Title: **A Next Generation Vertical Transportation System**

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A Next Generation Vertical Transportation System

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The world's first rope-free passenger elevator system for high-rise applications enables the building industry to face the challenges of global urbanization. MULTI represents the realization of a new elevator system offering several cabins in the same shaft, moving vertically and horizontally, permitting buildings to adopt different heights, shapes, and purposes. It represents a landmark revolution in the elevator industry and a new and efficient transport solution for mid- and high-rise buildings. Now, the long-pursued dream of operating multiple cabins in the same elevator shaft is made possible by applying the linear motor technology of the magnetic levitation train, Transrapid, to the elevator industry. A traffic control concept for a shaft-changing multi-cabin elevator system is now included in vertical transportation planning.

The propulsion and guiding system of multiple, low-weight elevator cabins overcomes traditional rope elevators. Also, functional safety goes beyond current solutions.

The era of the rope-dependent elevator is now 160 years old. The basic principle of a traction elevator, having one car and a counterweight in one hoistway, causes very high volume consumption in tall buildings. Floor space is the most valuable resource for building developers, who want to build taller, using less space for elevators. Therefore, elevator engineers are working on innovative methods to minimize the percentage of floor space necessary to lift people in buildings. The idea of a circulating elevator system was published more than 100 years ago (Condon, 1903).

In 1889, the Eiffel Tower in Paris opened with double deck lifts, becoming one of the oldest and most well-known buildings with an elevator system using two cars in one hoistway (Vogel, 1889). This was a great improvement, but at the same time, flexibility in the system is reduced, as the cars are in a fixed arrangement and loading and unloading happens on two floors, making it difficult to synchronize; the car ready for take-off has to wait for its partner to finish loading and unloading.

Even triple-deck lifts have been considered to take the next step towards better efficiency in the vertical transportation systems of tall buildings. This would be a very big step, as the sheer masses that must be moved in such systems increases tremendously.

Therefore, the next step aims to get back flexibility while reducing masses in the system. Over ten years ago, two independent elevator cars travelling in the same hoistway marked the next revolution in vertical transportation (Thumm, 2004). The TWIN was born and increased handling capacity without limiting itself to certain floor distances, travel sequences, and variation of traffic demands. At the same time, the machine sizes and peak power loads could be reduced compared to conventional systems (Müller, 2014, Bass, 2014).

The Paternoster invented by Mr. Hart in 1882, and first installed in England in 1884 (Elevator World, 2015), has been considered the most effective vertical transportation system, but very limited in height, speed, and safety. However the general idea is still considered as the prototype for the ideal system.

Still the old dream remained, to have a flexible number of several elevator cars in multiple elevator shafts using a circulating system, based on the already existing Paternoster (Elevator World, 1996). Traffic concepts and analyses based on these ideas were done and published (Jappsen, 2002). But there were still open technical and economic questions at that time. Answers to the open questions needed to be found in order to realize a successful circulating elevator system.

Circulating Rope-Less Multicar Elevators

In 2014, a rope-less elevator system called MULTI was unveiled (ThyssenKrupp Elevator AG, 2014), where multiple elevator cars use the same shafts and are able to change vertical shafts horizontally. The system has multiple, independent elevator cars circulating safely in multiple shafts (loops), propelled by linear motors.

Propulsion System

Already, back in the 1990s, a linear motor was designed by Dr. Jessenberger (Thyssen Aufzugswerke GmbH, 1998) and tested to lift a rope-less elevator car. The prototype is still running at the University of Aachen. Since then, the drive was considered to be feasible and today, the concept of a long stator synchronous linear drive will be used for MULTI.

The MULTI shafts are equipped with coil units and multiple frequency inverters, and the magnet yokes are mounted on the cars. Only coil units that are directly involved in moving a specific car are active, and multiple redundancies in the propulsion system ensure high reliability. To build an economical propulsion system, it is important to limit the weight of cabins.

Lightweight Cabin

Having the linear motor as a working propulsion system was not a breakthrough at the time, as the researchers found some other missing links in the technology. A conventional car design, using steel as the primary material, would be far too heavy to use with an economical linear motor propulsion system. New and optimized design and manufacturing technologies, together with the use of new materials like carbon composites, allowed for the achievement of the car weight target. The car was developed using topology optimization.

Beyond the optimized mechanical design of the car, all devices on the car necessary for the elevator controller, electrical power, safety, guiding, and the interior of the cabin are optimized in weight. Each cabin is capable of carrying eight passengers.

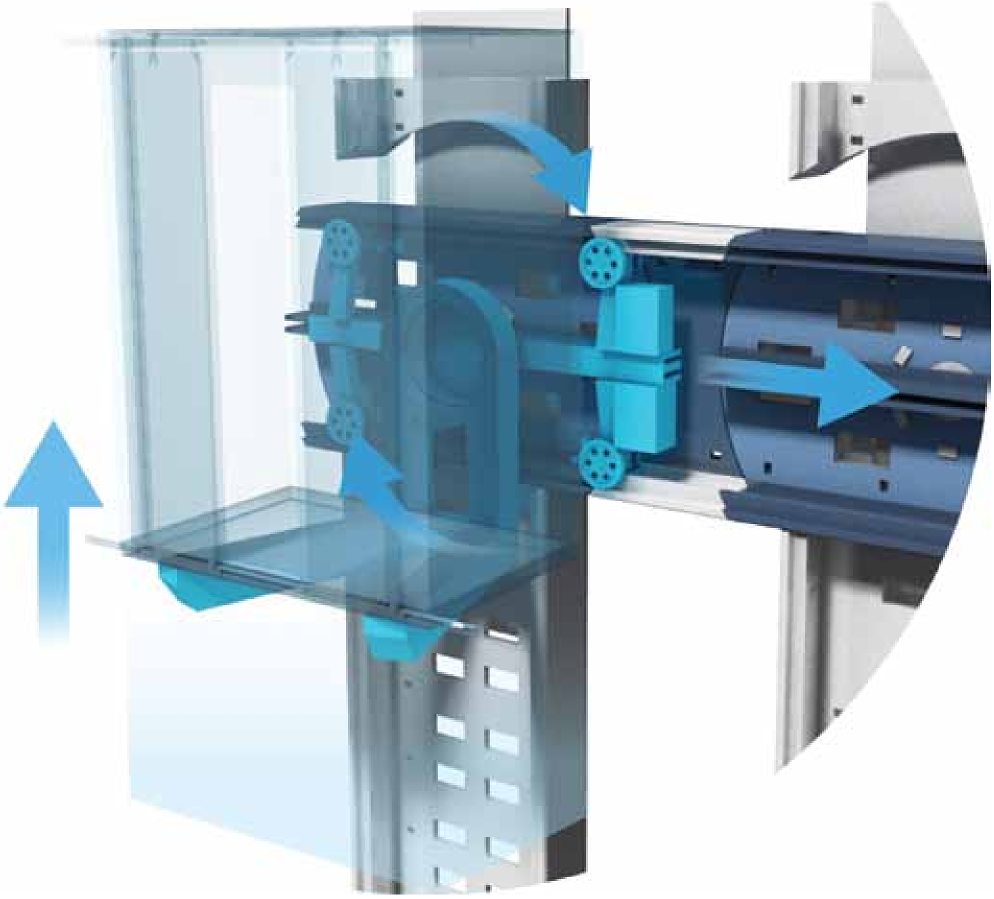
Guiding of Elevator Cars and Exchangers

How can cars be guided in the shaft, including the horizontal movement between the shafts? A backpack solution with guidance and an integrated linear motor was the favored design out of dozens of concepts. This also enables an optimized design for an exchanger unit. Shaft elements rotating 90° enable a horizontal movement using the same shaft elements. During the rotation process of the shaft elements, the cabin is held in the upright position. Passengers can load and unload the cabin during the rotation process. This guidance and exchanger concept enables an exchanger unit at every position in the shaft. It also enables an extended horizontal movement between more than two shafts and longer travel distances.

An animated, virtual 3D simulation model of a car moving and circulating in two shafts,

Opposite: A circulating rope-less elevator system called MULTI. Source: ThyssenKrupp

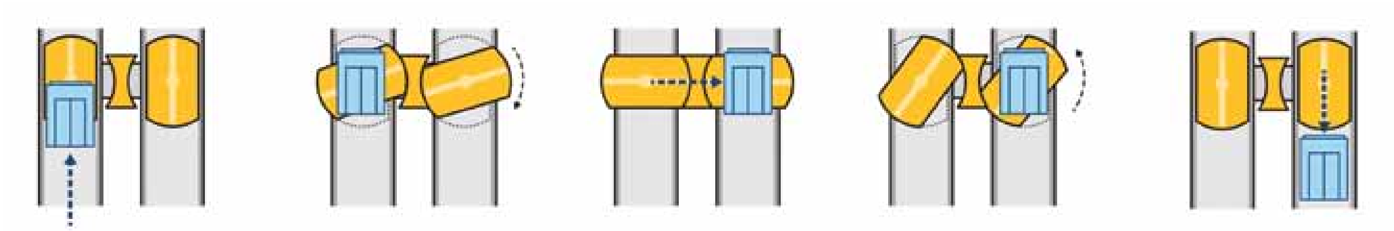
Left: Light weight car of a rope-less circulating multicar elevator system propelled by linear motors (MULTI). Source: ThyssenKrupp



Left: Cabin of a multicar system located at the exchanger unit. Source: ThyssenKrupp

Bottom: Exchange process of a multicar cabin. Source: ThyssenKrupp

Opposite: 3D model of MULTI at the High performance computing center Stuttgart (HLRS). Source: ThyssenKrupp



including shaft and exchanger design, gives an early impression of the real system.

Safety
One of the most important issues is the technology of functional safety. Anti-collision and shaft door monitoring is based on more than 10 years of experience with the TWIN safety solution. The safety concept of a circulating rope-less elevator system needs to go beyond known concepts. Multiple cars and exchanger units are monitored and mechanical safety devices like a new and special braking system are developed for a rope-less system. Also, the linear motor propulsions system is included in the safety concept to ensure additional safety during operations.

Energy
What about energy? With the latest technology of linear drives it is possible to come very close to the equivalent energy consumption we know from permanent magnet synchronous drives, used for conventional traction elevators.

The great advantage of the new system is the enormous reduction of peak currents by up to 60% as the moving masses can be reduced by a similar percentage. This allows for much better energy management in buildings to achieve a smart grid. The regenerated energy from all the cabins travelling downwards will not be fed back to the grid, but directly used internally by the system with fewer transition losses. Also, the number of cars in use within a loop can be adapted to the traffic demand.

Buildings, which are already in the planning phases, in the region of one mile in height and with the goal of generating more energy than they internally need using solar, wind, and geothermal energy, cannot be made efficiently accessible without elevator systems that omit elevator hoist ropes. Reducing the elevator footprint and number of elevator shafts generates potential energy savings by reducing the overall size and external surface area of the building.

Current Traffic Concept and Analysis

A classical approach in high-rise buildings to reduce the footprint of elevator equipment is to divide the building into different zones. Each zone is served by an elevator group dedicated to a specific zone. If not all elevators serve all floors in the building, core

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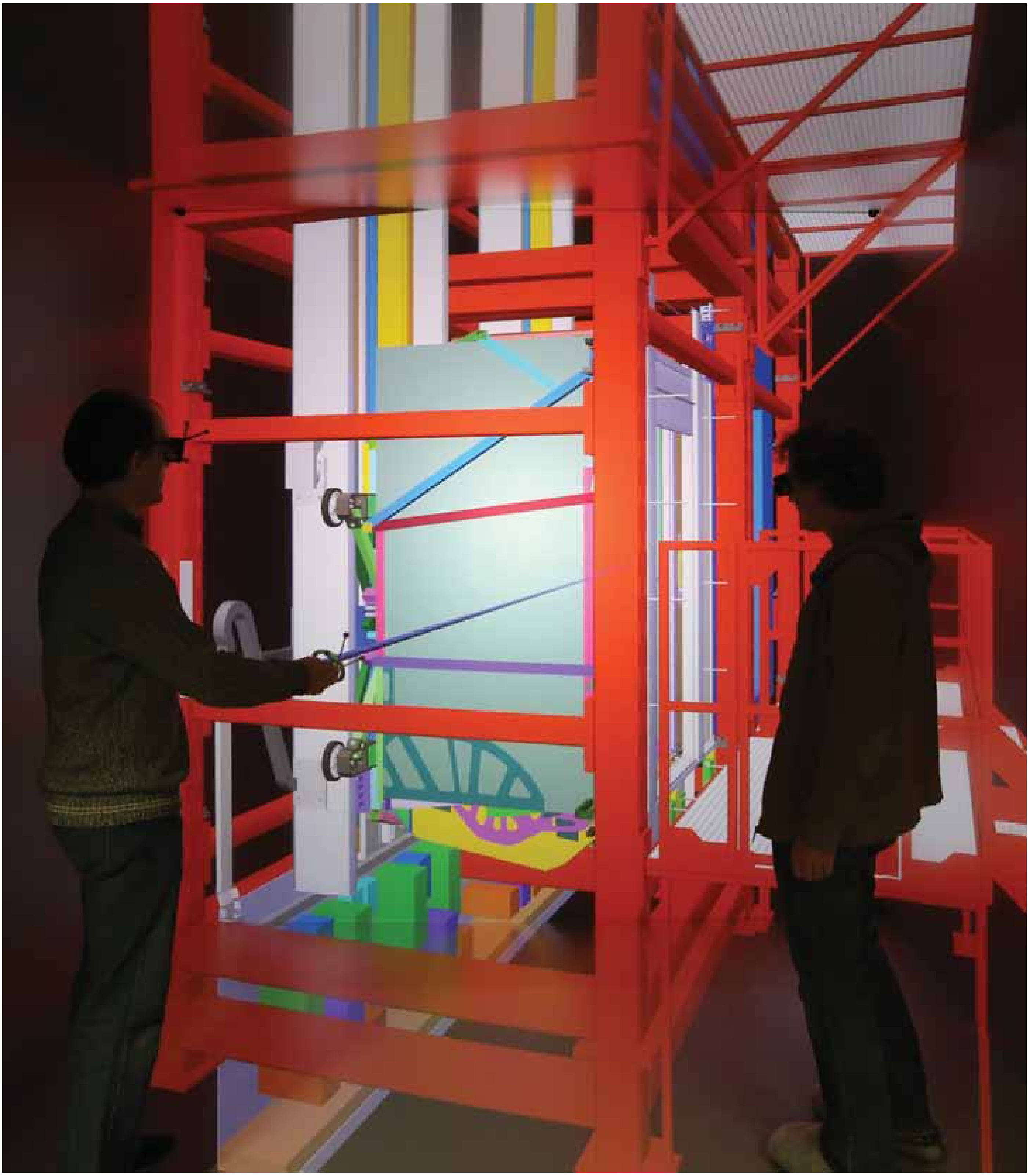
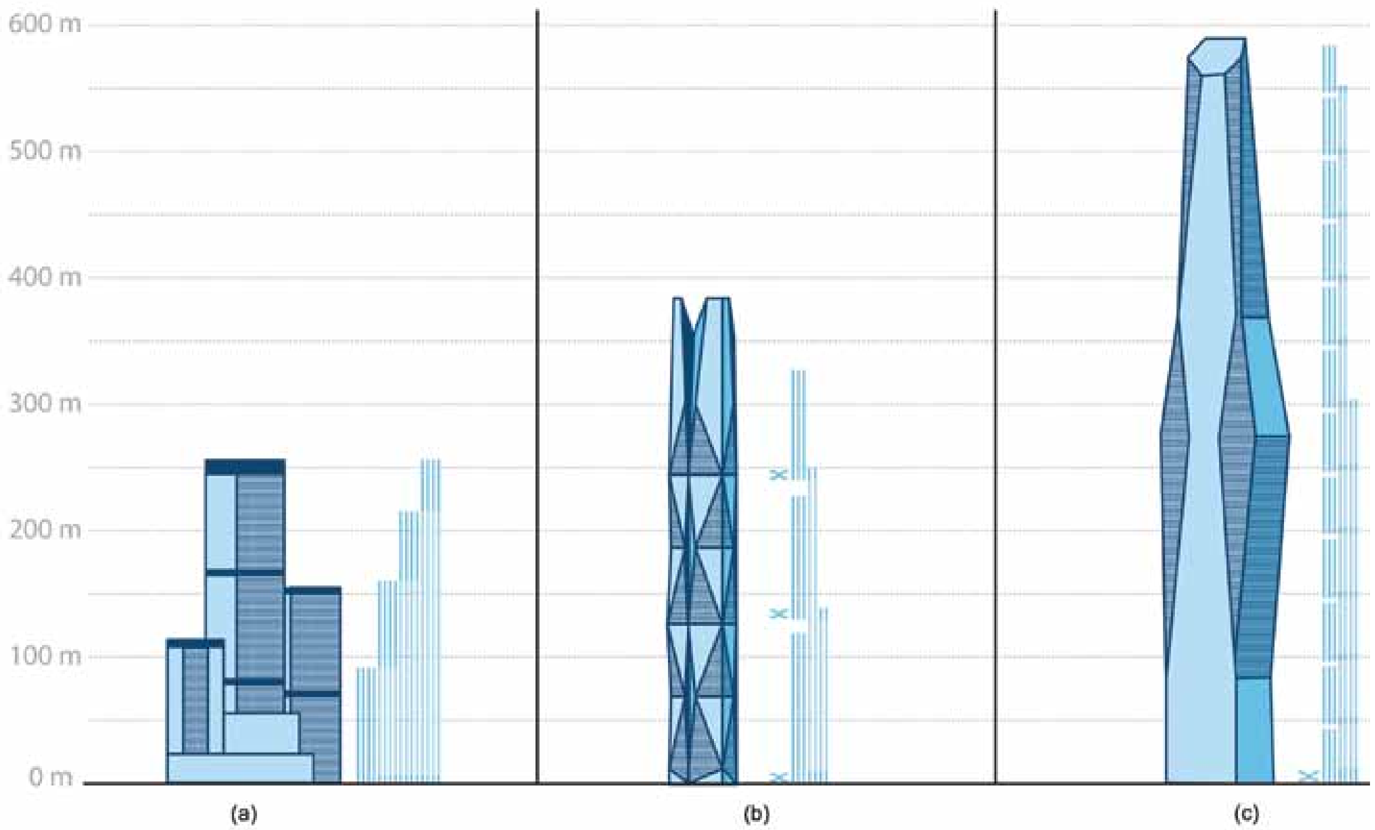


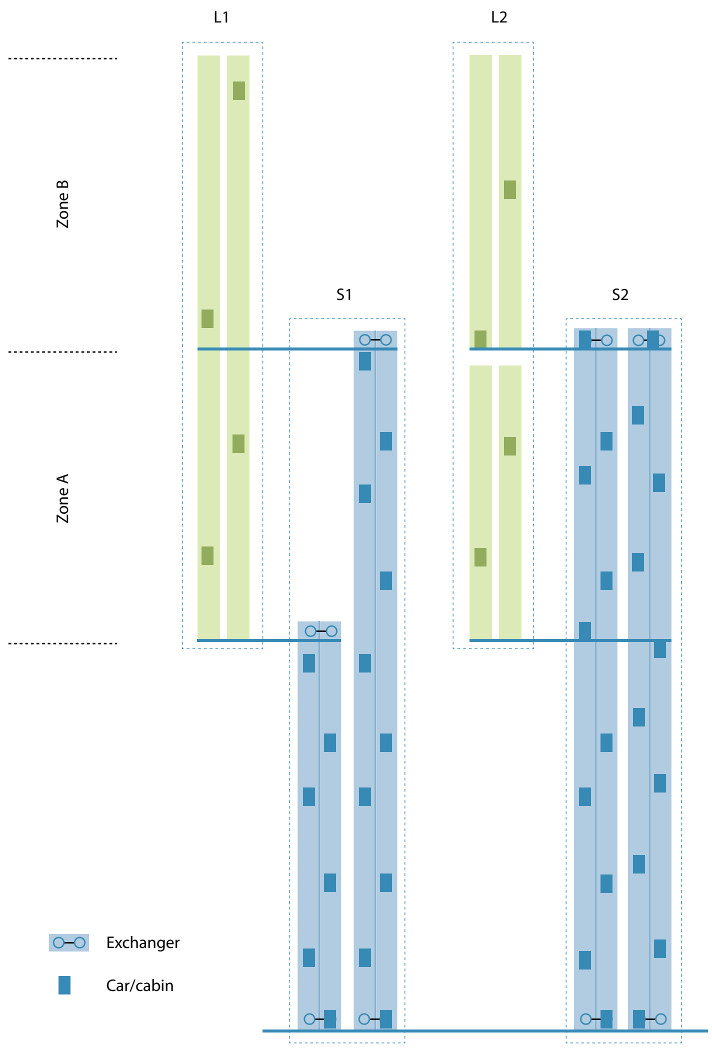
space can be reduced in the upper floors and low-rise elevators can be provided at lower velocities (Strakosch and Caporale, 2010). Dedicating elevator groups to zones reduces the number of probable stops. Based on the roundtrip time calculations, reducing the number of stops reduces the roundtrip time (CIBSE, 2010) which can reduce the total number of necessary elevators. Elevator groups for upper zones can have an express zone. Fast elevators are necessary to travel long distances and achieve necessary group handling capacities, waiting times, and times to destinations. Additionally, an installation with double entrance lobbies reduces the necessary footprints for elevators. Double-deck elevator cars and two independent cars in one shaft make it possible to get better shaft efficiency. The latter provides higher individual flexibility and can be seen as elevator groups of two zones, located within the same shaft. Regardless, there are limits in vertical transportation planning if no interzone transfer floors are used (Müller, 2014).

A state-of-the-art approach includes using sky lobbies as transfer floors in the vertical transportation plan. Local groups serving dedicated zones from a sky lobby are stacked, and express shuttle elevators serve the passenger demand between the ground lobbies and the sky lobbies. Vertical transportation concepts with interzone transfer floors can save elevator shaft space (Siikonen, 1997) and the shuttle arrangements can be realized with single- or with double-ground lobbies. The latter requires the use of two cabins in one shaft, mechanically coupled as double-decker or two independent cars. Also, escalators connecting between the ground lobbies may be necessary. Local groups can be single cabin shafts or multi-cabin shafts.

Next Generation Vertical Transportation Concepts

Shuttle and sky lobby arrangements using traditional single or double deck elevators do have limits and disadvantages in shaft efficiency. Still, only one or two cars or cabins use a long single elevator shaft. In particularly tall buildings, elevators are getting faster to keep the journey time to a minimum and to provide an adequate quantity and quality of service





Opposite: Comparison of different traffic concepts.
Source: ThyssenKrupp

Left: Options of simplified traffic concepts, including a circulating multicar system as a shuttle with a single ground lobby.
Source: ThyssenKrupp

with a minimum number of shuttle elevators. Limits in speed are related to human comfort regarding differential ear pressure. Limits in travel height are related to the maximum possible length of hoist cables. A circulating, rope-less multicar elevator system eliminates the limits and disadvantage of traditional shuttle elevators and also enables more flexible arrangements. Some simple examples demonstrate options and flexibility.

There are different options for simplified traffic concepts, including a circulating multicar system such as a shuttle with a single ground lobby. Different multicar loops can be assigned to different zones in the building (S1). A multicar loop can serve one or multiple sky lobbies, thus it can be assigned to multiple building zones (S2). Multiple multicar loops can be combined to a group serving the same zone(s)/sky lobbies in the building (S2).

Local elevator groups can be stacked as single car groups (L2) or groups of two independent cars in a single shaft having distributed lobbies for the lower and the upper cars (L1). This enables direct inter-zone traffic.

There are different options of simplified traffic concepts, including a circulation multicar system such as a shuttle with a double ground lobby. There are two options for a sky lobby arrangement: A double sky lobby (S3) and a pair of distributed sky lobbies (S4). In case of a double ground lobby arrangement, each ground lobby as well as the two highest sky lobbies will be equipped with an exchanger unit. This requires an exchanger unit somewhere in the middle of the shafts. Similar to a single ground lobby configuration, different multicar loops can be assigned to different and multiple zones in the building. That means a multicar loop can serve multiple, double sky lobbies or multiple pairs of distributed sky lobbies (S5), similar to solution (S2).

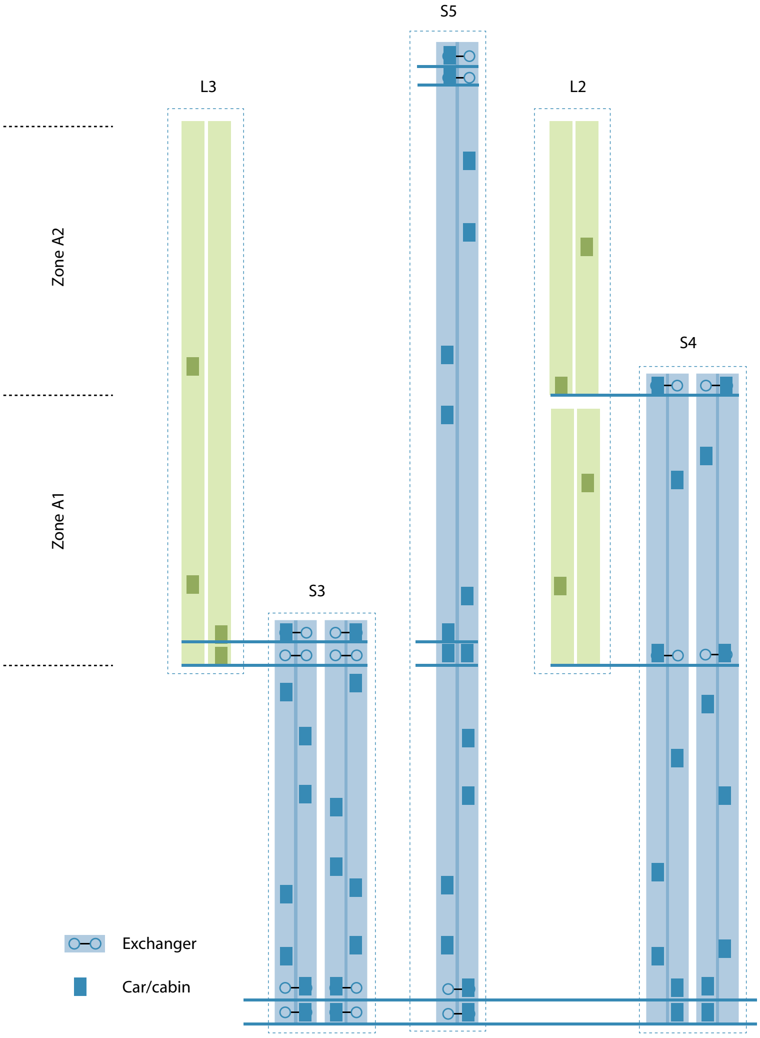
Local elevator group options for pairs of distributed sky lobbies are similar to the single ground lobby arrangement. Additional options for local groups are possible with a double sky lobby. Similar to local groups in double-decker shuttle concepts, a double-deck or two independent cars in one shaft can be used as a local group (L3).

Spatial plots of one pair of cabins shows how a pair of cabins move within the shafts. Travel in the upward direction is in a different shaft than the downward direction. Graph 1 shows the spatial plot of a circulating multicar with a pair of distributed sky lobbies like the arrangement in (S4). Graph 2 shows the spatial plot with two pairs of distributed sky lobbies similar to the arrangement in (S5), which has two double sky lobbies. A multicar loop can be assigned different zones with different pairs of distributed sky lobbies.

The arrangement of vertical transportation for vertical cities can be compared with horizontal transportation. The shuttle elevators are like little intercity trains connecting the main stations – the sky lobbies. The local elevator groups are like local transportation via bus or underground metro. The circulating inter-lobby elevator system enables flexible arrangements in vertical transportation concepts, is not limited to the shown examples and options, and is not limited in height.

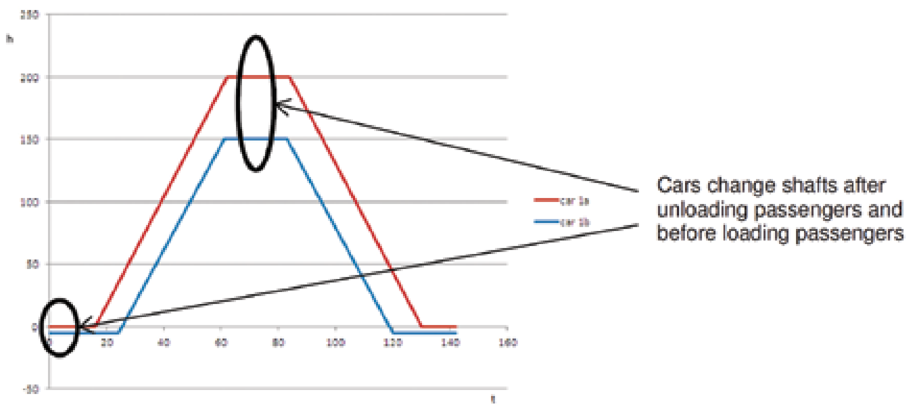
Traffic Analysis

The traffic analysis described here is based on the work submitted/presented at the lift

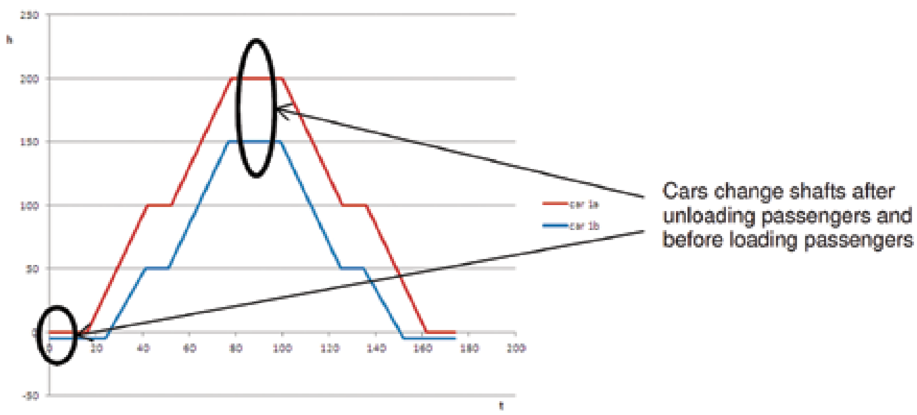


Left: Options of simplified traffic concepts including a circulation multicar system as a shuttle with a double ground lobby. Source: ThyssenKrupp

Opposite: Comparison of a group of circulating multicar systems with a double deck group. Source: ThyssenKrupp



Graph 1: Spatial plot of two cars with a pair of distributed sky lobbies. Source: ThyssenKrupp



Graph 2: Spatial plot of two cars with two pairs of distributed sky lobbies. Source: ThyssenKrupp

symposium Northampton (Gerstenmeyer and Peters, 2015).

The roundtrip time is based on velocity, number of stops, door times, highest reversal floor etc. and is a basic input parameter to calculate the interval and handling capacity of traditional elevators (CIBSE, 2010). The handling capacity of a circulating multicar system (loop) is based on the cycle time between two subsequent cars. The minimum possible cycle time defines the maximum possible handling capacity. The minimum possible cycle time of two subsequent cars depends on door times, passenger transfer times, arrival and departure processes of cars, special exchanger unit delays and required safety distances between cars. It does not depend on travel height and velocity of the cars.

The real cycle time depends on the roundtrip time and the number of cabins in a loop. A longer roundtrip time because of higher travel height, additional stops, or slower velocity enables the usage of a higher number of cars in a loop. If the number of cars and the velocity is ideally adapted, the real cycle time can be the minimum

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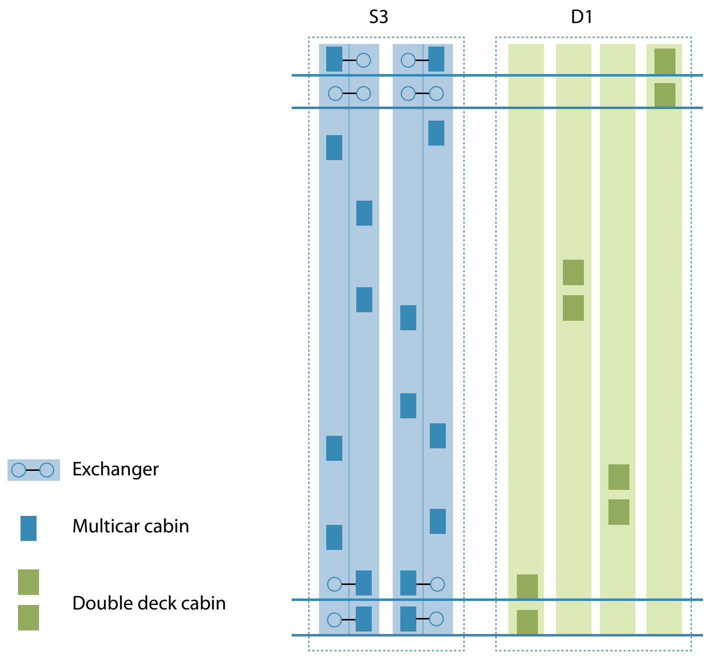


possible cycle time. So the handling capacity is a constant value not directly dependent on the roundtrip time. This also means it is independent of travel height and mostly independent of velocity. If a roundtrip or a loop has a defined number of stops like shuttle arrangements, a maximum constant handling capacity can be reached. Two-way traffic does not affect the upward direction handling capacity since the minimum possible cycle time is not affected by the traffic type. A traffic split of 50% incoming and 50% outgoing traffic does have double the maximum handling capacity of pure traffic in the up direction. The constant maximum handling capacity is the major benefit compared to traditional traction elevators.

Comparison of Circulating Multicar vs. Double Deck

How is the performance of the circulating multicar system compared to traditional double-deck elevator systems? The results of a simple case study demonstrate that. Comparison will be made across different travel heights (100 m, 200 m, 300 m and 400 m). The multicar loop excludes the horizontal transportation of passengers for this comparison.

Traffic split:

- 80% incoming, 20% outgoing

Lobbies:

- Double ground lobby
- Double sky lobby

Shafts:

- 4 double-deck shafts
- 2 multicar loops (= 4 shafts)

Cabin size/passengers per cabin:

- Double deck: 2 x 16 passengers
- Multicar: 8 passengers

Space required:

- Double deck: 36 m^2 shaft space + 18 m^2 waiting area
- Multicar: 24 m^2 shaft space + 12 m^2 waiting area

Velocity: This is a variable depending on travel height.

Number of cabins:

- Double deck: 4 x 2 cabins
- Multicar: variable depending on travel height and velocity

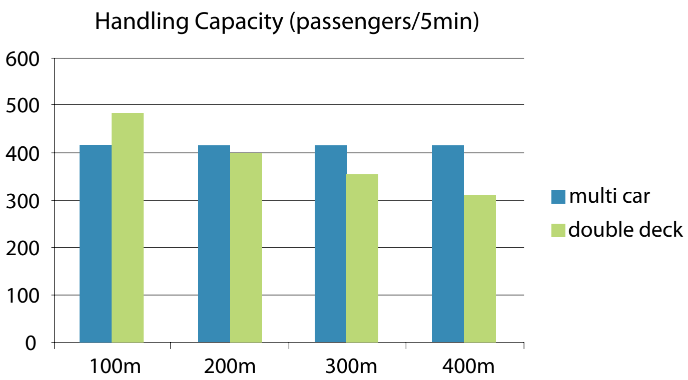
Graphs 3 through 6 show handling capacity, chosen velocity, number of cabins and interval at the ground lobby of both systems depending on travel height.

The handling capacity of the multicar system is constant. Starting with a travel height of about 200 m, it is going to be higher than the compared double-deck system. With increasing travel height, the benefit of the circulating multicar system can be seen. The number of cabins required can be adapted for the multicar system without additional shafts. The number of cabins is constant for the four double-deck shafts.

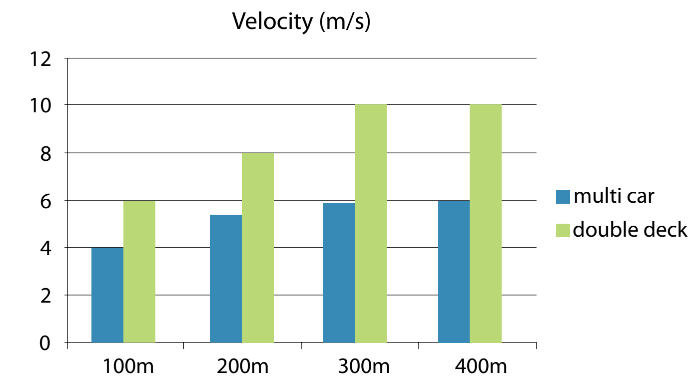
For both systems, the rated velocity is increased with increasing travel height. The velocity of the multicar system is lower than the velocity of the double-deck. While the intervals of the four double-deck shafts gets worse with increasing travel height, the interval of the multicar is constant as more cars can be added.

The average waiting time (AWT) and average time to destination (ATTD) of both systems was compared, as illustrated in Graph 7. The average waiting time is derived from the interval and cabin loading (CIBSE, 2010).

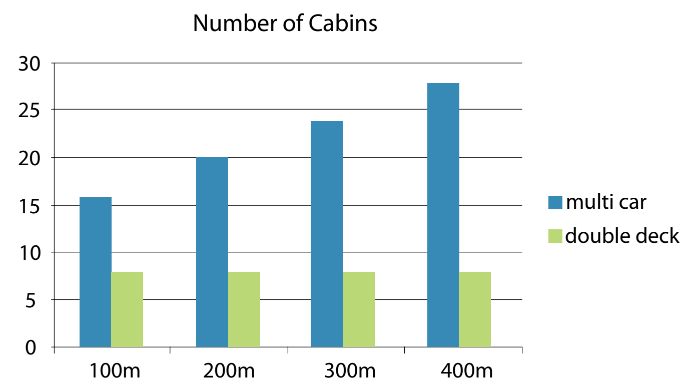
Since the interval of the multi car is constant, the average waiting time is constant. Although the chosen velocity of the multi



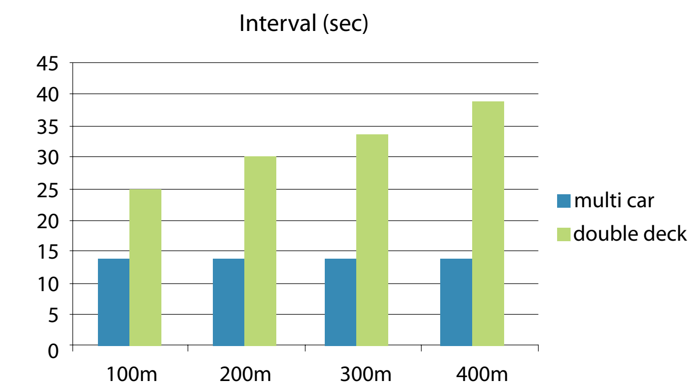
Graph 3: Comparison of multicar vs. double deck depending on travel height: handling capacity. Source: ThyssenKrupp



Graph 4: Comparison of multicar vs. double deck depending on travel height: velocity. Source: ThyssenKrupp



Graph 5: Comparison of multicar vs. double deck depending on travel height: number of cabins. Source: ThyssenKrupp



Graph 6: Comparison of multicar vs. double deck depending on travel height: interval. Source: ThyssenKrupp

car is less than the double-deck, the time to destination of the multicar systems provides better values. This is caused by lower average waiting times and shorter passenger loading/unloading times.

Additional Advantages

Building and Rope Sway

Tall buildings can vibrate at low frequencies (e.g., excited by strong winds). The building vibrations can excite the elevator hoist ropes, especially if the building vibration is close to its natural frequency and coincides with the rope's resonance frequency; large amplitudes of the rope sway may cause major problems and damages (Kaczmarczyk, 2008).

The taller the building, the lower the frequencies which are critical for the ropes. This causes elevator shut downs, especially in windy cities like Chicago. Great efforts are required for rope sway risk mitigations in buildings with natural frequencies between 0.1 – 0.2 Hz. Often, the predicted frequency does not come into being until after completion of the building, which can cause costly repairs.

Therefore, the elevator industry has to find a way to omit hoist ropes. They are the root cause of many challenges in supertall and megatall buildings and beyond: rope mass, rope sway, rope maintenance, rope change…so it is better to be rope-less.

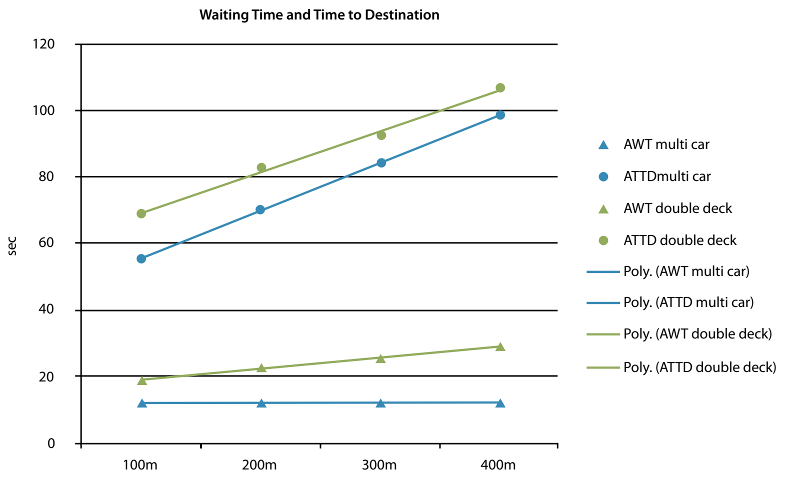
Option: Construction Elevator

Another requirement from the construction side becomes more and more relevant for the elevator industry: Why can't you grow with the building and provide an operating vertical transportation system in lower, finished sections?

It is quite typical that buildings grow during construction by one floor per day. Traditionally, the elevator installation starts when the machine room on top of the shaft is ready and handed over to the elevator installation team. This is very late and other temporary vertical transportation systems have to do the job in the meantime, at high cost and with a lot of time delay. A rope-less system can grow with the building in sections and provide the final elevator group functionality and speeds. Additional cars can also be added to service the growing demand. The MULTI keeps pace with the speed and height of the final building height.

In Summary

By taking all the best aspects of past achievements, including the Paternoster and the TWIN, and making them perfect with the addition of the latest available technology of linear synchronous drives, lightweight design, a new component to exchange cars between shafts and move horizontally, and doing that safely under all circumstances using functional safety for the whole system, it is possible to realize a circulating multicar system, the MULTI. Constant handling capacity and benefits in the elevator footprint with increasing travel heights are characteristics of the system. No super-high-speed elevators are necessary to achieve good travel times and handling capacities. An uninterrupted flow of the number of required elevator cabins enables short waiting times for a continuous passenger flow. MULTI is the latest application of new passenger transportation technology in vertical cities.



Graph 7: Comparison of multicar vs. double deck depending on travel height: average waiting time (AWT) and average time to destination (ATTD). Source: ThyssenKrupp

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