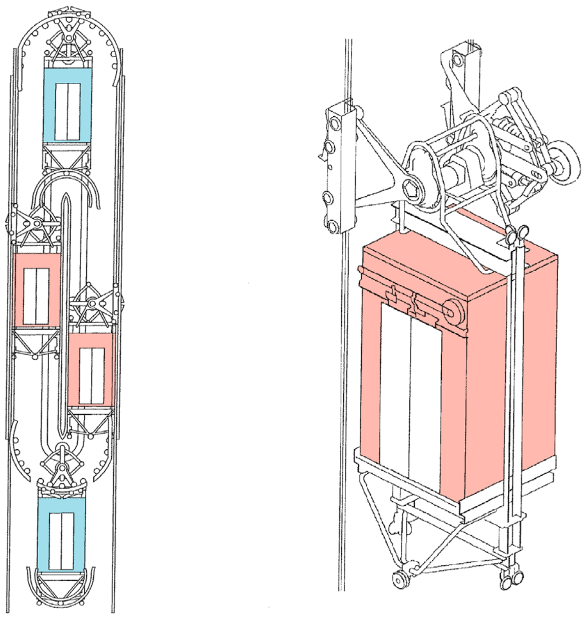


Figure 19 Drive wheel installed on the car (modified from Hagiwara et al. 2005)

In later technical publications, Hitachi has replaced the car mounted drives with indirect traction machines (Figure 20). Undoubtedly, the linear motors were removed to decrease the cost of the elevator. In this case, three motors (23) fitted in the upper section of the elevator system circulate two ropes each. The arrangement provides parallel drive ropes for each side of the both the hoistways. One rope circulates along the left walls and the second rope along the right walls of the hoistways. Each car mounts to two ropes. The rope fasteners are provided on a left-rear and a right-front of the upper surface of each of the car. (Seki et al. 2006)

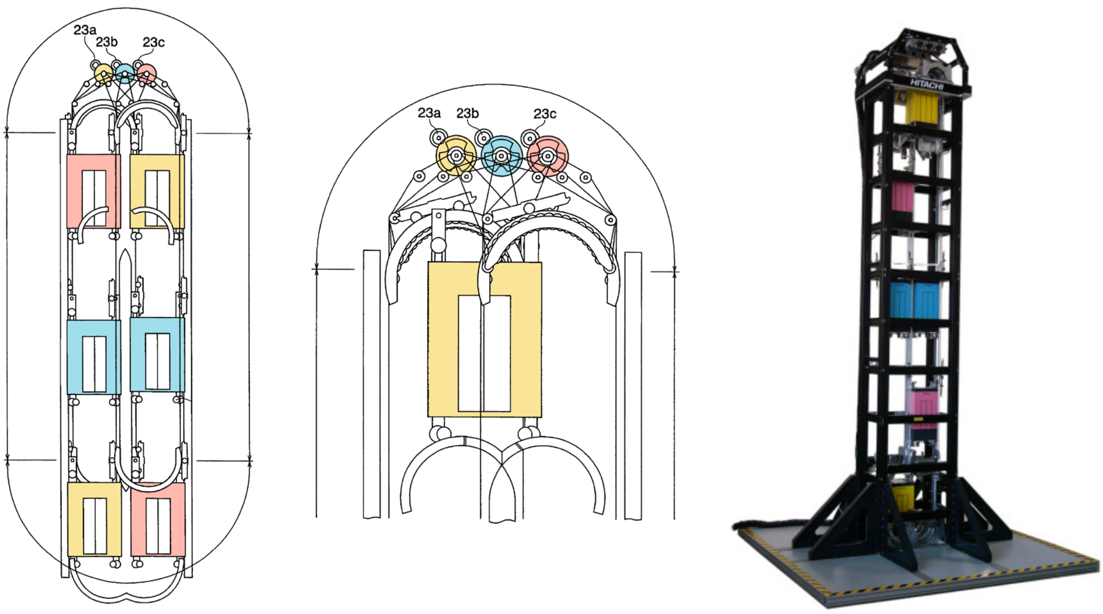


Figure 20 Illustration of the Hitachi's latest circulating multi-car elevator concept as presented in the patent EP1647513A3. On the left is a functional one-tenth scale model of the concept. (modified from Seki et al. 2006; Future of Transportation 2010)

Hitachi's circular elevator is promised to deliver a high transfer capacity particularly for interfloor traffic in 10 – 20 floors high installations. It is also claimed to occupy less than half of the space needed by conventional single-car elevators with equal capacity. The concept has been demonstrated in a one-tenth scale model shown in Figure 20, but the full-size installation has not been presented. (Hitachi 2006; Koroluk 2015)

4.1.2.2 Other Ro-Ci concepts

Since an old-fashioned paternoster is considered relatively unsafe, it has become obsolete concept. The simplest development step to make paternoster safer would be a similar elevator with doors. For example, Dalian Ship Engine Industry has applied a patent to an elevator in which all the cars are roped together to form a balanced weight distribution, as in paternoster. This invention is similar to Hitachi's linear motor elevator discussed in the previous section. However, the present invention flips a car upside down when it passes the hoistway changing point. (Yinggang 2011)

Even though equally moving cars affect greatly to control and capacity of the system, the arrangement has also a benefit: the stator of the linear motor is required only on a small section of the travel route. Thus, the linear motor can move the chain of cars even in case it covers only the distance of two consecutive cars. (Yinggang 2011)

Unfortunately, in an arrangement where all the elevator cars move simultaneously, the amount of the unnecessary stops would be intolerable for passengers. Therefore, the most Type Ro-Ci elevators are capable of stopping individual or paired cars for loading and unloading.

An elevator car does not need to be coupled with another car like in Hitachi's concepts. Instead, Tetsuzo Shibuya proposes an arrangement where cars are coupled with dedicated counterweights. The counterweights can pass the cars because they run along separate tracks. With this solution, each roped car can act virtually independently, but on the other hand the car count is decreased to half compared to the car pair designs. (Shibuya 1998)

Some Type Ro-Ci elevator concepts handle an elevator car as a detachable object. In these devices, a car is ostensibly independent to move but requires operation time of the external drive device. For example, Inventio has applied a patent for such a circular elevator. The concept in patent circulates cars in two hoistways. Hoisting can be implemented with traditional elevator components such as a traction machine, sheaves, ropes, and a counterweight. However, the roped hoisting machine is not permanently fixed on the car, but they interlock when the car is lifted or lowered. Each hoistway has two identical hoisting machines to double the transportation capacity. (Bachmann 2006)

A separate drive system manipulates the car to transfer between hoistways. Before the horizontal movement can be maneuvered, the car connects with horizontal guide rails. As seen in Figure 21, the flipping apparatus positions rollers (38) between two profiled rails (36). After the rollers are in place, the car can detach from the hoisting device. The sequence to move between hoistways does not need to be completely smooth because the car is intended to stay empty of passengers at the time. Thus, the horizontal thrust can be implemented, for example, with chain drive. (Bachmann 2006)

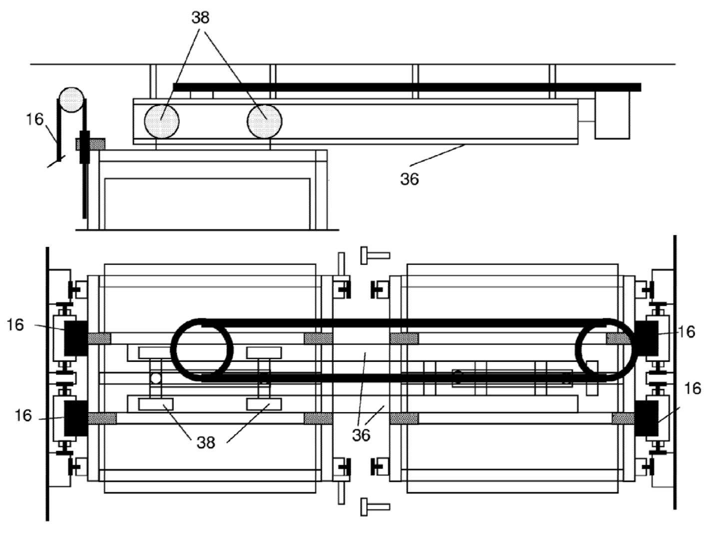


Figure 21 Elevator system that allows a car to be detached from the hoisting ropes (16) to connect with the lateral rails (36). The guide wheel construction sits on the top of the car, and it can flip around vertical axis to fit between rails. (modified from Bachmann 2006)

In described concept, after the hoisting machine has delivered the car to the end of the hoistway, the counterbalance is transported back to receive the next car on the line. The Odyssey system, presented in Section 4.1.3, utilizes a similar functionality. The return operation can be driven at relatively high speed because the car or passengers are not involved. (Bachmann 2006)

The more recent patent of Inventio presents a similar elevator construction, shown in Figure 22. This improved system is simpler, and the horizontal displacement unit can be realized with fewer components. The most important advantage over the older version is that guide shoes (rollers) do not ever detach from a vertical guide (5, 18). Instead, a section of the vertical guide is displaced horizontally to move the car between hoistways. (Grundmann 2011)

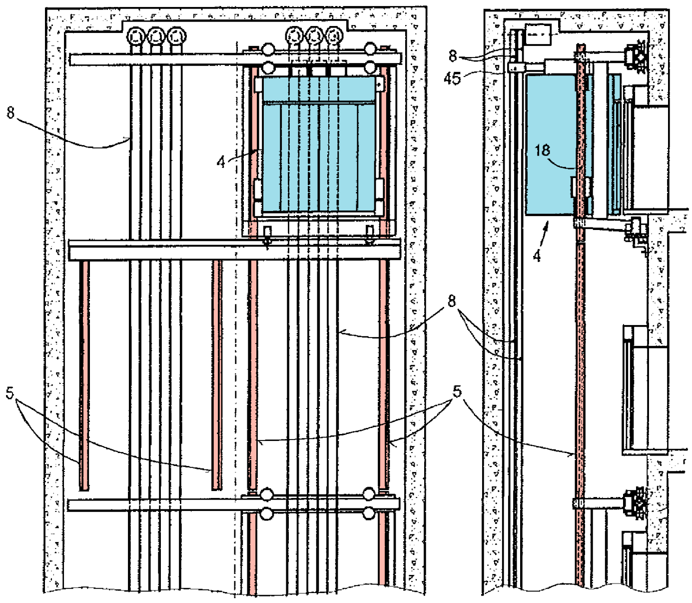


Figure 22 Multi-car elevator with hoisting ropes that car can temporarily attach. In presented case, three cars can travel inside the same hoistway simultaneously. (modified from Grundmann 2011)

Hoistways include three separate hoisting rope loops. Each car (4) has clamping devices (45) capable of attaching to ropes (8) so that the maximum number of the individually operating cars per hoistway is same as the number of the ropes. The elevator includes a car brake that can be utilized to stop and hold the car, but also to secure the car to the vertical rail (18) during the horizontal movement. Besides brakes, a separate locking device may be necessary to remove the risk of the car falling off the moving horizontal unit. (Grundmann 2011)

KONE has been mostly reticent of its multi-car elevator development with a couple of exceptions. In 2006, the company patented a circulating shuttle concept that aims to eliminate waiting times for the car. The basic concept is to circulate four cars between two floors in coupled hoistways. The operated floors have two stops: a door for unloading and a second door for loading the passengers. A horizontally moving elevator car, between the mentioned two stops, ensures that an empty car can arrive and pick up passengers as soon as the previous car has left. The patent suggests the use of a transparent hoistway wall on the horizontal section between unloading and loading stops. Thus, the view to the hoistway would naturally indicate about the incoming car. (Löksy 2006)

Löksy (2006) claims that the above described elevator would be an efficient replacement of an escalator or inclined travellator. The elevator would save floor space and because of its ”instant elevator” capabilities the waiting times would remain relatively short. In addition, the horizontal movement in this concept does not cause new safety issues because the passengers never traverse the horizontal section inside the car. Furthermore, due to separate in going and out coming flows, the passengers do not have to dodge oncoming traffic. (Löksy 2006)

KONE's patent does not state how the elevator design would be technically implemented. Because all the cars move simultaneously, they could be attached to a common hoisting rope loop. However, the elevator could also be equipped with a linear hoisting system, which would allow more design freedom regarding the dimensions of the hoistways. With the linear hoisting, the elevator could also be more adaptive to varying traffic situations.

4.1.3 Type Ro-Mu: Roped multi-path

Sometimes horizontal transportation could be beneficial. Therefore, multi-car elevators are not only about lifting passengers. A multi-path system capable of vertical and horizontal transfer may be implemented with roped hoisting technologies, although a multi-car elevator driven solely by linear motors sounds exciting (Section 4.2.3). Besides Otis' Odyssey, the patents of the Type Ro-Mu elevators are few in number. In practice, Odyssey is almost the sole representative of the category, but also an actual evidence of the possibility to build such a device.

4.1.3.1 Otis' Odyssey

In 1996, Otis presented a multi-car elevator system, Odyssey, in which cars can move horizontally, in addition to the traditional vertical movement. Due to the unusual transportation dimension, the company marketed the elevator cars as “transitors” (Strakosch & Caporale 2010, p.176). In the Odyssey system, an elevator car is not capable of moving by itself, instead dedicated car frames and platforms transport the car to the desired location. The vertical transportation is implemented by using conventional elevator components, which helps to maintain the safety and cost effectiveness of the system. In practice, the car frame that handles vertical transportation remains attached to the hoisting ropes at all times. The ropes themselves connect with a traction machine and counterweights. (Barker 1997)

Odyssey reduces the travel time to top floors of tall buildings. Since passengers can travel longer distances in one car, they waste less time locating elevators at sky lobbies. In addition to interfloor traffic, Odyssey could also function as a shuttle elevator between a ground level and a sky lobby. An ability to store cars at the ends of the hoistway enhances the shuttle properties of the elevator. Odyssey had two development trends for sky lobby shuttle elevator: “switch” and “shuffle”. The “switch” (on right in Figure 23) trades cars between frames at hoistway offsets. In the “shuffle” the frames trade cars at a main lobby and sky lobbies (on left in Figure 23). (Barker 1997)

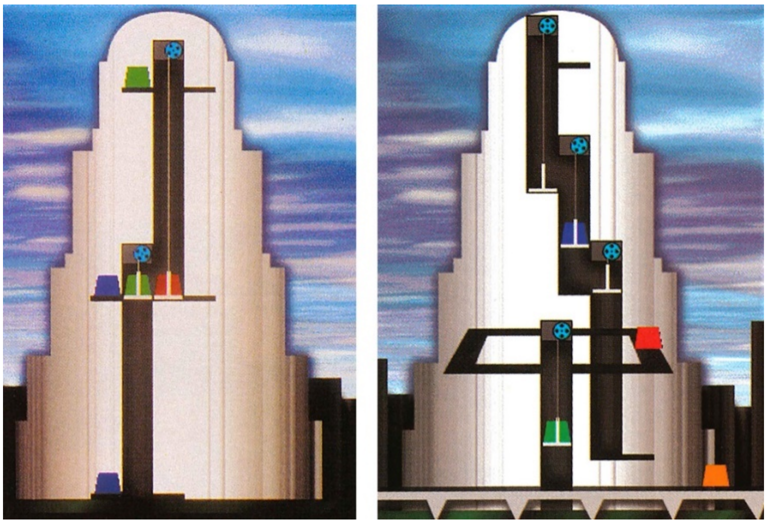


Figure 23 Couple layouts of Odyssey system. As seen in the picture, a combination of short hoistways can be used to provide the trip all the way from the bottom to the top of the building. (Sturgeon 1996)

In the situation of Figure 24, the double-deck elevators save about 30% space when compared to the single-car local elevators. Otis claimed that the Odyssey with double-deck cars could reduce required space by 25 to 30% over a conventional double-deck elevator, and 70% over a single-car elevator system. In a higher building, the difference would be even greater. For these estimates, the 417-meter-high original World Trade Center was used as an example building. (Barker 1997, p.62-63)

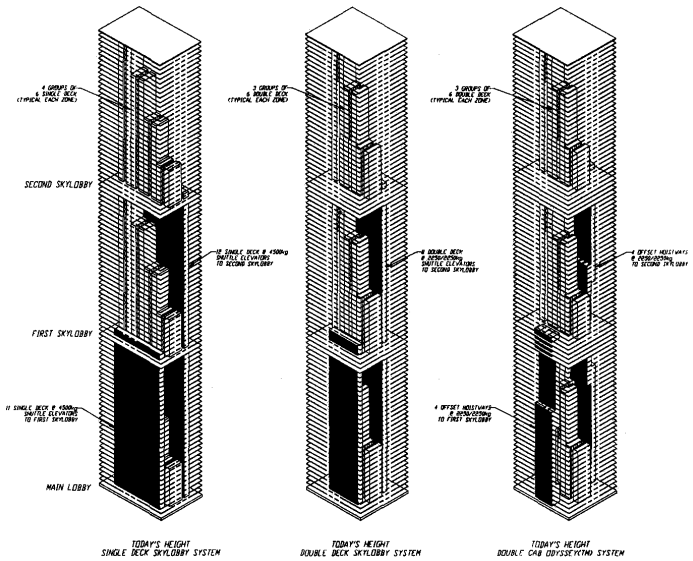


Figure 24 Example how Odyssey saves building's core space. On the left is a conventional single-car elevator sky lobby system, in the middle is a conventional double-deck system, and on the right is a double-deck Odyssey system. (Barker 1997)

Some controversy exists regarding the nature of the technical implementation of the horizontal transportation in Odyssey. First of all, the system consists of two levels of horizontal movement: the car needs to be able to move short distances between car frames, but also long horizontal journeys have to be handled. Therefore, some of the frames are dedicated for the horizontal transportation. Barker (1997) claims that a LIM will propel cars smoothly on and off the frames. Otis has also patented pinion solutions for same purpose as presented in Figure 27 on page 49. To move greater distances, the car frames can include rope driven system similar to the company's automated people mover (APM) at Tokyo's Narita Airport. The patents also suggest the use of a LIM for the same purpose. In such a case, the linear motor would be mounted under the frame. (Salmon et al. 1998; Barker 1997, p.72)

At the time, Otis saw that a ropeless elevator could one day reduce the number of needed hoistways. However, they calculated that the costs of the ropeless system would take too long to pay back. A few years earlier Otis had released a single-car elevator driven by a tubular linear induction motor (TLIM). The same motor technology was considered to be also implemented into Odyssey in low-rise buildings. (Barker 1997, p.56, p.72)

Due to Odyssey's ability to drive virtually limitless distances, both horizontally and vertically, the system could be utilized for very different purposes. As seen in Figure 25, one of the concepts was to reduce long walks in the vast building complexes; such as airports and shopping centers. Odyssey could have operated as a miniature train, allowing personnel transportation from distant car parks to another end of the building, or even to a sky lobby, without changing cars. (Barker 1997, p.71-74)

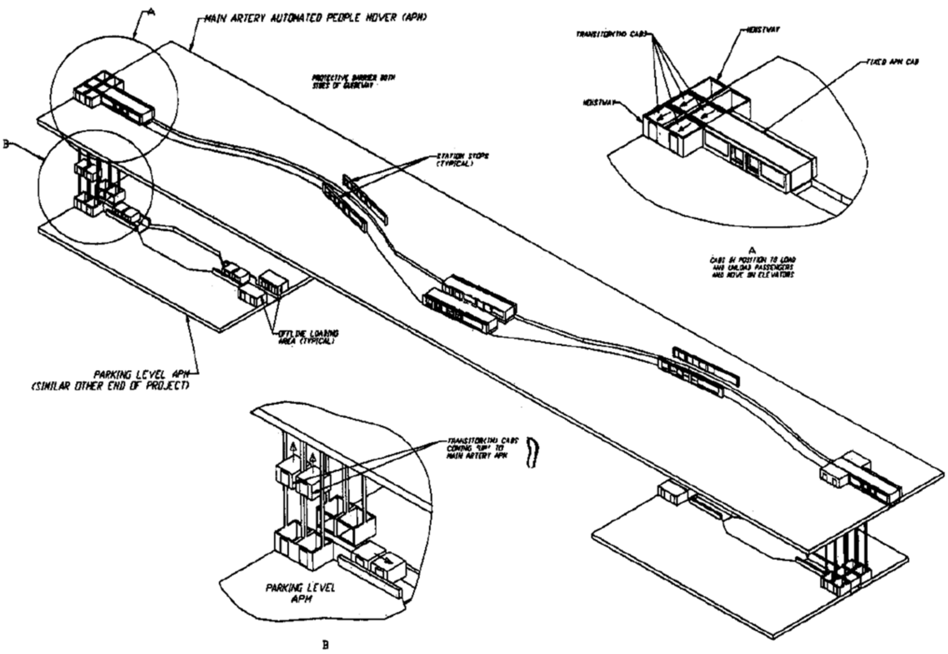


Figure 25 Illustration of Odyssey system's ability to transport people long distances horizontally. (Barker 1997, p.71)

One of the biggest bottlenecks of Odyssey is the system's manner to handle hoisted cars. The hoisting system is capable of transferring only one elevator car per hoistway at the time. This limits the reasonable height of the hoistway and forces hoistways to be divided into shorter consecutive sections. Each stop decreases the efficiency of the elevator because the sequence to level, unload, and load the car frame again takes time. Thus, finding the most suitable hoistway layout is seemingly challenging.

Odyssey's capacity could be increased with a hoisting system capable of operating two cars simultaneously, as seen in invention presented in Figure 21 on page 42. In this case, one hoisting frame could be operating a car, while another frame is returning to starting point. The device could be built in a way, that the empty elevator frame could always pass the occupied one.

Odyssey truly never had the commercial success. After the initial release in 1996, Odyssey did not result in a public building installation for elevator use. However, an adaptation of the system has carried millions of passengers in Disney World's The Twilight Zone Tower of Terror in Florida. (Sturgeon-Hendrick 2015)

4.1.3.1 Other Ro-Mu concepts

Judging from the patents, LG Industrial Systems had research on a similar concept to Odyssey in the mid-1990s. Otis soon later bought the company, and therefore it is possible that LG's patents even relate to the Odyssey project. Similar to Odyssey, LG's concept inserts a traction machine driven elevator frame to the hoistway. However, devices capability to horizontal movement is limited because hydraulic cylinders push cars from one hoistway to other. Alternatively, a pinion track was planned to be used in longer horizontal transitions. (Whang et al. 1998)

The same group of inventors has also applied for a patent number KR20000033344A. The publication proposes the use of circulating Type Ro-Mu elevator (Figure 26) in a megatall building. In this invention, the cars are handled in a similar fashion to Odyssey. To transfer cars horizontally, the car frames (2A, 2B) are driven next to each other. A uniform guide rail (31) between the frames provides support for the car while it rolls directly from one frame to another. (Whang et al. 2000)

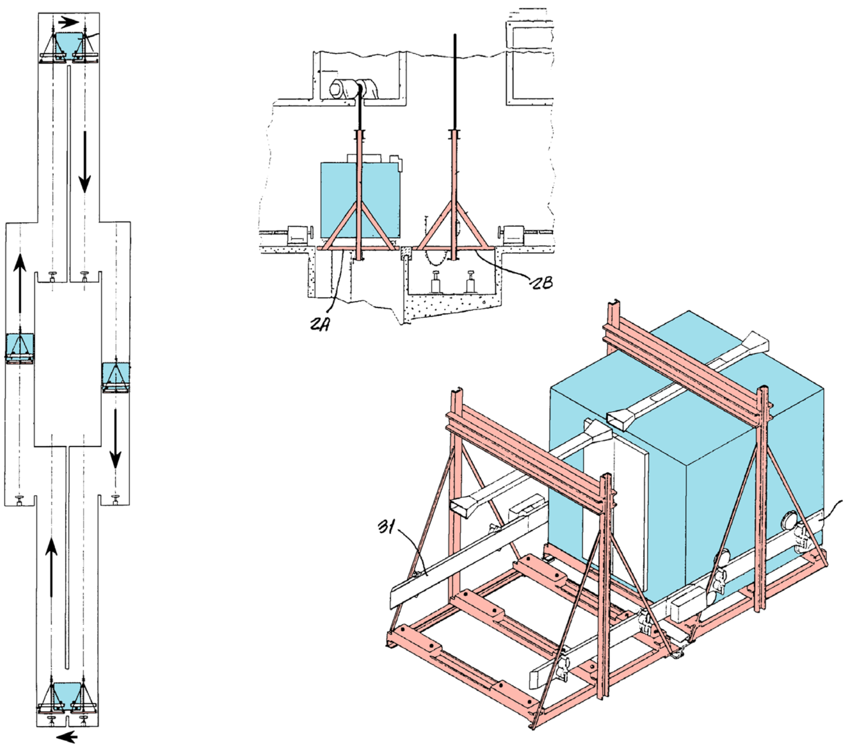


Figure 26 Roped multi-path elevator can be divided into short hoistway sections to increase hoisting capacity. (redrawn from Whang et al. 2000)

As mentioned earlier, Otis also has a patented pinion driven system that moves elevator cars horizontally between car frames and landings (i.e. storage stops). Each car has guide rollers and two rack rails at the bottom. The main rack rail is firmly secured to the base of the car, but the auxiliary rack is able to move relatively to the car to reach the adjacent frame. The car frames and the landings include guide rails and motorized pinions that provide the power to move the car. (Wan et al. 1998)

The pinion system moves the car only between car frames and landings. To reach longer horizontal distances a dedicated car frame is required. As shown in Figure 27, the frame (107) moves on guide rollers (93). A LIM secondary (128) attaches to the car frame and primaries (60) run parallel to the guide rail. (Salmon et al. 1998)

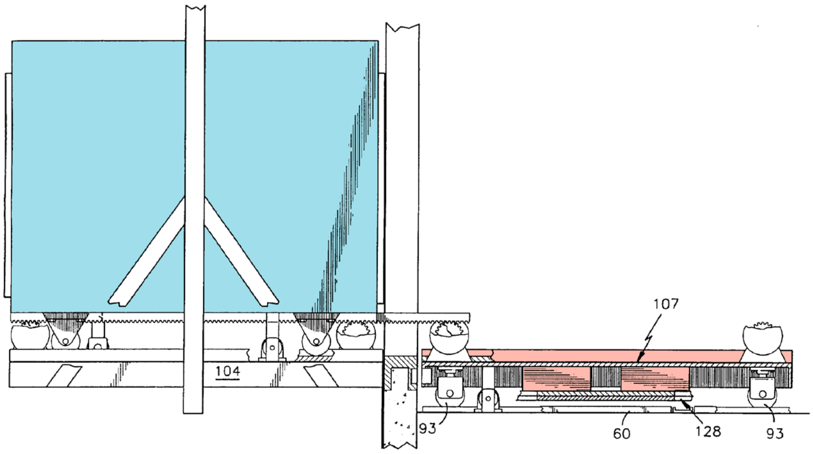


Figure 27 Two type of car frames of Odyssey system; roped vertical frame (104) and LIM driven horizontal frame (107) (modified from Salmon et al. 1998)

Otis also has an alternative proposal how roped individual cars could travel in one hoistway. Unlike Odyssey, this concept does not include car frames. However, the cars attach to couplers as show in Figure 28. In case of the illustration, the coupler Z is moving the car A upwards while the coupler W is attaching to the car. After the both couplers have ensured connection, the coupler Z can be detached, and the car can continue travel with its new pair. Thus, series of overlapped hoisting mechanisms could seamlessly transfer cars effectively especially in megatall buildings. The cars could also move horizontally between landings, so each hoistway can be dedicated for one-way traffic. (Barrett et al. 1999)

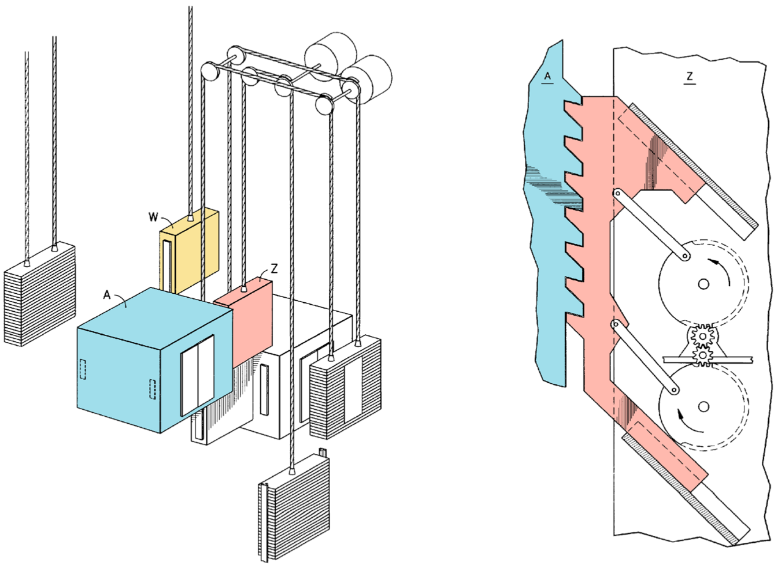


Figure 28 Rope system that includes overlapped hoisting mechanisms able to transfer cars for great distances. (modified from Barrett et al. 1999)

4.2 Self-propelled elevators

In this thesis, the word *self-propelled* is used to designate an elevator that does not include an indirect hoisting system via a rope, belt, or chain. This type of elevators usually cannot take an advantage of a physical counterweight.

Many of the self-propelled (i.e. climbing or ropeless) elevators include a linear hoisting motor (Section 3.1.2). This type of motor offers a new kind of freedom to operate the cars because ropes and counterweights do not restrict the design. In theory, instead of a linear motor the self-propelled elevator could be provided with a friction-wheel drive, a rack drive, a gearwheel drive, or a similar direct drive device (Dünser & Deplazes 2003). Conventionally, the weight of the hoisting ropes limits the maximum height of the elevator. However, the self-propelled elevator does not have height limitation, and the height should not affect to the system's power efficiency.

Ropeless elevators also have other advantages compared to roped systems. Tall buildings are designed to sway in high-wind conditions. The movement of the building structures leads ropes to vibrate and sway. This motion may cause the ropes to hit to other hoistway equipment or even the hoistway walls. Under such conditions, the elevator speed is reduced to manage the free length of the ropes so that their natural frequency does not match with the resonant frequency of the building. The linear motor should be less sensitive to weather conditions. (Strakosch & Caporale 2010)

A typical elevator installation can be started when the machine room on the top of the hoistway is completed. In theory, the self-propelled elevator could be assembled in sections while the building grows. Early installation would reduce the installation delay and the need for temporary vertical transportation systems. (Jetter & Gerstenmeyer 2015)

This section examines the patent publications that cover climbing elevator systems. Similarly to Section 4.1, the findings are categorized into three groups:

- **Type Sp-Si:** Self-propelled Single hoistway multi-car elevator consists of one main hoistway,

- **Type Sp-Ci:** Self-propelled Circular multi-car elevator consists of at least two hoistways that form a circular drive path,

- **Type Sp-Mu:** Self-propelled Multi-path elevator consists of multiple hoistways, and is capable to provide horizontal transportation.

4.2.1 Type Sp-Si: Self-propelled single hoistway

Section 4.1.1 discussed elevator systems that fit multiple roped cars above each other into a common hoistway. That kind of multi-car elevator has already proven to be commercially feasible, but the current implementations miss the possibility to change the mutual order of the cars. Therefore, this section gathers elevator concepts with adaptive car management, which can be accomplished by adding passing lanes, car storages, and other similar features to the system. All the presented concepts fit the essential components approximately into the space of one hoistway.

Because electric linear motors appear to be the most promising propulsion technology for self-propelled elevators, Otis' Skylinear is discussed in this this section, even though the product was a single-car elevator.

4.2.1.1 Otis' Skylinear

In the early 1990s, Nippon Otis Elevator Company introduced a linear motor elevator to compete with hydraulic elevators in the Japanese market. The company promised the new system to have lower operation costs than the common hydraulic elevators. Furthermore, the new product was claimed set into same price group with hydraulic elevators (Gieras et al. 2011). According to Barker (1997, p.72), the Japanese ordered about a thousand installations, but the development died after a couple years as a result of technical difficulties. Still today, the system remains the sole representative of the group of commercialized linear motor elevators.

In the Skylinear elevator, the linear motor is an integral part of the counterweight. In consequence, the elevator mostly has conventional traction elevator parts (a car, guides, ropes, sheaves, and a counterweight), with an exception of a solid iron rail in an aluminum sheath. The rail is a round bar, about 100 mm in diameter, and it passes through the center of the counterweight. This bar, LIM secondary, reaches the whole length of the hoistway. Due to a tubular construction, the rail can only be supported at the ends. Therefore, the rail's structural properties limit the elevator's maximum height approximately to 25 meters. (Carpenter 1991)

The LIM primary mover is a tube constructed of iron bars arranged in a circle. The construction is held together by iron rings that fit around the stationary secondary element like a sleeve. The current applied to the windings of the primary generates a magnetic flux including the driving force to move the primary along the bar. The significant advantage of the tubular construction is that the air gap is maintained automatically because the shape offsets the attractive forces. Janovský (1999, p.5) mentions that the Skylinear's rated speed was 1.75 m/s at the time, which can be considered to be relatively slow.

The motor's primary mover inside the counterweight requires power. A group of power cables connects from the counterweight to the bottom of the car. From the car the cables run to a power source in the hoistway. This cable arrangement provides the required balance weight to compensate the rope weight. (Nakai & Suganuma 1993)

Because all the sheaves in Skylinear act as idlers, they do not have friction requirement. As shown in Figure 29, the system includes mechanical brakes that are installed on the counterweight. The brake is built to act whenever it is de-energized. Without power, the solenoid releases a spring mechanism that presses the brake shoes directly upon the counterweight's guide rails. (Janovský 1999)

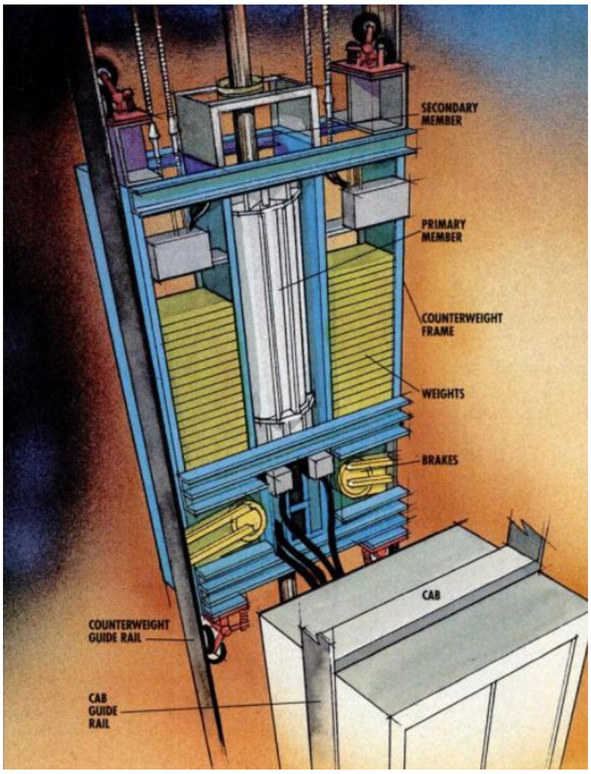


Figure 29 Stylized illustration of the Otis' Skylinear elevator with linear motor in the counterweight (Normile 1991)

Because of the utilization of ropes and a counterweight, Skylinear's potential to transform into a multi-car elevator is not ideal. Most likely, the multi-car use was not Otis' key concern since the maximum height of the tubular drive construction is relatively limited.

A linear motor together with dedicated counterweight is an unnecessarily expensive technical solution when compared to the modern traction machines. However, the Skylinear elevator was probably the first application of a linear motor in an elevator (So et al. 2014). The possibility to gather experience of the linear hoisting devices on a large scale would be a significant benefit of such a system.

4.2.1.2 Mitsubishi's multi-car concept

Mitsubishi was actively working on a completely ropeless elevator concept around the same time with Otis' Skylinear development. Mitsubishi's design mounts a primary stator stationary on the hoistway walls. Because of this arrangement, the energy to drive the motors does not need to be transferred to a moving car. Since the elevator has no ropes or power cables, the number of cars can be easily increased. However, for the same reasons the suggested elevator requires more power and more complicated safety systems than roped elevators.

Mitsubishi used a flat PMLSM design. In theory, the motor type does not set any restrictions on the hoistway height. However, unlike the tubular motors, the flat linear motors have challenges on maintaining an air gap between the motor primary and secondary. In Mitsubishi's concept, the same guide rollers that hold the car on track also maintain the distance between the motor elements. As shown in Figure 30, the motor components are divided to each side of the guide rail.

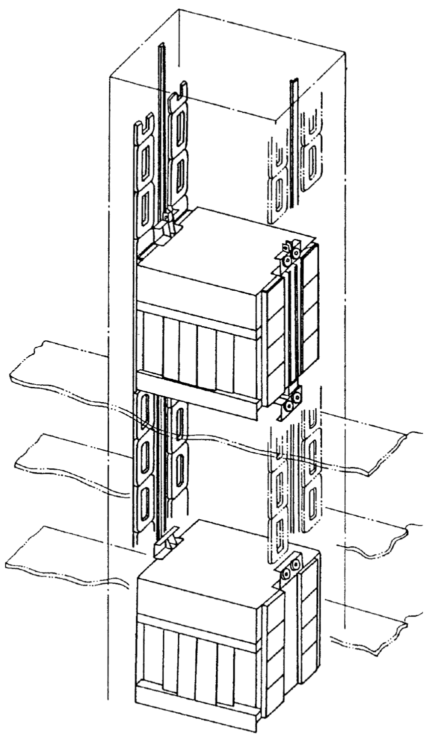


Figure 30 Mitsubishi's self-propelling elevator concept. (modified from Watanabe et al. 1990)

The stationary motor primary is split into sections corresponding to the floor height. Each section reaches from the middle of the one floor to the middle of the adjacent floor. The system monitors the position of the elevator car and activates only necessary sections occupied by cars. (Janovský 1999, p.8-9)

The secondary mover of the PMLSM consists of a group of permanent magnets, and it mounts directly on the sidewalls of the car that face the motor primary. The magnets are about 5 mm thick and covered with sheet metal reinforcement of similar thickness. A plastic coating helps to maintain magnets clean of magnetic particles. (Janovský 1999, p.8-9)

The Mitsubishi's concept has a similar brake design as Otis' Skylinear presented in the previous section. If the elevator loses power, the primary element would be short-circuited in order to slow the car. If we assume that the impedance percentage of the primary coil is 5%, a braking action would hold the velocity of the car within 5% of the rated value. (Janovský 1999, p.8-9)

4.2.1.3 Other Sp-Si concepts

In addition to developing the roped TWIN elevator system, ThyssenKrupp also has applied for patents related to a similar self-propelled system. Their invention enables the possibility to operate at least two ropeless cars in a single elevator hoistway. Unlike in the roped version, the height of the hoistway can be virtually limitless. As in Mitsubishi's concept, Smith & Sweet (2002) place the stationary primary to the walls of the hoistway. Thus, each car is equipped with a secondary.

A significant limitation of the current TWIN is that the cars are unable to pass each other because they drive on the same lane. Smith & Sweet (2002) claim that their system could be modified by adding dedicated passing areas for the cars. In this case, one car could slow down, move horizontally out of the driving lane, and permit another car to pass it. Unfortunately, the patent documentation does not provide any technical statement of how the horizontal movement could be implemented.

Kazuhiro (2006) has concepted a self-propelled multi-car elevator at Toshiba. The invention installs straight vertical rails on two sides of the car, and each car has two guide units operating along both rails as proposed in Figure 31. The guide unit (10) consists of rollers and most likely a linear motor element. In addition, each car has a spring-loaded electromagnetic braking device. The brake secures the car to the rail while the segment rotates. It also activates to stop the car in case of power failure. (Kazuhiro 2007)

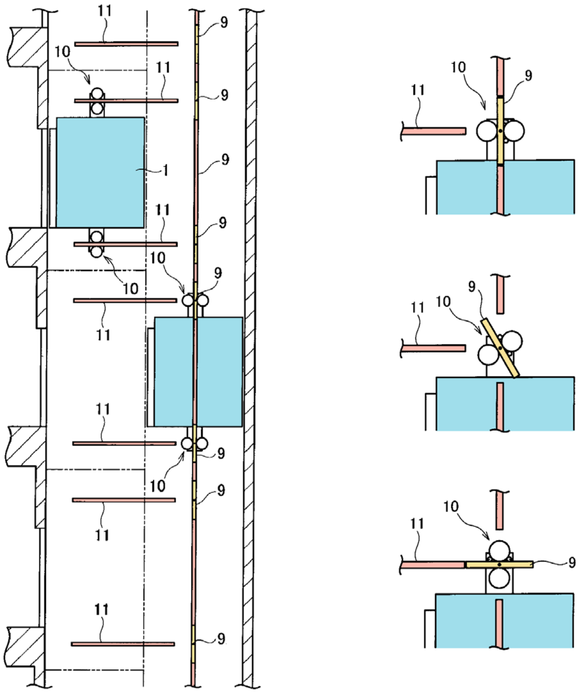


Figure 31 Cross-section of the elevator concept where cars exit the main track for loading and unloading passengers (modified from Kazuhiro 2006)

The major advantage of the Kazuhiro's system comes from routable rail segments (9) that allow cars to move between horizontal and vertical rail sections. The loading and unloading of the passengers can be done at the end of the horizontal rail (11). Thus, the parked car does not block the transition of other cars. This elevator concept also offers the possibility to install additional vertical rails. With such an arrangement, one rail can guide cars up and other down, forming a circular elevator system with passing cars. As a drawback, the circular version would require a space of three hoistways. (Kazuhiro 2006)

According to Kazuhiro, the elevator illustrated in Figure 32 can also contain a car storage section. Mechanically, the storage is a longer adaptation of the horizontal rail parts utilized on floors. It can take advantage of existing rotation sections and share the floor with a door, as shown in Figure 32.

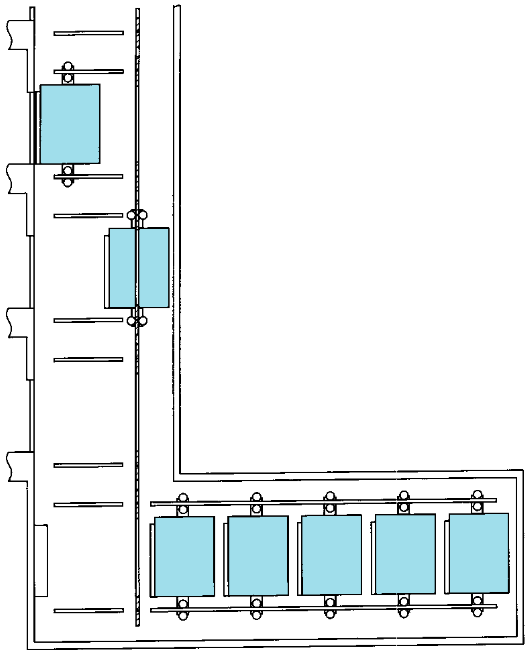


Figure 32 Bottom floor car storage section (modified from Kazuhiro 2007)

Toshiba's earlier multi-car elevator concept represents an entirely different way of thinking (Figure 33), but it also underlines the importance of the by-pass zone for the cars. According to the patent, the elevator cars could drive along a helical guide rail. The rail could be installed on the wall of the cylindrical hoistway. Alongside the main rail, each floor would have a circle loop to accommodate the parked cars. (Shiobara & Tanabe 1993)

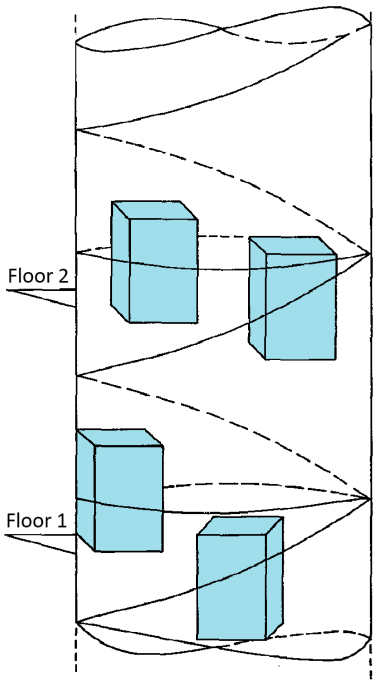


Figure 33 Toshiba's cylindrical elevator concept (redrawn from Shiobara & Tanabe 1993)

The realization of the Toshiba's cylindrical concept would most likely be challenging. The patent does not state clearly how the rail locates in relation to hoistway doors.

There is also a concern of passenger safety because the car is in constant rotation. Thus, standing inside the car would not be an option. In addition, the intersections of the rails with given angles can also be problematic.

By-pass zones are the logical solution to allow cars passing, but the problem can also be approached differently. Inventio has combined two adjacent hoistways to form one dual hoistway elevator running two car pairs (Figure 34). The paired cars always move simultaneously in opposite directions. In the middle of the hoistway, cars arrive in a change zone (marked with ‘Z’ in Figure 34) where they cross over hoistways. According to the patent, toothed guide rollers could provide stable movement of the car. These rollers would be driven by an electric motor installed on each car. Alternatively, a linear drive hoisting could be utilized. (Tschuppert 2013)

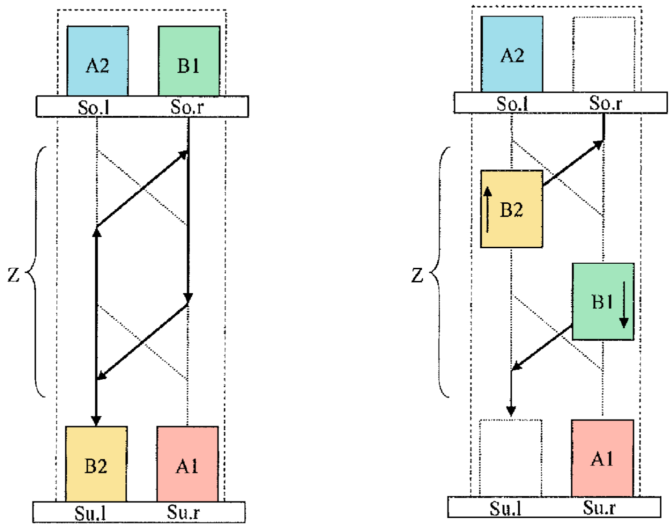


Figure 34 Elevator capable to operate four cars in two hoistways. Cars A1 and A2 work as a pair and change place once per each trip. B1 and B2 perform in an equal manner. (modified from Tschuppert 2013)

If the topic of this section is taken literally, the dual hoistway elevator would not belong under it. However, this type of elevator differs only a little of the two single hoistway systems installed side by side. The self-propelled hoisting system could also be replaced with two traction machines installed stationary into the top of the elevator. The rope would run along the track and connect paired cars so that they would work as counterweights for each other. (Tschuppert 2013)

The elevator described above would be the most beneficial as a shuttle elevator between two platforms. The estimated height of the changing zone is approximately from 10 to 20 meters. Because the total height of the hoistway is most likely much greater, all the four cars can be in motion at the same time. (Tschuppert 2013)

4.2.2 Type Sp-Ci: Self-propelled circular

Type Sp-Ci elevator, also called an independent multi-car circular elevator (IMCE), resembles a more advanced version of the old paternoster. On the opposite to paternoster's chain of cars, the cars in IMCE system move along a circular path independently. Unlike in Type Sp-Si elevator, the hoistways in the IMCE can be dedicated for one-way traffic. While one hoistway travels cars up and other down, the maximum capacity of the elevator system increases.

In theory, the only limit to the number of cars in the IMCE system is safety clearance between the cars. The clearance can be shorter than in a Type Sp-Si elevator because the cars never drive towards each other. However, the practical car count is probably relatively low if the system does not allow cars to pass each other.

The IMCE and a multi-path system described in Section 4.2.3 can in some cases resemble one another. The nature and performance of the concept changes remarkably if alternative paths are added alongside the circular track. Therefore, this section focuses only to inventions with a circular track.

The concept of IMCE is not new. In 1896 American engineer, John R. Hamilton received Patent No. 561223 for his multi-car elevator concept. In Hamilton's concept, each elevator car includes an electric motor, which is linked to a rack-and-pinion drive system. As shown in Figure 35, the cars in the elevator drive along guide-rails similar to train tracks. (Hamilton 1896; Gray 2005)

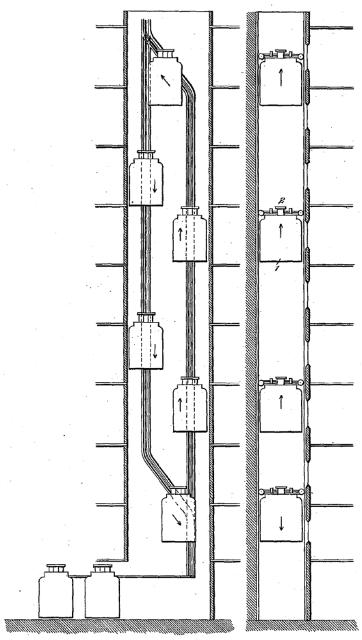


Figure 35 Early self-propelled elevator concept with a rack-and-pinion drive (modified from Hamilton 1896)

The more recent patent publication WO2012038760A2 proposes the use of two parallel hoistways with at least two partially combined track systems. The two rotatable track sections enable possibility to transfer elevator cars from one hoistway to the other. The connecting section rotates around its vertical axis (2), as shown in Figure 36. A locking mechanism keeps sections aligned when a car passes the seam. (Godwin & Godwin 2012)

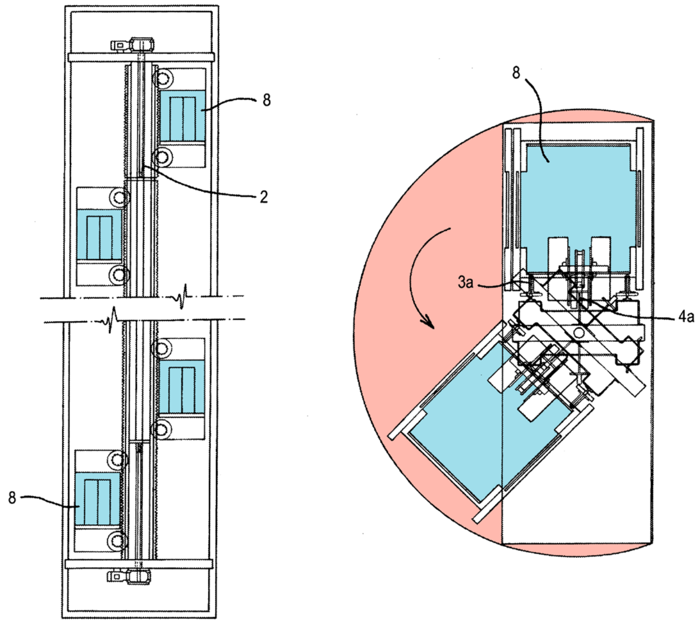


Figure 36 Elevator that consist of two parallel hoistways and a rotating flip system to transfer cars between hoistways (modified from Godwin & Godwin 2012)

Each car (8) has guide wheels on both sides of the central rail (4a). In order to achieve acceptable stability of the cars, additional guide wheels (3a) are required closer to the corners of the car. Conventional rectangular hoistways can be applied to the fixed track sections, but the rotating sections require a semi-circular enlargement, as seen in cross-section in Figure 36. (Godwin & Godwin 2012)

The inventors do not propose the use of a linear motor. Instead, each car has a drive motor that directly rotates a lantern pinion engaged with a rack. The pinion parts can be formed from carbon fiber reinforced self-lubricating PEEK. Alternatively, metal parts could be used, and the contact surfaces could be coated with a polymer material to reduce noise caused by the pinion touching the rack. No mechanical obstacles exist why a linear motor could not be implemented in similar fashion. (Godwin & Godwin 2012)

The system is claimed to achieve a car speed of 2.5 m/s. The motors have two functions: they provide power for lifting, but also act as a regenerative brake system while the car is moving down. The relatively large pinion with a large pitch in the gearless system requires significant torque from the motor. On the other hand, the large pinion results in slower and quieter operation of the motor. (Godwin & Godwin 2012)

The proposed structure is highly adjustable to various installation heights. The efficiency of the system could be increased by adding intermediate rotating stations. With the additional stations, the car could travel shorter routes without unnecessarily passing through the ends of the hoistway. The intermediate rotating station would also improve the accessibility of the elevator car in emergency situations. (Godwin & Godwin 2012; Piech 2014)

Hitachi has also patented concepts that resemble the previously mentioned pinion based solution. In Hitachi's elevator, the rotating drive wheels move the cars. The wheels do not have teeth, but the lifting is based on the friction between the wheel and the guide track. A set of secondary rollers maintains the car's orientation and necessary tension on the drive wheel. Each car has its own drive motor that rotates the driving wheel. The car is also fastened to a rope loop that connects it with the opposite car to form a weight-couple. This installation reduces the required motor power and improves energy efficiency. (Seki et al. 2005)

Otis has applied a patent for a similar system equipped with a linear hoisting machine. The change of the hoisting method does not affect the basic concept of the rotating structure. Figure 37 depicts three installation configurations of motors and the guide rail for this type of system. The leftmost proposal places the guide rail into the center column of the system. The motor parts are installed on both sides of the guide. Such a layout is one of the simplest possibilities considering the rotating rail section because the equipment is close together. The suggestion is also similar to propulsion system shown in Figure 6 on page 20.

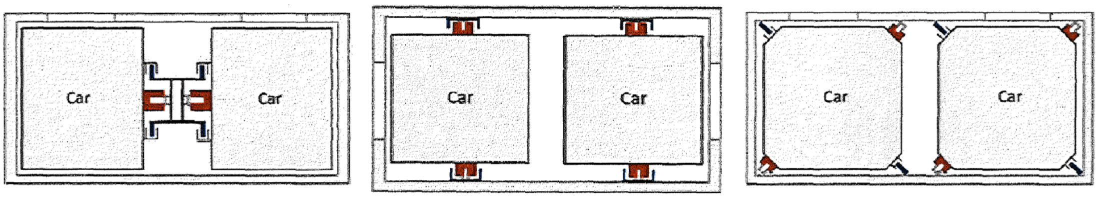


Figure 37 Examples of a linear motor and guide rail installation positions on a car (redrawn from Piech 2014)

The concept in the middle of Figure 37 installs the guide-motor pairs on two opposite sidewalls of each hoistway. The rightmost proposal has guides at two corners of the hoistway. Moreover, the linear motors locate at two diagonally opposite corners. (Piech 2014)

Figure 38 illustrates a circulating elevator system that also includes a rotatable section for transferring cars from hoistway to another. In this case, the car is flipped around its horizontal axis, which permits to transfer cars to another hoistway, a horizontal track section (21), or a storage space. Unlike in the previous concepts, the car does not retain its orientation during the rotation. Therefore, a separate stabilization system is required to rotate the interior of each car. Otherwise, the car needs to be horizontally symmetrical. (Godwin & Godwin 2012)

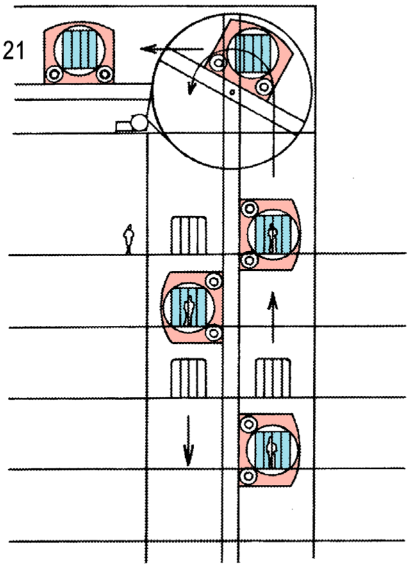


Figure 38 Rotating track that allows cars to transfer to horizontal route (modified from Godwin & Godwin 2012)

The researchers at University Henan Polytechnic have applied patent for a few multi-car elevator concepts with a linear hoisting device. Their inventions run independent cars in a circular hoistway. To move vertically, the cars travel on a straight linear stator. However, the horizontal movement can be achieved by either a sled system or a rotating transfer device, both shown in Figure 39. The rotating device is similar to the previously discussed system in Figure 36, but requires additional space on two sides of the hoistway to perform the rotation maneuver. (Xudong et al. 2010)

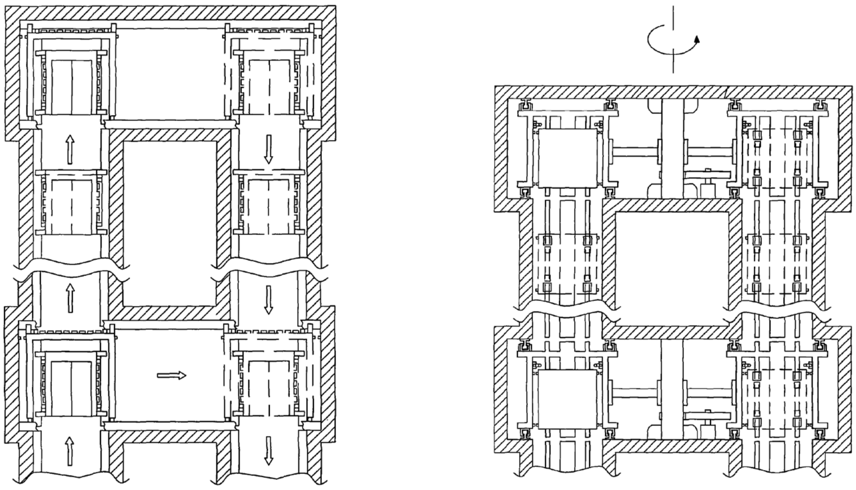


Figure 39 Two concepts to transfer cars between hoistways. The left elevator includes a horizontally moving sled, and the right elevator uses a rotating apparatus (modified from Xudong et al. 2010)

Xudong et al. (2010) also suggest that the multiple circular elevators could be combined to form more complex elevator layouts, as shown in Figure 40. These combinations feature the same principle as single loop elevators, maintaining the one-way trafic in the hoistways. In practice, these systems could be included in the next section discussing Type Sp-Mu elevators because there are no particular technical restrictions for the shape of the elevator system. However, if the rails are constructed as physically independent, the system does not necessarily allow cross-loop car operation. This is also the case in Figure 40.

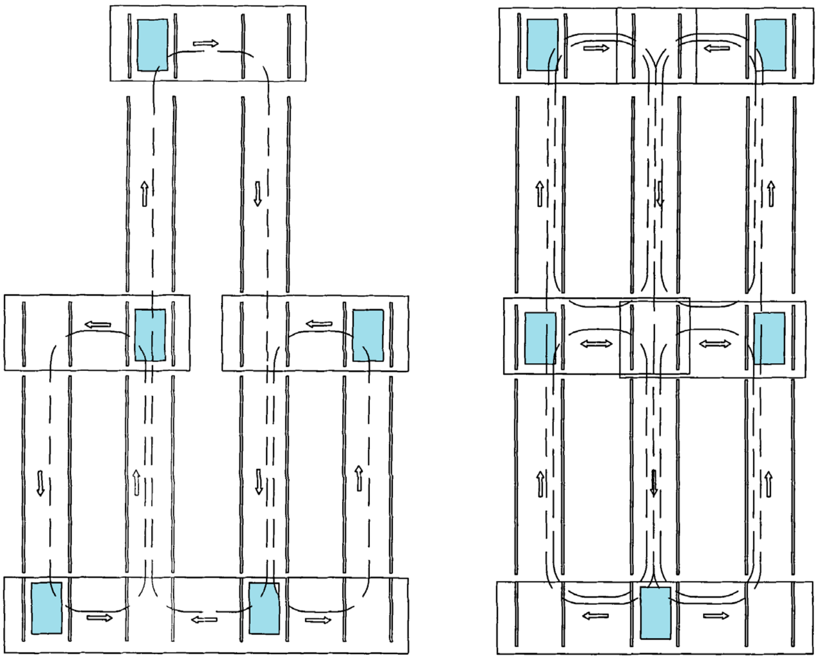


Figure 40 Multiple circular elevators connected to form a group that shares hoistway sections. The shared sections save space, and moreover less doors are needed. (modified from Xudong et al. 2010)

The same research team has also patented a concept shown in Figure 41, which includes a chain like actuator that moves the car. The rear wall of the car contains a rotating drive component that consists of a linear motor element, guide elements, and a car brake. The axis of rotation goes thought the car's center of mass, so the car remains stable, even though the drive element turns along the track. The car also has four guide wheels to stabilize the ride and to hold the correct orientation. (Xudong et al. 2013b)

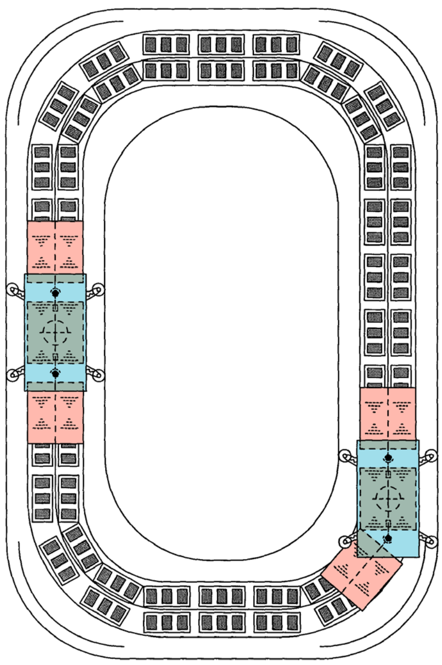


Figure 41 Guide system for circulating linear elevator (modified from Xudong et al. 2013b)

A curved track provides a continuous motion for the whole travel cycle of the car. When compared to the previously presented concepts, the lack of stopping points may reduce the travel time of the elevator. Moreover, no kind of track positioning problem can occur because all the guides are stationary. The horizontal acceleration on a curved track does not depend on the accuracy of motor control, so a curved track may even provide the more pleasant ride experience for a passenger than stopping solutions.

A similar elevator can also be constructed by using only one guide wheel on each car, as shown in Figure 42. The elevator shares the basic principle with the traditional paternoster, where a car is lifted from the diagonally opposite corners by identical rope loops (Figure 3 on page 13). The fix point arrangement prevents the car to turn over. However, two fixed tracks and a guide wheel are utilized instead of ropes in the invention of Xudong et al. (2013a). The rotating axle in the middle of the car, connecting the linear motor and the car, serves as the first connection point. The second connection is a dedicated guide wheel rolling along the guide surface.

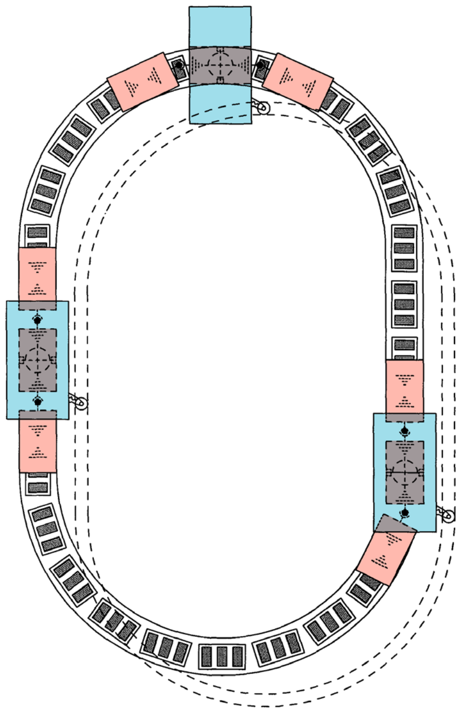


Figure 42 Circulating elevator with a single wheel guide system (modified from Xudong et al. 2013a)

The guide track in the form of loop enables the possibility to build a climbing elevator with the advantages of the counterweight. In a vast group of patent publications, the elevator cars form weight-couples, but this solution is rarely seen in self-propelled elevator concepts. However, paired cars could result in smaller torque and improved energy efficiency. The disadvantage of such a system is that paired cars have to move equally. (Seki et al. 2005)

4.2.3 Type Sp-Mu: Self-propelled multi-path

An elevator capable of transferring multiple cars in a mutual space seemingly without restrictions is considered to be the Holy Grail of the elevator industry. The self-propelled multi-path elevator could, in theory, be installed into any kind of building with various traffic expectations. The basic concept of Type Sp-Mu elevator is not new, but only recently, ThyssenKrupp's MULTI concept put it back on the table.

4.2.3.1 ThyssenKrupp's MULTI

In late 2014, ThyssenKrupp announced a new elevator concept called MULTI. According to the manufacturer, this innovation will be the world's first rope-free elevator system. Unfortunately, at the time of this thesis work, very little is known about the technical solutions utilized in the MULTI elevator.

The ideal building height of the MULTI elevator starts at 300 meters. However, there are no impediments to shorter installations. The system will allow access to an elevator car every 15 to 30 seconds, with a transfer stop every 50 meters. Furthermore, the car's travel can achieve the vertical speed of 5 m/s. (Ridder 2014a)

The linear motor locates at rear wall of the car. The backpack solution allows the cars to travel both vertically and horizontally. Similar motor arrangement has been proposed in the past, for example in the systems of Figure 41 (on page 62), and Figure 45 (on page 66). The mechanical design allows track construction with various shapes and sizes. Direction changes occur at the connection points, where the section of the track rotates similar to a railway turntable. (Jetter & Gerstenmeyer 2015; Ridder 2014b)

ThyssenKrupp expects their new elevator system to cut the required space to half compared to traditional solutions (Brown 2014). The space saving is achieved not only by the efficient management of the elevator cars but also with smaller hoistways. While other technologies such as the TWIN elevator require roughly 9 m² of floor space, the MULTI system fits into 6 m². (Ridder 2014a)

The elevator system utilizes carbon fiber reinforcement in the car body. The use of expensive materials is justified because self-propelled cars benefit from mass reduction more than roped cars. The lighter materials will pay back their installation cost through reduced energy consumption. With current knowledge, the elevator also employs magnetic levitation familiar from the Transrapid monorail train (Jetter & Gerstenmeyer 2015; Ridder 2014b).

The company aims have a running MULTI prototype by the end of 2016. The test tower, height 246 meters, is currently under construction in Rottweil, Germany. Three 100 m high hoistways will be used only for testing of the MULTI elevator. (Wilkinson 2015; Sturgeon-Hendrick 2015)

4.2.3.2 Other Sp-Mu concepts

A car in Otis' Odyssey, and supposedly in ThyssenKrupp's MULTI elevator, has to stop vertically before it can move to another hoistway. However, a more time-efficient action would be to perform the hoistway change on the move. Mitsubishi Electric has taken an approach that has similarities with train tracks. Certain sections of the car guide track can be rotated to connect two parallel pathways so that a car can reach the other hoistway. To achieve a turning track, both the linear stator, and the car guidance have to be installed into a relatively compact construction. (Kimimoto & Toshiaki 1993a)

If drive elements are installed on both sides of the car as in Figure 43, the car cannot be driven through the turns of the pathway by a linear motor. Some external lift equipment is required to secure a suitable air gap of the motor elements. Kimimoto & Toshiaki (1993b) mentions a hydraulic powered platform (28 and 29 at Figure 43) that could transfer the car to the position, in which connection between linear motor elements can be created. The positioning device has to operate precisely to avoid collisions.

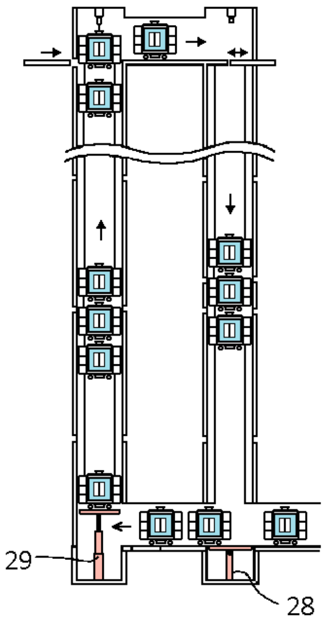


Figure 43 Lift mechanism in corners (redrawn from Kimimoto & Toshiaki 1993b)

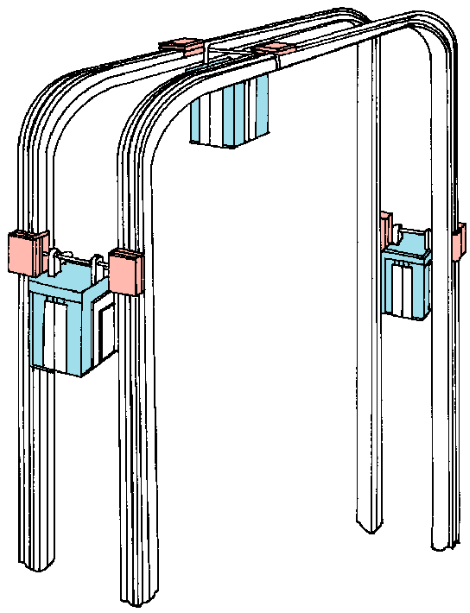


Figure 44 Curved elevator track (modified from Kimimoto & Toshiaki 1993b)

If the linear motors are needed on two sides of the car, the curved rail section could be a sophisticated solution to transfer the cars between horizontal and vertical travel paths. In this case, the car maintains a connection to the main track whole time. Figure 44 illustrates a part of such system. (Kimimoto & Toshiaki 1993b)

U.S Patent number 6955245 describes a TYPE Sp-Mu elevator that consists of self-propelled cars. Unlike the previous suggestions, this elevator system illustrated in Figure 45 requires a dedicated hoistway (11) for parking purposes. In case of a three-hoistway system, the leftmost hoistway (10) transfers the cars (16) up, while the rightmost hoistway (12) maintains the downward traffic. The passenger cannot access the hoistway in the middle that only stores empty cars. The system checks if the car is occupied before every horizontal movement, and the car is allowed to move only when it occurs empty. (Dünser & Deplazes 2003)

The motor secondary is installed on the rear wall of the hoistway. A section of the main drive could be rotated in such a manner that the same motor could operate both vertical and horizontal movements. When the both motor components are rotated together, the attraction forces between them cause less concern. Alternatively, the elevator car may have an additional drive to move in a horizontal direction. (Dünser & Deplazes 2003)

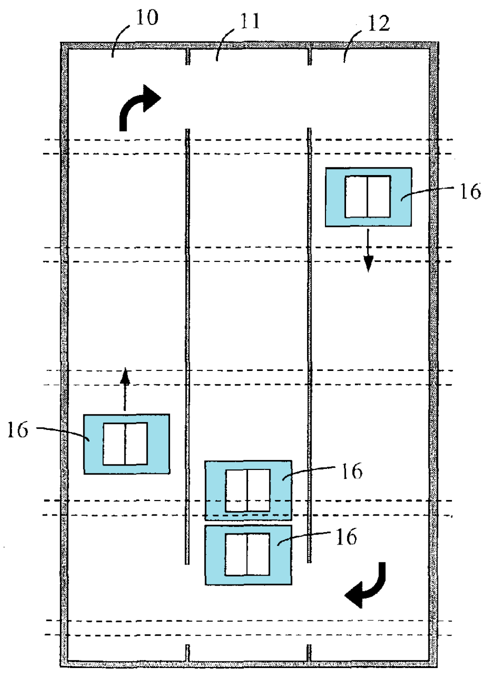


Figure 45 Multi-car elevator that has a dedicated storage hoistway in the middle of the transportation hoistways (modified from Dünser & Deplazes 2003)

An additional hoistway between main transportation routes could also be allocated for other type of use. Lingzhong (2006) has proposed a hoistway layout where each door locates in separate landing stops (Figure 46). The advantage of Lingzhong's arrangement is that stopped cars do not cause blockades to others. The installation of such an elevator requires substantial space reservation because there needs to be at least one car width between vertical hoistways.

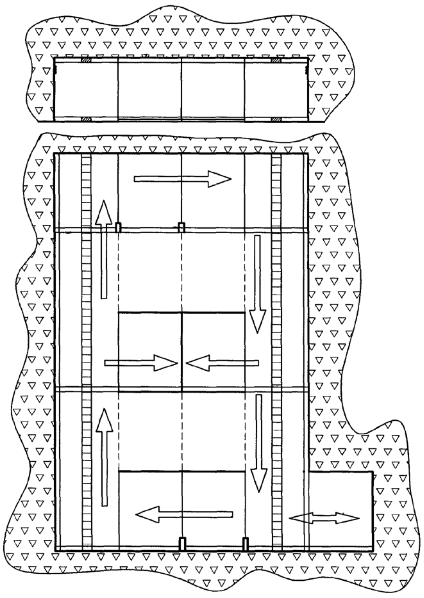


Figure 46 Hoistway layout with landing stops (modified from Lingzhong 2006)

The most important goal of multi-car elevators is to save floor space. Therefore, storing empty elevator cars vertically is impractical because the value of the space increases with every floor up the building. The patent CN201857183U describes a circulating elevator with a storage room at the bottom of the system. Storage floor in basement level has only a minor effect on the cost-effectiveness of construction because those floors are already dedicated for garages and service spaces. The idea of the invention is similar to system illustrated in Figure 32 on page 56. The storage space can be used for storing unused car at off-peak times, but also for maintenance purposes. (Zhong 2011)

5 Comparison of multi-car elevator concepts

The aim of this thesis was to discover the existing multi-car elevator concepts and related technologies presented in patents and literature. The previous chapter objectively compiled the most interesting elevator concepts. This chapter evaluates and compares features of the findings, and takes a stand on their feasibility.

Patents represent a very subjective perspective on their topic. They do not take into account all the technical constraints and codes that are associated with the elevator designing. Many of the multi-car elevator concepts in patents could never become to commercial products because of their complexity. Some concepts also include questionable design solutions in terms of safety, while others are unfeasible because they set impossible requirements for durability of the materials or the weight-power ratio of the hoisting equipment.

The journey time and the handling capacity are the two most important traffic performance indicators of an elevator (So et al. 2014). However, a realistic mathematical modeling and valuation of the multi-car elevator concepts is challenging. A single multi-car elevator system can have thousands of variations that affect greatly to its performance. Furthermore, an elevator system is expected to manage manifold traffic through a building. If the system is not a shuttle elevator, the passengers can call a ride from multiple floors to several other floors. Thus, the calculations would require notable simplifications, strict definitions, and assumptions of the author. Therefore, the results would not be universally applicable.

The challenge is that there is an infinite number of combinations of

- the flow of people
    - the design of the building affects the elevator (and the other way around)
- the physical implementation of the multi-car elevator
    - as shown in the previous chapter, a multi-car elevator can be implemented with various methods
- the control system
    - car management influences to response and travel time

To the best knowledge of the author, the comparison table in Appendix 2. collects features of different multi-car elevator categories. The table illustrates the limitations and possibilities of the different type of multi-cars, but the evaluation does not apply to any specific elevator concept.

Especially the selection of **Type Ro-Si** elevators is large and diverse. However, the vast majority of the patents deal with dual-car solutions (discussed in Section 4.1.1.1). In practice, the group exists in the form of two variants:

- elevators that include passing cars, and

- dual-car elevators (such as TWIN) that cannot shuffle the order of the cars.

One of the main concerns of Type Ro-Si is find a method to allow car passing. Technical feasibility of the concepts that include a wide by-pass zone in the middle of the hoistway seems unrealistic. First of all, the partly widened hoistway structure is not compact if stacked sideways. Thus, the demand of different floor area on different heights creates challenges to form a functional elevator group. If adjacent hoistways cannot be built imbricate, the system does not necessarily save space at all compared to a similar system without the passing possibility.

Secondly, moving even a section of the roping horizontally causes issues, especially when it is done during the normal hoisting operation. Typically, there is a change to vibrations and ropes hitting to each other or other equipment. Additionally, the attachment point and direction of the lifting forces may vary about the car's center of mass, which may be impossible to control in an acceptable way.

The by-pass zone in a Type Ro-Si elevator does not offer as significant advantage as could be expected. Due to the fact that the cars have to operate synchronously to position at the passing point at the same time, the overall capacity this type of elevator is not equal to two independent single-car elevators. The elevator should have at least a possibility to park unused elevator cars out of the way to save energy. The cars could be stored inside the existing by-pass sections. Alternatively, the dedicated car storage could be reserved, for example, under the operated floors.

The practicality of the Type Ro-Si concept with passing cars can be enhanced by relocating the passing section. Each car could have its own hoistway in the busy lower part of the building and a common hoistway in the upper part (page 36). In this case, the hoistway structure follows the conventional construction technical guidelines. The elevator could be located at the side end of the elevator group to minimize the previously mentioned stacking issue.

A well-thought aspect of Type Ro-Si is how the ropes could be arranged when multiple cars locate above each other. In practice, elevator companies have the technical competence to build single hoistway multi-car elevators. Some manufacturers have been interested in MRL multi-car elevators that could save space compared to ThyssenKrupp's solution. These devices would most likely include similar permanent magnet synchronous motors (PMSM) that are generally used in single-car MRL elevators. However, the installation heights of MRL elevators are usually more limited than the heights of MR elevators.

Taller the Type Ro-Si elevator gets, the more inefficient the elevator becomes in terms of space usage. The maximum number of the cars remains roughly at two to three per hoistway, although, if each car operates only a particular zone, the car count could be increased (Okabe & Ishii 2000). In fact, the hoistway segmentation in vertical direction is the simplest technique to increase the utilization of the hoistway space. However, a zoned elevator system is too limited to be called a multi-car elevator because the operation zones can overlap only a few floors. Therefore, the most floors are only accessed by one car. (Jokela et al. 2003)

In order to improve the space efficiency with a roped system, the **Type Ro-Ci** elevators are usually proposed. Type Ro-Ci represents a logical development step to solve the problem of cars decreasing each other's functional capasity. Because the hoistways are dedicated to either ascending or descending traffic, ideally, the blockages does not become a problem.

There are two basic solutions how a circular hoistway arrangement can be achieved:

- closed rope loops,
    - The cars may be fixed to the rope, or some clamping device may be included to allow the cars to attach and detach from the rope.
- separate drive systems for vertical and horizontal movement.

The roped elevator systems benefit greatly from the existence of the counterweight. Therefore, the most roped systems place cars symmetrically along the rope, so that the car masses offset each other. The system can be built in a way, that each car has a balance pair on the same rope. Multiple pairs are installed parallel into the same space (Hitachi's concept in Section 4.1.2.1). It is questionable, how effectively this type of arrangement can operate because stopping cars would inevitably bother each other, and if one door is kept open, the operation of the whole system could freeze.

Type Ro-Ci elevator could also include a dedicated counterweight. Thus, the elevator could operate, for example, three independent cars. The cars could use common guidance, but each car would need a rope loop and a drive machine. In this case, the volume of the hoisting equipment would limit the maximum number of the cars. The same limitation also applies to the other Type Ro-Ci devices, thus they are not suitable for high-rise installations.

The Type Ro-Ci elevator can also be implemented in the same manner as a Type Ro-Mu elevator. The car can be hoisted with one device, and moved to an adjacent hoistway with another. However, this style of car management causes significant safety concerns because the cars are not constantly attached to the hoisting equipment.

Type Ro-Mu elevator concepts are few in number. Maybe the Otis' unsuccessful Odyssey system (Section 4.1.3.1) frightened others not to design such ambitious elevators. Alternatively, maybe the industry has become to the conclusion that this kind of technology does not have technical nor commercial potential. Moreover, horizontal transportation is not the main concern of the elevator industry. Thus, the industry has no rush to develop it. However, currently, it seems that eventually the Type Sp-Mu elevators will realize, as long as the linear motor technology becomes available.

There is a fundamental difference between Type Ro-Mu and all the other elevator types mentioned in this thesis. While the other types can be scaled to relatively compact units for different size of buildings, the Type Ro-Mu is meant to replace a complete elevator group instead of an individual elevator.

The Type Ro-Mu does not offer any advantages over the Type Sp-Mu, expect the most likely lower price due to the more familiar technical implementation. If the Type Ro-Ci and Ro-Mu concepts are compared, the Type Ro-Mu loses in low installations because the cars have to move with larger spacing. However, a Type Ro-Mu elevator could provide faster and easier experience for the passenger in buildings where Type Ro-Ci elevators require sky lobbies.

As the Odyssey project proved, Type Ro-Mu elevators are not easily feasible. The handling of the independent car units could work in an industrial environment, but to build a low-maintenance elevator with such complex and precise mechanical instruments has to be challenging. The horizontal propulsion and guidance should also be provided in a way that noise and vibrations do not lower the ride comfort. Furthermore, the achievable vertical transportation capacity (page 46) settles too close to double-deck elevators to justify the elevator's mechanical complexity.

As mentioned previously, the saved building core space is the main motivation of the multi-car elevator development. Regardless of the hoisting system, the multi-car elevator equipment most likely requires more room around the car in the hoistway than current solutions. However, the size of an individual hoistway is not a factor of saved space. Instead, the overall space savings are the result of higher car density. Multi-car elevators may also result to indirect space savings because some concepts reduce the size of lobbies, and requirement for escalators and travelators.

The roped elevators loose capasity compared to self-propelled elevators in high-rise installations. The number of cars can not be increased beyond a certain limit because ropes need space. However, in self-propelled elevator the space saving could be considered to be greater the higher the hoistway grows.

If the heading of the Section 4.2.1 is taken literally, the **Type Sp-Si** elevator is maybe something that should not exist. There is no economic reason to make the effort to install a linear hoisting device into a single hoistway system. On the other hand, this may be the necessary step before other type of self-propelled elevators. Therefore, almost all of the current linear elevator motor development focuses on prototypes implementing the single hoistway form factor. If more space is allowed for the use of the system, the circulation of the cars becomes the more appealing option.

Figure 31 (page 55) depicts a Type Sp-Si elevator with the dedicated unloading and loading stops. This arrangement is feasible if passengers are denied to travel horizontally with the car. Arrangement may also be challenging for the car control if both ascending and descending traffic occur in the same hoistway. Especially problems come up at the lower floors where traffic is more intensive and more cars desire to visit the ground floor. The greatest bottlenecks could be resolved with an additional hoistway that would enable the one-way traffic.

In a sense, the dedicated landings waste space because the same volume could be used to build a drive track. The circular drive patch construction is mechanically simpler solution because the vertical track can be almost seamless. On the other hand, dedicated landings save the cost of the second stationary element of the linear motor.

Fundamentally, the four-car system introduced in Figure 34 (page 57) resembles a circulating shuttle elevator. However, the described arrangement could increase the utilization rate of the cars compared to a four cars circulating elevator because all cars can be accessed simultaneously. On the other hand, the travel path includes horizontal movement and loading stops can be time consuming, which increases the interval.

Type Sp-Si elevators resemble the most matured technology of self-propelled elevators. Because self-propelled elevators base almost exclusively on a linear motor, the straight track gives options to motor positioning, simplifies safety concerns, and even allows the use of a roped counterweight. Nevertheless, the most basic Type Sp-Si elevators have difficult time to compete roped elevators in efficiency. Moreover, the Type Sp-Si variations with horizontal movement do not offer extra feasibility or capacity over the Types Sp-Ci and Sp-Mu.

The number of **Type Sp-Ci** elevator patents indicates that notable potential is seen in circulating self-propelled elevators. Because the Type Sp-Ci elevator can consist of relatively high number of cars, the cost of hoistway long stationary linear motor element per car is lower than in Type Sp-Si. The presented concepts form a vast and very divergent group of possibilities. The most basic question of Type Sp-Ci elevator is how the cars shift from one hoistway to another. A few possible design solutions are:

- Uninterrupted connection to track during the entire work cycle
    - Closed track loops
    - Turning track section (stationary car)
    - Rotating track section (car moves horizontally)
    - Horizontal sledge section
- Separate drive systems for vertical and horizontal movements

Utilization of the same propulsion components for hoistway change and hoisting simplifies the mechanical construction, and control of the car. Moreover, the mechanical safety is improved because the car never disconnects from the track. Closed track loops and turning track sections require an axially free motor mounting on the car. Both solutions are feasible but challenging the regarding motor size. Usually, linear motors obtain a cost-benefit from being narrow, which results in the relatively long moving element. Therefore, track curves cannot be designed too steep. For the same reason, the required size of a turning table may cause difficulties.

Rotating track sections that also rotate the car are impractical. A passenger most likely senses the rotating motion of the car uncomfortable. Thus, the car may have to remain empty during the hoistway change. Apart from being unsuitable for people transportation, a rotating track section also complicates hoistway structures and impedes door installations. However, the same principle can be implemented in a horizontally moving sled section that does not alter the orientation of the car.

Similar to Type Ro-Ci, also in Type Sp-Ci elevator both horizontal and vertical movement can have dedicated drives. The operation of horizontal drive can be relatively rugged, but it also has to be precise enough to pair elements of the main drive back in position. This type of concept may be unrealistic because construction of a safety device that prevents the car to be dropped is difficult.

To guarantee the continuous operation of the elevator, it is crucial that a local malfunction does not paralyze the entire system. The multi-car elevator system underlines the effect of the system malfunctions because one elevator is responsible for a larger portion of the building's transportation than a single-car elevator. Therefore, the multi-car elevator should be capable to minimize the effect of a faulty elevator car or a section of a hoistway. For example, Type Sp-Ci elevator could park a faulty car on the horizontal segment and operate like two single-car elevators, or even similarly to two double car elevators.

Type Sp-Mu devices are the final evolutionary step of self-propelled elevators. They can be built with the same basic technical principles as Type Sp-Ci elevators. However, the main difference is the possibility to drive longer horizontal trips and this way enable the possibility to more than two hoistway sections.

Type Ro-Mu and Sp-Mu elevators require a space of more than two hoistways to operate properly. The additional space over a circular elevator may be required for horizontal hoistways, storage spaces, or off-track landings. However, some parts of the system can contain only one hoistway that is utilized for two-way traffic. This type of section may locate for example in top floors of the building.

The round-trip time is the key parameter in an elevator system's design. It is the average time for a single car trip around the building from opening of doors until the reopening of the doors at the same location (Sakita 2010). In multi-car elevator system, a round-trip can be relatively time consuming, but travel times may still stay at acceptable level because of the overall car capacity. Especially in Type Ro-Ci, Sp-Ci, and Sp-Mu elevators the interval of the car is expected to be very short, thus the response time to passenger's service request stays short.

An interesting question regarding Type Sp-Ci and Type Sp-Mu elevators is: should the car move in the depth or width direction in relation to the access openings? This decision defines how the linear hoisting device and guides should be oriented between the elevator car and the hoistway.

Case 1. Cars moving in the depth direction (Figure 47)

a. Motors can be installed on both sides of the car.
b. Practical number of hoistways is limited by the fact that only one or two hoistways have access to doors.

c. Not all the hoistways can have doors if they locate wall against the wall. Thus, a passenger travels more likely inside the car during horizontal movement, although, the system can have access openings on two opposite sides.

Case 2. Cars moving in the width direction (Figure 48)

a. The most logical placement for a motor would be the so called backpack on the rear wall. Some inventions suggest the side installation, but this causes additional challenges in the corners of the pathway.
b. A number of hoistways or doors is not limited.
c. Easier to build a system that avoids horizontal passenger transportation.

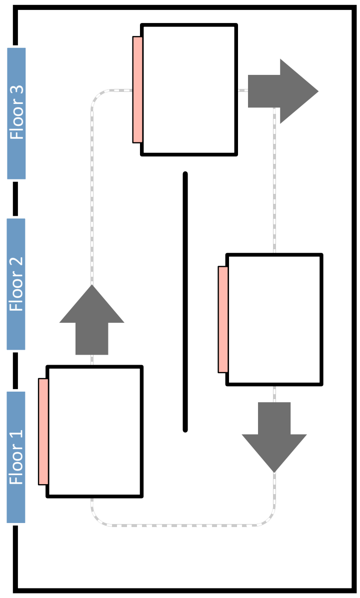


Figure 47 Case 1: Cars circulating in depth, side view

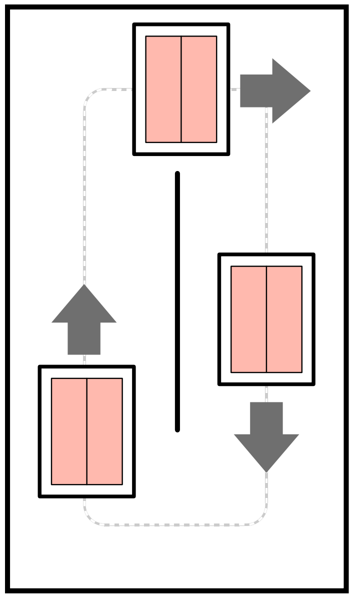


Figure 48 Case 2: Cars circulating in width, front view

Case 1 can also be constructed in the way that passenger never travels horizontally. To accomplish this, each elevator can has doors on two sides, which separates up going and down going passengers to different sides of the elevators. Alternatively, an empty lobby area can be left between hoistways, so that same car door can be used at landings in every hoistway. However, in this case, the downward traffic from the uppermost floor is not possible.

Even though the motor and guidance arrangements of Type Sp-Ci and Type Sp-Mu differ greatly from conventional elevators, only a few patent publications illustrate this mechanical aspect. The guidance of the self-propelled car is not all about the mass of the car and the passengers. Linear motors run along the walls of the hoistway, and therefore the uneven lifting configurations are more likely than in roped elevators. For example, the backpack solution illustrated in the press material of MULTI elevator causes significant torsional forces to the car. Additionally, a linear motor also generates enormous attractive forces between the rotor and the stator that need to be overcome.

In Case 1, the guide rail arrangement remains similar to conventional single-car elevators. A car can be supported equally from both sides. The linear motors can similarly be installed on the sides of the car, adjacent to the guide rails. However, the placement of the guides on the both sides of the car is not as obvious solution in Case 2, even though it is feasible. Alternatively, the motor and guides can be arranged to one sidewall or rear wall of the car. The choice is linked with the method to move the car between hoistways.

6 Discussion

This chapter discusses the hoisting system development, the development paths of the multi-car elevators, and the statistics of the patents processed in the literature study.

6.1 Hoisting

The vast majority of the source material of this thesis relates to traction sheave elevators, as shown in Figure 49. The quantitative difference between included hoisting types is understandable because still today, the traction machines remain far more familiar than linear motors. Thus, the number of material does not correlate well with the feasibility of the concepts.

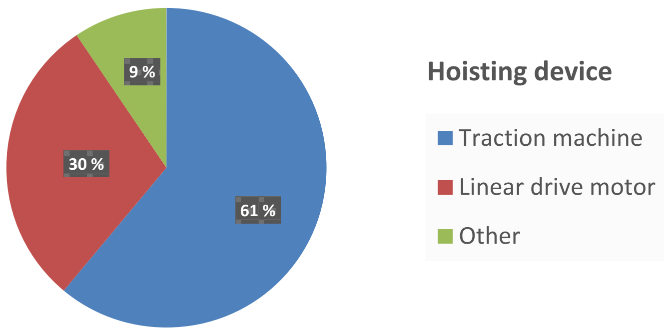


Figure 49 Crude estimate of how the source material divides between hoisting systems. The graph ignores the material that does not take a stand on the hoisting system, and therefore cannot be categorized unambiguously.

The choice of a hoisting principle is a mandatory decision at the beginning of any multi-car development project. Hoisting forms the basis for the elevator and determines the possible development paths. Some basic comparison between the three most common hoisting devices is gathered in Table 2.

Table 2 Comparison of common hoisting principles

	Rope drive	Belt drive	Linear drive
Material Cost	Low	Low	High
Control	Conventional	Conventional	Experimental
Operating height	Low – Medium	Low – High	Limitless
Counterweight	Common	Common	Impractical
Power requirement	Low with counterweight	Low with counterweight	High
Feasability with existing technology	Common technology	Existing technology, but less used than ropes	Experimental
Maintenance	Ropes require lubrication	Relatively maintenance free, bearings need lubrication	No mechanical wear, only bearings need lubrication

Rope and belt drives embody the conventional single-car elevator machinery. In technical standpoint, they enable the possibility to construct a multi-car elevator that easily matches with current elevators in energy efficiency and ride comfort. However, due to this similarity of the equipment, the indirect-drive systems make challenging to design a multi-car elevator assembly that matches the current solutions also in economic terms.

Finding a rational multi-car development path is difficult because all the limitations that indirect-drive adds to the design. Moreover, a risk exists that a multi-car elevator as a complete unit does not necessarily surpass even the single-car solutions built with same resources, as mentioned in Section 4.1.1.1.

Linear motor hoisting devices would be the most natural source of propulsion for a multi-car elevator. Since linear motors consist of only few moving parts, they could offer a high reliability. Furthermore, the linear motors offer freedom to design multi-car elevators that are impossible to build with conventional hoisting principles. The design freedom needs to be turned as an advantage because, due the lack of counterweight and increased mass of the car, linear drives lack in power efficiency to roped solutions.

One of the problems of self-propelled elevators is how the power is translated into the car. The increased spread of electric vehicles will most likely lower the prices of high-capacity battery packs that could also be suitable for elevator installations. Thus, the evolution of the batteries may in near future open new possibilities to development of the self-propelled multi-car elevators.

6.2 Trends in multi-car development

The following graph, in Figure 50, illustrates the amount of source material regarding the conceptual and technical aspects of the multi-car elevators that is presented in the patents in recent decades. The data, on which the chart is based, consists of 170 relevant patent families collected for this thesis. For comparison purposes, the graph in Figure 51 illustrates all the patent families published by seven major companies in the elevator industry in this decade. The data contains both elevators and escalators.

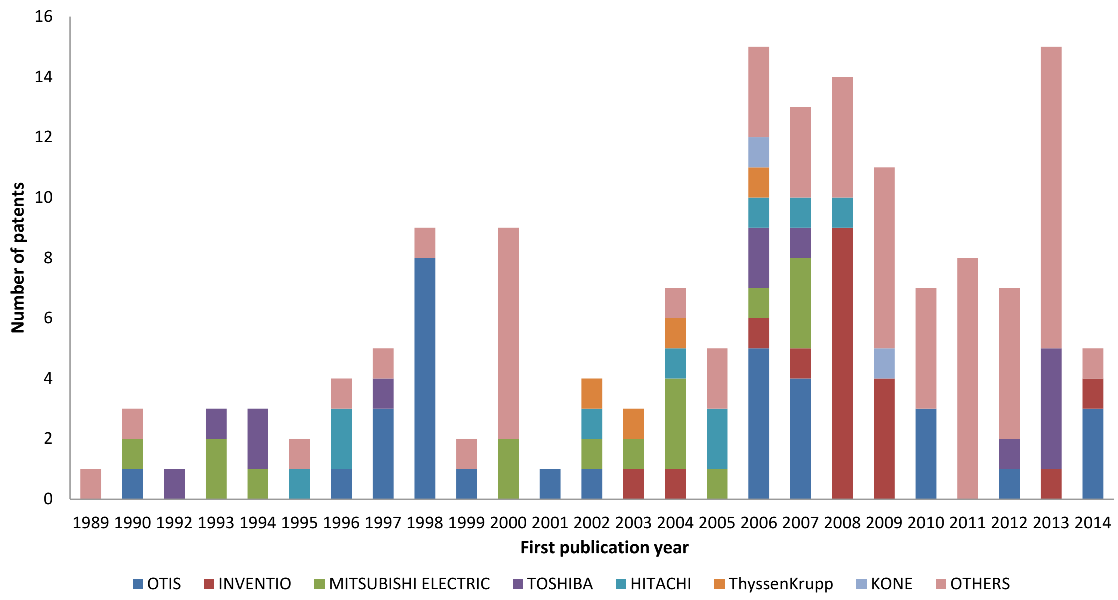


Figure 50 Number of reviewed patents related to a conceptual and technical aspect of the multi-car elevator. The material is sorted by the first publication year.

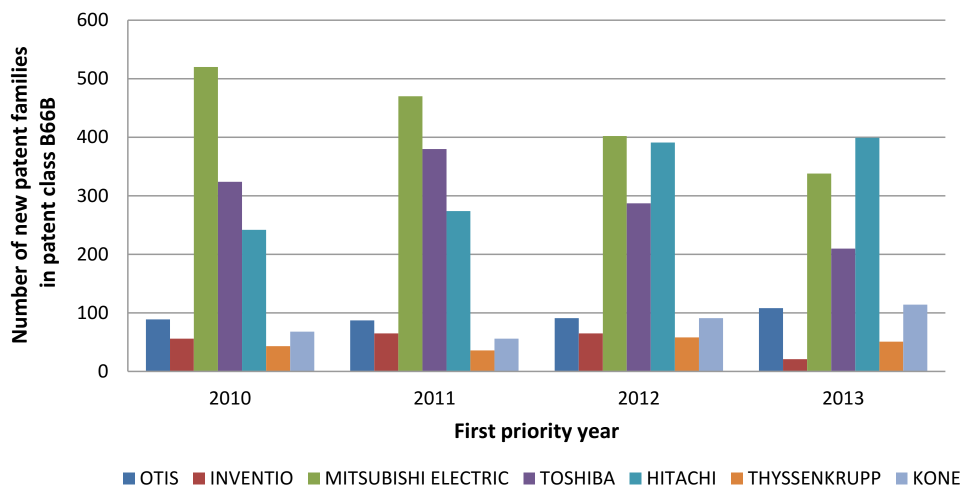


Figure 51 Patent activity in the elevator industry [Questel FamPat-database, retrieved 12.8.2015]

A few clear peaks and trends can be seen in the patenting activity in the charts in Figure 50 and Figure 51. At least in this material, the named companies have applied a patent only for a few multi-car elevator inventions in recent years. The largest peak places to time when ThyssenKrupp's TWIN was released about ten years ago. Moreover, it can be noted that the same companies, that are generally active to apply for patents (Figure 51), also actively protect inventions related to multi-car elevators (Figure 50). However, Otis has significantly more multi-car elevator patents than could be expected from company's general patenting activity.

The studied patent material relies heavily on the business world. In almost 72% of the cases, the applicant was a company. Moreover, in 25% of the cases the applicant was a private individual. A university applied only five of 170 patents. The distribution between commercial and academic applicants is surprisingly steep, particularly because the linear hoisting devices are quite researched in academic literature (Wang et al. 2012). On the other hand, the most of the research focuses solely on the drive technology. Thus, the practical implementations lack the academic interest.

In the late 1990s, Otis patented several technologies related to their Odyssey system (Section 4.1.3.1). The company has also been industrious in recent years, but there is no indication of a particular product that would relate to these publications. Recently the company has protected several linear motor concepts related to multi-car elevators.

Inventio AG, a company of the Schindler Group, has protected various multi-car elevator technologies in the 2000s. Most of these patents relate to their development of the roped single hoistway elevator, similar to ThyssenKrupp's TWIN. They also have some patents of the elevators with a circular hoistway. In the early 2000s, Mitsubishi Electric patented multi-car elevator concepts, and multi-car safety devices, actively. The patents are also mostly related to variations of the "TWIN-type" traction elevators.

Hitachi has protected various multi-car elevator inventions during the 2000s, all related to the development of their circular elevator system. As mentioned in Section 4.1.2.1, these concepts utilize both linear drives and roped traction machines. Toshiba has also been interested in how the cars could be moved horizontally.

It should be noted that the number of patent publications correlates poorly with feasibility and commercial potential of the technology. The major factor causing the poor correlation is the fact, that the mechanical aspect of the elevator technology is already well established. Furthermore, companies do not always see patenting as the convenient protection of intellectual property. For example, only a few patents regarding the ThyssenKrupp's TWIN system exists, even though it is the only remarkable multi-car elevator product on the market currently. Similarly, the potential patents regarding ThyssenKrupp's upcoming MULTI system either does not exist or are not public at the moment.

Figure 52 presents the number of the reviewed patents with the categorization that is commonly used in this thesis. It is worth to mention; that the source material also includes patents that do not take a stand on the layout of the system. The chart in Figure 52 leaves these unsuitable cases out of account.

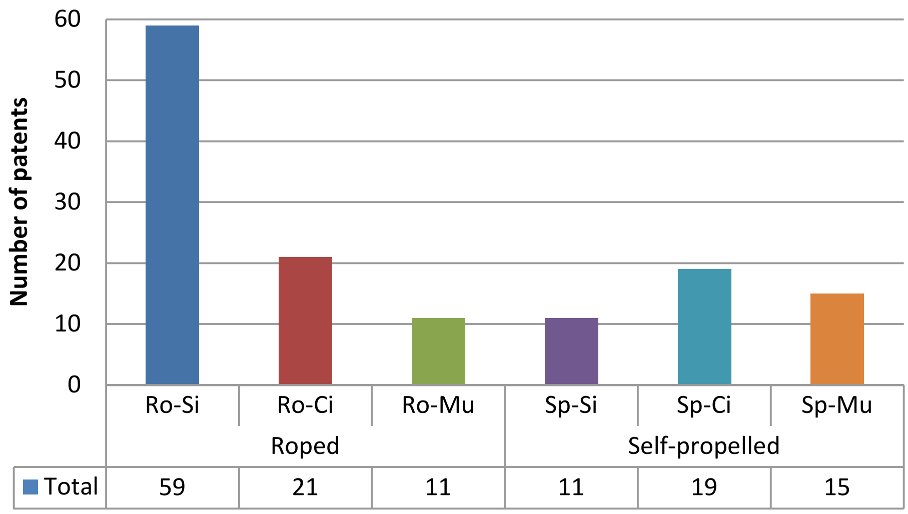


Figure 52 Diversity of the reviewed patent publications. The graph represents the same grouping as Chapters 4 (see Appendix 1).

Roped single hoistway devices are clearly the most notable group of patents. Most of these inventions are similar to ThyssenKrupp’s TWIN. Moreover, both roped and self-propelled circular elevators are quite popular in the patent publications. Otis’ Odyssey project dominates the Type Ro-Mu elevator patents, but a group of Type Sp-Mu elevators does not have obvious trends.

Self-propelled elevators that consist of only one hoistway (Type Sp-Si) form a surprisingly small group. The horizontal movement, which is not featured in the single hoistway elevators, may be considered a mandatory feature to justify the high cost of the linear motor in a self-propelled elevator. However, the self-propelled elevators would form much larger groups if the material would also include the patents of linear motors.

6.3 Development paths

Several noticeable development paths are present in multi-car elevator technology. Old paternoster devices offered a decent passenger handling capacity but lacked in safety because the paternoster car is in constant motion. If the cars could stop at floors, this safety issue would not exist. Therefore, several circulating elevators with stopping capability have been in development for years, but any commercially ready products have not been introduced. Figure 53 gathers relations of the most remarkable multi-car elevators in history to chronological order. The concepts marked with dashed borderlines have not led to any commercial installations.

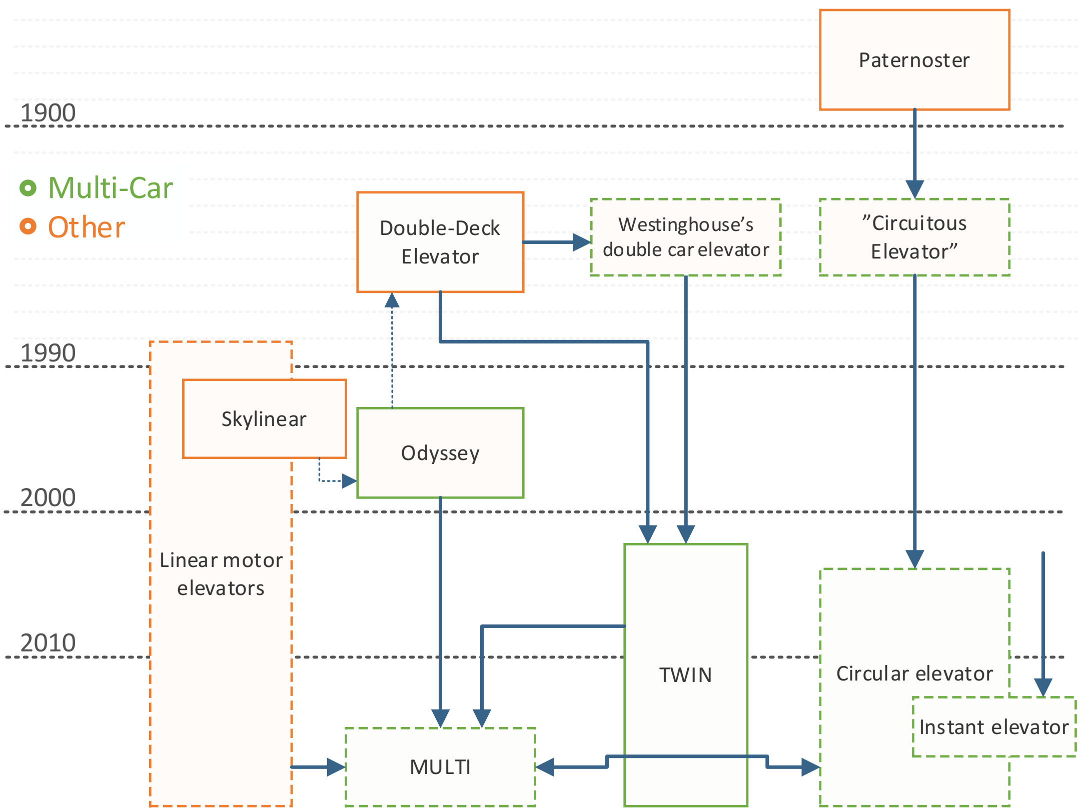


Figure 53 Development paths of multi-car elevator development

In 1934, Henry D. James received patent for a *Circuitous Elevator.* James' goal was same as current developers of the multi-car elevators have: to maximize the utilization rate of the reserved space. Unlike the paternoster, the James' concept parks cars as conventional elevators allowing passenger's safe entrance and leaving. He also equipped cars and hoistway with standard safety devices of the time. Despite the detailed patent, the concept did not lead to installations. (James 1934; Gray 2005)

Currently, Hitachi is the main pioneer of circulating elevator technology. Their prototypes have indicated promising, and not so distant, future of the circular multi-car elevators. However, something has held the products away from the market. Maybe the company has estimated that the real-life benefits of their prototype system are not significant enough to compensate the risks.

The next logical step from circulating elevators would be to allow individual cars to travel truly independently and include additional paths so the car could take shortcuts if required. A closed rope loop does not offer this adaptivity. Thus, unlike the Hitachi's concept, a multi-path elevator would require drives for both horizontal and vertical movement. In patents, some roped circulating elevator designs rely on solutions that handle cars as detachable objects. In this case, each car does not require dedicated hoisting equipment. Alternatively, a self-propelled construction could be used.

On the other hand, the added complexity is not always necessary to further develop the elevator concept. An extremely simplified circular elevator could also be a valid solution for shuttle installations, and a great successor of the paternoster.

The second clear development path was already described in Section 4.1.1.1. The dual-car elevators are advanced versions of the double-deck elevators. Westinghouse promoted their dual-car elevator in the 1930s, but most likely, the safety was too great a challenge at the time. Ultimately, it took almost 70 years until the TWIN elevator was released, thanks to new type of electronic safety devices and PESSRAL.

The development of the self-propelled elevator appeared promising at the turn of the 1980s and 1990s. At the time, major players, Otis and Mitsubishi in front, promoted elevators that would remove the need for a dedicated machine room. Even though not all the projects aimed at a multi-car elevator at the time, a commercialized linear hoisting machine would have been a real step towards the multi-car elevators. In 1995, the KONE MonoSpace elevators eliminated the machine rooms with quite conventional elevator hardware in low-rise installations (de Jong & Hakala 2000), which may have had an effect on linear motor development.

Otis drew public interest in the mid-1990s. The media hype surrounded the upcoming Odyssey system, which was promised to be the first multi-path elevator. The new system utilized linear motors to move elevator cars horizontally, but ropes were still used for the vertical movement. The choice to abandon linear hoisting was most likely done for the sake of feasibility because the operational control of three-dimensional transfer alone was inevitably challenging. Moreover, there were difficulties regarding the safety features, and with a ropeless hoisting device, the concern of safety would have been even greater.

The conventional hoisting solutions that tried to simplify the Odyssey project decreased the attractiveness of the concept. A large proportion of the multi-car elevator’s potential is ignored if the hoistway can handle only one car at the time. However, Otis specified the possibility to equip the elevator with a previously developed TLIM in the later iterations of the system.

Over a decade later, ThyssenKrupp began to promote a multi-path elevator driven solely by the linear motors. The company’s MULTI concept seems a natural evolution of multi-path elevators. Because the elevator includes a linear hoisting device, it is capable of operating multiple cars simultaneously in the hoistway. However, the new technology will take time. It takes years before the company can prove MULTI elevator safe as the old systems.

7 Conclusions and recommendations

The aim of this thesis has been to search for technical solutions to build a multi-car elevator, and especially to distinguish concepts and development paths of multi-car elevators. In order to find the most interesting multi-car elevator concepts, hundreds of patents were viewed for the literature study.

The multi-car elevator development has had some obvious trends during the past decades. In the 1990s, a small boom occurred in the development of self-propelled elevators. However, no commercially important products became public at the time. The elevator industry is conservative, and the elevator companies follow each other closely. For a long time, development has focused on conventional roped hoisting solutions. However, recently ThyssenKrupp possibly changed the focus of interest when they announced the upcoming MULTI elevator.

ThyssenKrupp was the first to enter the market of commercial multi-car elevators in 2003, and since then over a hundred TWIN installations have been made. The commercial success of TWIN has admittedly been sluggish and maybe, therefore, the competitors have not published similar elevators. The competitors' lack of interest may also indicate that TWIN-elevators are not seen as the multi-car elevators of the future. On the other hand, ThyssenKrupp has now over a decade's worth of field experience of the multi-car control and safety systems. If nothing more, TWIN has been an educational step before transition to more sophisticated systems.

In the past, steps to the wrong direction have been taken. The Otis' Odyssey failed because it could not offer enough lifting capacity to justify overall complexity of the system. In contrast, Hitachi's circulating roped prototypes seem feasible, but the company has not hurried to release the product. Maybe the conventional mechanical design, that makes the elevator appear ready, has led to problems in fulfilling the expectations. No doubt, the operational control of the previously described car-pair design must be challenging.

Horizontal transition of an elevator car can be considered as almost necessary feature of a multi-car elevator because it diversifies car management. However, no definite answer exists how it should be implemented. The system transferring passengers along horizontal routes could provide versatile transportations through the building, but complex mechanical solutions would be required to ensure comfort and safety. Alternatively, the car could remain empty while a substantial horizontal movement is needed. In that case, there is no worry about drive comfort or acceleration rate of the car, but emptying the car requires time and restricts the layout of the elevator system.

Either way, it seems that the current state of the available drive technologies sets the most significant restrictions for the multi-car elevator development, since the traditional technologies to move an elevator car do not easily match with developers' visions. A linear motor performs well in a wide range of rise and reduces moving equipment in the elevator construction. On the contrary, a linear motor would turn the electronic systems of the elevator more complicated. The self-propelled multi-car elevators also come with a new safety concern because they include new possibilities for free falling and collisions.

It is unlikely that a straight single hoistway elevator powered by a linear hoisting device could compete with the current roped devices. At least with current technology, the differences in material cost and efficiency are too significant. Instead, even a simple circulating elevator could provide something that the current solutions do not offer; a continuous chain of cars. Especially self-propelled circulating multi-car elevators (Type Sp-Ci) seem promising because they offer great scalability for future projects. After we have an operational Type Sp-Ci elevator, it should not be a major mechanical design problem to further develop it to Type Sp-Mu elevator. The largest challenges of this evolution exist on the control side.

A low-rise multi-car elevator could be developed to gather market feedback and test equipment. Later on, similar components could be utilized for complex high capacity elevator systems (Type Sp-Mu). This would be a natural path to start in a multi-car elevator business. Changes in the scale affect to the cost-capacity ratio of the elevator, but in Type Sp-Ci elevators, the change may not be as dramatic as in other multi-cars. Similar Type Ro-Ci elevators can also be built with hoisting ropes, but roped elevators do not offer equivalent developmental potential.

For example, KONE's "Instant elevator" concept (discussed on page 43) could serve as a stepping-stone to larger multi-car elevators. With linear hoisting, the elevator would most likely to be too expensive to compete with escalators in general, and in some cases the elevator would only pay-back in improved passenger satisfaction. However, the escalators demand expensive building structures, and the overall space requirement of them is greater than Instant elevator's. Because of these and other factors, the overall cost of the concept could be competitive, for example, in shopping malls. Thus, this two-floor shuttle elevator could offer a straightforward platform to improve the mechanical, electrical, and software systems of the multi-car elevator.

Regardless of the concept, the evolution of the elevator technology will inevitably lead to the multi-car elevators. The demand for such a device is too high to be put aside.

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Appendices

Appendix 1. Multi-car categories. 1 page.
Appendix 2. Comparison table. 1 page.

Appendix 1. Multi-car categories

Type Ro-Si — A multi-car elevator that consists mainly of a single elevator hoistway. A rope or similar machine element suspends and moves the elevator car.

Type Ro-Ci — A multi-car elevator with a circular elevator hoistway structure. The hoistways are dedicated to either ascending or descending traffic. A rope or similar machine element suspends and moves the elevator car.

Type Ro-Mu — A multi-car elevator that consists of a complex hoistway structure. The elevator is capable to provide horizontal transportation. A rope or similar machine element suspends and moves the elevator car.

Type Sp-Si — A multi-car elevator that consists of a single elevator hoistway. The self-propelled elevator cars are able to move independently.

Type Sp-Ci — A multi-car elevator with a circular elevator hoistway structure. The hoistways are dedicated to either ascending or descending traffic. The self-propelled elevator cars are able to move independently.

Type Sp-Mu — A multi-car elevator that consists of a complex hoistway structure. The self-propelled elevator cars are able to move independently and capable to provide horizontal transportation.

	Type Ro-Si	Type Ro-Ci	Type Ro-Mu	Type Sp-Si	Type Sp-Ci	Type Sp-Mu
Hoisting	Roped					
				Self-propelled (ropeless)		
Hoistway shape	Single			Single		
		Circular			Circular	
			Multi			Multi

Appendix 2. Comparison table

		Roped			Self-propelled		
		Type Ro-Si	Type Ro-Ci	Type Ro-Mu	Type Sp-Si	Type Sp-Ci	Type Sp-Mu
	Material Cost	Moderate	Moderate	Fair	High	High	High
	Floor space requirement	1	2	2.5 or more	1 - 2	2	2.5 or more
Suitable use	Shuttle	Poor (loses effiency in high heights)	Good	Moderate	Moderate	Excellent	Excellent
	Local elevators	Poor for a multi-car, but can be zoned	Fair	Poor	Fair	Moderate	Excellent
Operating height	Low-rise	Yes	Yes	-	Yes	Yes	-
	Medium-rise	Yes	Yes	Yes	Yes	Yes	Yes
	High-rise	Ineffective	Ineffective	Yes	Yes	Yes	Yes
Handling Capacity	Vertical	Poor	Moderate	Poor	Poor	Moderate / Excellent	Excellent
	Horizontal	-	-	Moderate	-	-	Excellent
	Interval	Moderate	Short	Moderate	Moderate	Short	Short
	Round-trip time	Long	Short	Long	Long	Short	Long
Energy efficiency	Energy Consumption	Moderate	Moderate	High / Moderate	High*	High*	High*
	Possiblity to include counterweight	Counterweight or car masses cancel each other out	Counterweight or car masses cancel each other out	Counterweight	No	No	No
	Control of traffic	Simple	Difficult	Difficult	Simple / Difficult	Moderate	Difficult
	Maturity of the technology	Exists	Feasible with existing components	Feasible, but mechanically	Prototype stage, inefficient solutions	Feasible, but not cost efficient	Feasible, but not cost efficient

Reference values are general estimates to differentiate the multi-car categories

* According to current knowledge, the elevators without the counterweight consume more energy than the elevators with the counterweight. Value does not take a stand on the overall energy consumption of the building.