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Elevator Systems for Future Intelligent Buildings

Part 1: Speed and Multi-dimensionality

A CABA WHITE PAPER

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1. ABSTRACT

Globally intelligent buildings are getting taller because of increasing city center real estate costs. At the same time, some buildings are getting wider and deeper to facilitate large organizations. One of the most critical services of high-rise and super high-rise buildings is vertical transportation. In this series of white papers, we examine recent technological developments and concepts possibly leading to new features for elevators in intelligent buildings over the next 10 to 20 years. These features include: speed and drives, multi-dimensionality, remote control, monitoring and maintenance, passenger dispatching, energy efficiency, emergency operation, and others. Part 1 focuses on issues related to speed and dimensionality.

2. RATED SPEED OF ELEVATORS

2.1 Super-high rise buildings around the world – a brief review

Let's review the proliferation of super high-rise buildings (Hollister N. et al., 2012). At the start of the 21st century the *Petronas Towers* in Kuala Lumpur, Malaysia were considered "the world's tallest" with a height of 452 m (1,482 ft.). Then in 2004 the *Taipei 101* in Taipei, Taiwan became the tallest with a height of 508 m (1,667 ft.). In 2009, the distinction shifted to *Burj Khalifa* in Dubai, United Arab Emirates with a height of 830 m (2,723 ft.). The next world record may go to the *Jeddah Tower* (previously named *Kingdom Tower*) in Jeddah, Saudi Arabia (under construction). Planned for completion in 2020, it will reach a height of 1,600 m (1 mile), thus named the *Mile-High Tower* informally. Besides these world records, others at the top of the 2020 list may include *Wuhan Greenland Center* in Wuhan, China to be completed next year with a height of 636 m (2,087 ft), *Shanghai Tower* in Shanghai, China with a height of 632 m (2,073 ft), the *Makkah Royal Clock Tower* in Mecca, Saudi Arabia with a height of 601 m (1,972 ft), and the *Ping An Finance Center* in Shenzhen, China with a height of 599 m (1,965 ft.). By 2020 each of the top five buildings will stand at least 600 m (1,969 ft) tall or higher.

2.2 The limit of rated speed

To populate these towers, in particular during the morning rush or at lunch time, a very efficient elevator system must be available. Modern design usually involves the assignment of sky lobbies served by shuttle or express elevators between the ground floor and these lobbies. Passengers take shuttle elevators that serve two to three stops before reaching the sky lobbies from the ground floor and then connect to local elevators. In this way, the travel of local elevators can be limited and the square-footage of one vertical hoistway or elevator shaft can be shared by local elevators operating in different vertical zones, as designed by Fortune Shepler Saling Elevator Consultants. As shown in Figure 1, the vertical hoistway of an elevator serving the high zone is just on top of that serving the mid zone and then the low zone. Three elevators can operate at the same time though there is always one elevator per hoistway rather than allocating building interior space to three parallel shafts.

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The rated speed of the express elevator is crucial to service. Time to travel a distance, D, with an acceleration/deceleration, A, and a jerk, J, (jerk is the rate-of-change of acceleration) by an elevator is equal to $D/V + A/J + V/A$ (Peters, 1995), the study of which is called "kinematics," a very important topic in elevator motion and traffic control. For example, if the sky lobby is at a height of 400 m (1,312 ft), an elevator with a rated speed of 2.5 m/s (500 fpm), acceleration/deceleration rate of 1 m/s^2 and a jerk of 1.5 m/s^3 takes 400/2.5+1/1.5+2.5/1 = 163 s to travel the whole journey of 400 m, while one with a rated speed of 10 m/s (2,000 fpm), and same acceleration/deceleration and jerk only takes 400/10 + 1/1.5 + 10/1 = 51 s to cover the whole journey. That shows the importance of developing super high-speed elevators for super high-rise buildings.

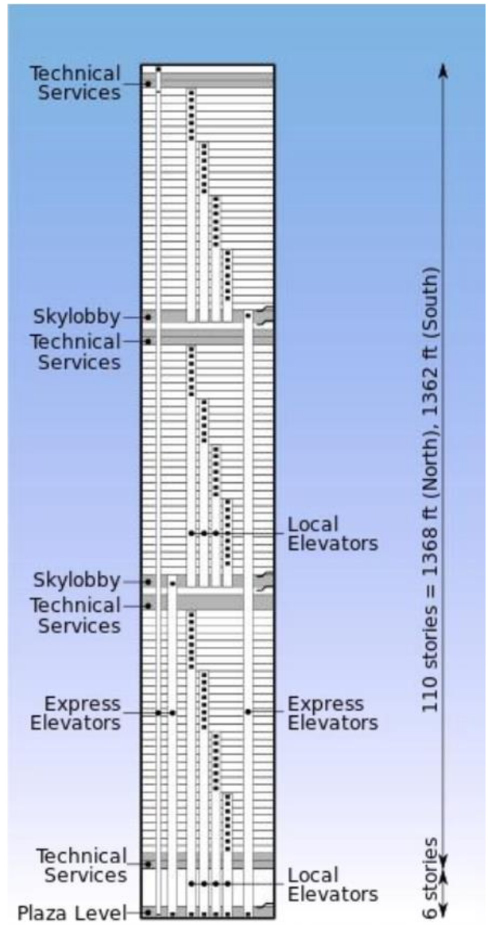

Figure 1 Express (Shuttle) and Local Elevators serving a super-high-rise building (extracted from https://www.fs2ec.com/office-buildings)

The acceleration/deceleration rate and jerk rate are limited by physics that affect passenger comfort. A normal, untrained passenger can tolerate an acceleration/deceleration around 10 percent – 15 percent of the gravity acceleration on earth, approximately 9.81 m/s^2 (called g) without feeling uncomfortable. It should be noted that when a human being is subject to acceleration vertically upward, he or she feels an increase in weight proportional to the percentage of g. That means someone with a weight of 150 lbs. would suddenly feel the weight of 165 lbs. when subject to an upward acceleration of 0.1g. Similarly, when someone is experiencing a downward acceleration, the corresponding weight is reduced. Of course, air force fighter pilots or astronauts can stand several g's without any problem. Technically speaking, the rated speed is unlimited from the point of view of the elevator drive itself. However, human comfort must be considered, which limits elevator drive parameters, and will be discussed further.

Since the early 1990s there have been three breakthroughs in the speed record. The first one was 750 mpm (meters per minute) (12.5 m/s or 2,460 fpm) installed at the *Yokohama Landmark Tower* in Japan by Mitsubishi. Then, the *Taipei 101* elevators in Taiwan by Toshiba attained a speed record of 1,010 mpm (16.8 m/s or 3,313 fpm). But it should be noted that 1,010 mpm is only the upward speed; the downward speed is reduced to 600 mpm. Last year, the world record was broken by an installation at the *CTF Finance Centre*, Guangzhou, China, by Hitachi, rated at 1,260 mpm (21 m/s or 4,134 fpm). Lots of new technologies were developed in order for an elevator to achieve these speed records, including: drive, aerodynamics, car shape, vibration control, and numerous safety devices (reviewed in So 2014a).

2.3 What limits the rated speed?

The obvious question is what's next and are there limits? If the currently fastest elevator in the world is to travel a distance of 1,600 m between two stops even with the acceptable acceleration rate of 1.5 m/s^2 and jerk of 2 m/s^3, it still takes $1{,}600/21 + 1.5/2.0 + 21/1.5 = 91$ s to reach the top of the building from the ground floor, which is too long. Can the speed be increased more and by how much? The limit has nothing to do with the elevator drive or safety technologies; it is due to the aerodynamics of the building. According to physics air pressure decreases at higher elevations about 0.12 mb (12 Pascals or N/m^2) per meter in altitude. That explains why a passenger's ears normally feel uncomfortable when moving up or down at high speed such as on an airplane during climbing and descending. In the *Taipei 101* elevators, a special air pressure balancing system was utilized to limit the in-car pressure change to 1.26 mb/s (1 Pascal = 0.01 mb) under the rated operating speed, versus 2 mb/s ($\approx 16.8 * 0.12$) without it. A rapid change in pressure during a high-speed elevator journey causes discomfort for the passengers by blocking ears and muffling sounds. A method to measure the displacement and motion of the tympanic membrane, i.e., the eardrum, of passengers was developed by using the "shape from shading" method by Toshiba when the 101 elevators were first designed (Funai et al., 2006). An optical fiber was inserted into the ear of a test passenger to inject a laser beam onto the eardrum and then measure the distortion of the image when the passenger is under a high speed journey inside the elevator car.

In other words, to provide passengers with a comfortable journey, the rate of in-car air pressure change must be kept within 1.26 mb/s. Since 0.12 mb of atmospheric pressure is reduced for every meter rise, 1.26 mb/s is almost equivalent to a limit of 10.5 m/s. That explains why most high-speed elevators now are rated at 10 m/s or below without any in-car pressure control, except the few world records where in-car air pressure change control has been implemented. With in-car air-pressure control, the in-car air pressure is reduced at a relatively higher rate during the initial acceleration stage, and then at a relatively lower rate during the operating speed stage, and finally at a relatively higher rate during the deceleration stage. On average, the rate is kept at 1.26 mb/s throughout the journey.

The management of cabin air pressure does not allow unlimited cabin travel speed. The passengers eventually need to exit the car at the destination floor, say at the top of the building. Even though the elevator car is air sealed, once the landing/car doors are opened at the destination floor, there is unavoidably a sudden significant and unacceptable drop in pressure inside and outside the car if the in-car pressure has not been reduced to a level associated with the present altitude of the car. In other words, the automatic air pressure change control system needs to make sure the in-car pressure is equal to the lobby pressure at the destination floor right before the doors are opened. By buying time during

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the long acceleration and deceleration periods, the maximum rated speed as estimated by the author is around 21 m/s (So et al., 2016), which was recently achieved at Guangzhou by Hitachi.

Is there an alternative to this apparent elevator speed limitation? Yes, a proposal was suggested in (So et al., 2016). Modern building design favors air tightness for the whole building where infiltration and exfiltration are both considered undesirable. The goal is to avoid bringing in unconditioned hot or cold air from outside the building without any treatment by the building HVAC (heating, ventilation, and air conditioning) plant. If the whole building can be made air tight, like an airplane cabin during flight or a submarine, it is possible to maintain a relatively high air pressure at the upper floors to minimize the air pressure difference between the upper floors and the ground floor. In this way, it is possible a further increase, in the rated speed, may be realized eventually.

2.4 Modern elevator drives for super-high-rise buildings

Elevator drives are key components in achieving super high-speed operation. Half a century ago AC-2 (alternating current 2 speed) drives and MG (motor generator DC) drives dominated the elevator industry, the former for low-speed elevators and the latter for high-speed elevators. An AC-2 drive consists of a conventional induction motor with two sets of windings on the stator, one high speed – low pole number and one low speed – high pole number, because the synchronous speed of an induction motor is inversely proportional to the number of poles of the stator winding. The MG set utilizes an AC induction motor mechanically driving a DC generator that energizes a DC motor with variably controllable DC voltage. Such a DC motor is mechanically coupled to the sheave (a pulley with grooves around the circumference) that drives the ropes of the elevator. By varying the DC voltage and the field current applied to the DC motor, the motor speed and rotational direction can be controlled.

In the early 1970s ACVV (alternating current, variable voltage) drives started to gain popularity as they offered riding comfort while not relying on DC motors that require intensive maintenance even though DC motors are easy to control. These ACVV drives also utilize conventional AC induction motors. In mid 80s, ACVVVF (alternating current, variable voltage, variable frequency) drives started to become the best choice based on good speed control and energy efficiency. The scalar mode of ACVVVF drives with good steady-state performance was mainly used, while in the mid-1990s, the vector control mode was introduced with good dynamic performance during transient states. The vector control mode virtually converts an AC motor into a DC motor mathematically where field and torque control could be decoupled from one another. So far, these drives have been associated with squirrel-cage type induction motors, which require almost no maintenance but the power-to-size or torque-to-size ratio is rather limited.

An ultra high-speed elevator requires a power capacity so large that an induction motor is not practical because it would be too big. A huge power capacity is needed because of the long travel distance where the inertia is high during the acceleration stage. The inertia includes not just the elevator car and passenger, but also the long ropes. AC induction motors are not practical because part of the stator current is needed to produce a magnetic field for the rotor, thereby making the motor unacceptable. Slim motors that are powerful enough and have high torque are becoming popular because these motors are installed inside the elevator shaft instead of in a separate machine room.

The technology of PMSM (permanent magnetic synchronous machine) was employed in the elevator industry by the beginning of the 21st century. The stator of a PMSM motor is not much different from that of a conventional AC induction motor, but the rotor more resembles a DC motor. Permanent magnets are installed on the rotor so a strong magnetic field is intrinsically produced by the rotor. In this case, a large torque can be produced with a slightly lower stator current or power. Standard control methods include "field orientation control" and "direct torque control," which are modified versions of the vector typed VVVF control. This is the state-of-the-art technology used in the elevator industry. Although some research has been conducted on the use of reluctance motors, the performance may not be as good as PMSM motors, at least in the near future. Another new type of motor, the linear motor is becoming popular, which will be introduced in the next section.

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3. MULTI-DIMENSIONAL ELEVATORS

3.1 One-dimensional elevators

As noted in the previous section, modern intelligent buildings are getting taller, but the rated speed of elevators is limited by physical laws. The full height of an elevator car is usually three to four meters (10-13 ft) while the elevator shaft could be hundreds of meters long. It is inefficient and a big waste to run just one car throughout the whole shaft.

Decades ago, the idea of double or even triple decker elevator cars was implemented where two or three cars were connected together to form one big car, spanning two to three floors. In this way, the number of passengers conveyed in one trip could be doubled or even tripled. But these elevator cars have limitations. First, passengers going to odd or even floors need to take separate cars of a double-decker. It is even more inconvenient when a triple decker is considered. At the ground terminal floors, escalators have to be installed nearby to connect two or three floors served by a double-decker or triple-decker. Second, the main inconvenience occurs when a passenger on the lower car needs to enter or exit the car, all passengers on the upper car need to wait and do nothing, and vice versa. That is a highly inefficient situation.

It has long been accepted that occupying the whole vertical hoistway by one single-decker or one double-decker car is a great waste, not dissimilar to dedicating one whole railway track between two remote cities to one train. The development of TWIN™ elevators by thyssenkrupp is an important step toward the ultimate goal of having multiple cars running in one vertical hoistway or shaft independently; but the number of allowable cars is still limited to two, due to the sophisticated roping arrangement. In 2003, the first TWIN™ elevator was installed at Stuttgart University to transport more professors and students without making any structural change to the existing building. With TWIN™, two independent cars share the same shaft or hoistway, one always above the other. Two sets of hoisting ropes and counterweights are necessary to facilitate the two cars. The supervisory control needs to be very intelligent because the upper car cannot bypass the lower car in a downward journey and vice versa. Nevertheless, the arrangement is still a one-dimensional system.

3.2 Two-dimensional elevators

Section 23.4 of Chapter 23 in So et al., (2009) predicts that with the use of linear motors, elevator systems will upgrade from one dimension to two dimensions. The external facade of modern buildings is usually in the form of a large flat panel, which may be visualized as a chessboard. Elevators could operate on the facade, like rook chess pieces, that can move only horizontally or vertically. The first benefit is that no hoistway occupies the floor area of the building anymore. Second is that the passengers can take an elevator to their final destination rooms, not just the floor. No wide corridor outside each room is required. The windows of the room also form the landing doors. An elevator can go up for a few stories, turn right and move forward for a few rooms, turn left to go further up and few stories again and turn left to arrive at the destination room. The elevator structure automatically

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becomes a protective screen for the whole building. More details about such a two-dimensional system can be found in So et al., (2015) and So et al., (2016). The concepts are depicted in Figure 2.

The idea of a "double facade" on modern buildings is popular when sustainability is included in the design. Air is trapped between the external facade and the internal facade, which can help to carry heat away in summer and to trap heat in winter. Such an arrangement reduces the energy consumed by the building HVAC. The moving cars of such a two-dimensional system, like rooks on a chessboard, can help to distribute the air evenly between the two facades. In this case, the use of booster fans and movable blinds can be reduced.

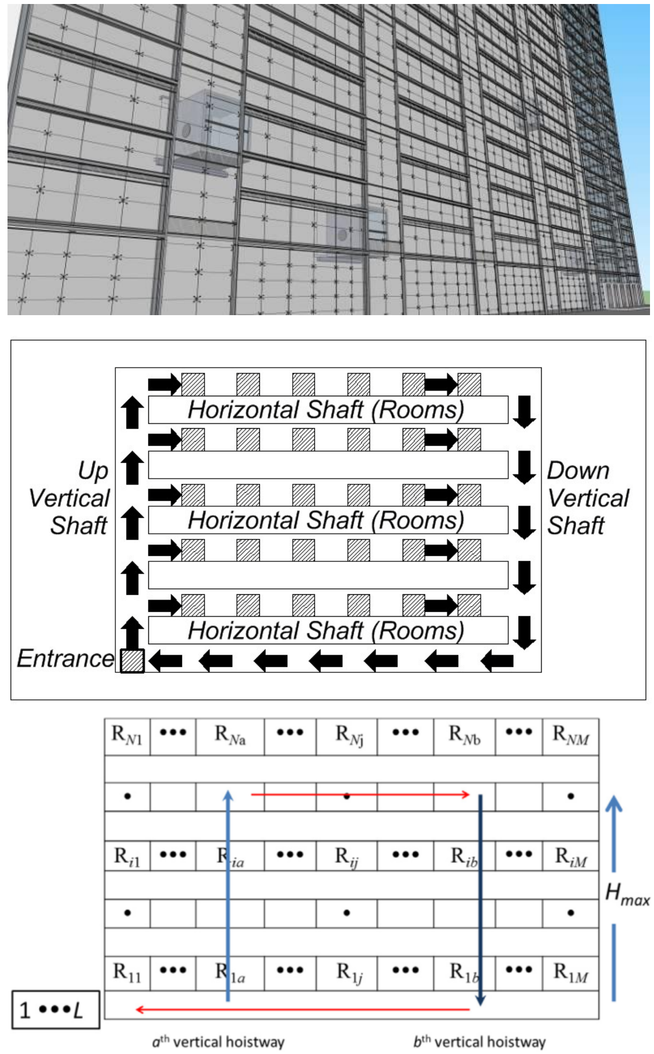

Figure 2 Concepts of a two-dimensional elevator system

The uppermost diagram of Figure 2 shows the simulated artwork where cars freely move on the facade. The middle diagram of Figure 2 shows a simplified, or special, system where the elevator cars can go up and down along a combination of designated vertical hoistways, or columns, at two ends of the building. There could be more than one single hoistway at one side of the building. On every floor, elevator cars are only allowed to move horizontally. The bottom diagram shows a general two-dimensional system where elevator cars can move freely vertically and horizontally. There are L number of elevators picking up passengers at the main terminal and there are M number of rooms on every floor of the building with N number of floors above the ground floor. For efficient and practical operation, each car is only allowed to move up along one vertical column and down along another vertical column during one round trip though there could virtually be M number of vertical shafts.

3.3 Three-dimensional elevators

Finally, a true three-dimensional system was proposed (So et al., 2017). The concept and the simulated artwork are shown in Figure 3. In a true three-dimensional system, cars can move up and down only along a designated group of vertical shafts outside the building

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envelope because free vertical movement in the interior of the building could make the structure unsound. For every trip, the elevator car serves one floor only. In other words, passengers with the same destination floor are grouped together and served by one car. This is not difficult based on the current "destination control" technology. Once the car gets to the destination floor, it moves to the interior along a bridge and then along a "scanner" path until all passengers exit the car. That means the car actually moves along the corridors on a floor as shown in the bottom diagram of Figure 3. The track is laid at the middle of every corridor. Such horizontal tracks are protected by transparent glass walls where doors are provided at every intersection of tracks. When no car is present at the vicinity of an intersection, all doors are opened and building occupants can freely walk between either sides of the corridors to reach any room as desired. Once a car gets close to an intersection, all doors are closed beforehand and only doors associated with the car doors can be opened. In this way, occupant safety can always be ensured.

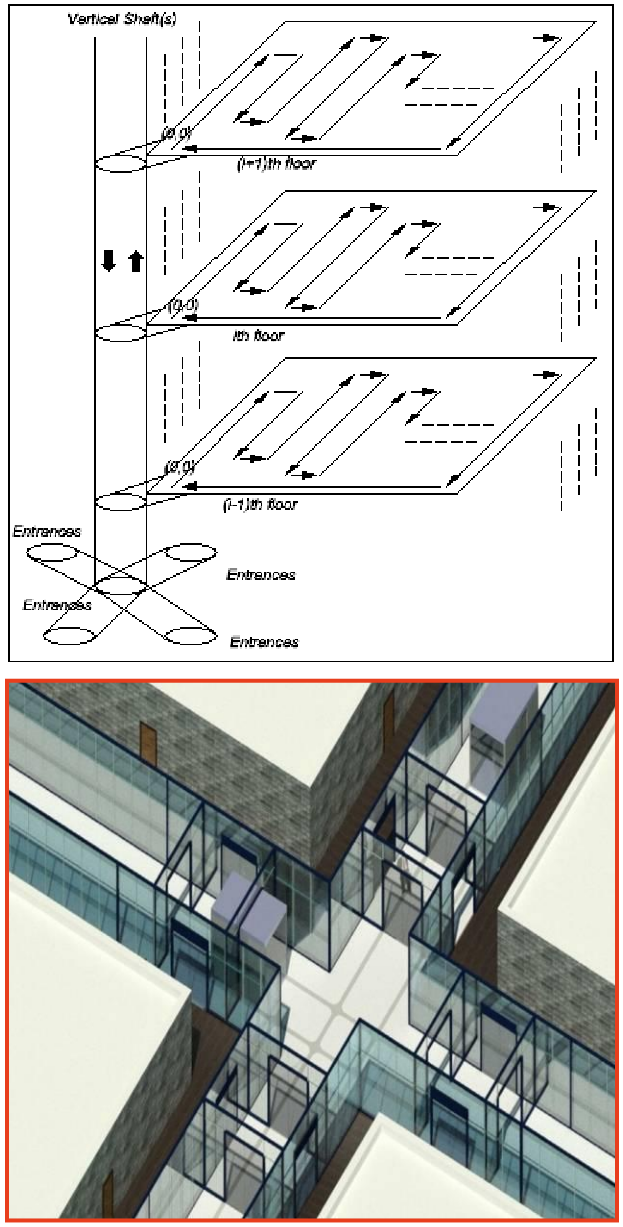

Figure 3 Concepts of a true three-dimensional elevator system

3.4 Drives for Two- or Three-dimensional elevators

All these two-dimensional and three-dimensional systems rely on one critical piece of technology, i.e., the use of linear motors. Linear induction machines are not new, having been available for a few decades. Both the stator and the rotor are planar, like unrolling the cylindrical stator and rotor of a conventional induction motor to form flat panels. In this

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way, instead of producing a torque when the stator is energized, a linear force along the length of the flat stator is produced. Similar to the design of a conventional induction motor, the air gap between the stator and rotor needs to be precisely small; otherwise, the force generated is too small to be useful. Linear motors have been applied to railway train propulsion for many decades. The rotor could be a piece of metal or consist of permanent magnets to increase the force produced. The latter is called a "linear permanent magnetic synchronous motor." Since a high torque and power capacity is needed for elevators, the use of linear synchronous machines would be more appropriate.

Linear motors were employed in the 1980s to 1990s in the elevator industry to develop roped or ropeless elevators. The roped one was invented by Otis (US patent 4402386A filed in 1981) where the linear motor was mounted on the counterweight. The ropeless one was invented by Mitsubishi (US patent 5234079A filed in 1991) where coils were mounted on the walls of the elevator shaft and permanent magnets were mounted on the car to convert the car into the rotor of the linear motor. However, neither invention has been realized and marketed.

3.5 State-of-the-art technology of Two-dimensional elevators

By the end of 2015 Thyssenkrupp, the creator of TWIN™, first demonstrated the model of MULTI™, a two-dimensional elevator system. On the back of every elevator car is the rotor of a linear motor, making it able to move vertically up and down and horizontally left and right. Wheels and rails are available to keep the rotor at a fixed distance from the track and to enhance safety. To change direction a section of the track or rails needs to rotate using the same concept as when a train changes tracks. Without ropes, the elevator can also run horizontally to connect other buildings and eventually may prompt changes in building layouts. Switching shafts and running in a loop are the main feature of MULTI™. From an operating point of view, it is like a mass transit system built inside a building or a group of buildings in a community. The number of elevators is not limited in such a system. As announced, the first real MULTI™ elevator system in the world will be installed in the campus of Stuttgart University in mid 2018.

Some fantastic concepts have been suggested by researchers. Two examples are described here. The idea of "articulated funiculator" was proposed with two shafts (King, 2014). It is a series of connected trains, each fitted with one to four cars on the same track system. When one set of trains is arriving at the stations, the other set of trains is leaving the stations and one set is idling and one set is moving between two stations. It is like a vertical subway.

Another suggestion consists of a group of large circular tracks around the building (Godwin, 2010), similar to a Ferris wheel in an amusement park, shown in Figure 4. Round-shaped cars sitting on linear motors move around the building where there are up to two stopping stations on every floor. The cars rotate automatically to make sure passengers always stand on a horizontal car floor irrespective of the position of them along

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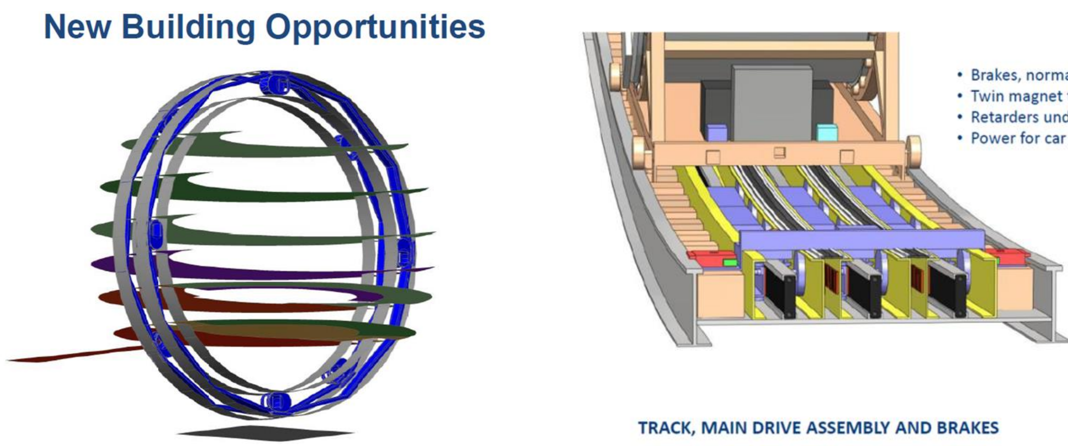

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Figure 4 Concept of In-building Circular Transportation (extracted from a presentation of Adrian Godwin in Elevcon 2010)

track. In this case, there could be as many cars as possible around the tracks. By using linear motors, there is no need to include any counterweights.

4. CONCLUSION

In this White Paper two issues related to modern elevators in super-high-rise and wide buildings have been discussed. To serve a mile-high intelligent building, super high-speed elevators are needed. However, the rated speed is limited and, therefore, the time to reach the top floor from the ground floor cannot be too short due to aerodynamic constraints subject to air pressure variations. Linear permanent magnet synchronous motors enable ropeless applications to maximize the use of vertical hoistways in a super-high-rise building and to serve extremely wide buildings. And the existing one dimension should be expanded to two dimensions, though my personal research actually includes a three-dimensional design. A key observation is that the technologies of modern elevators are quite advanced, and smart elevators are important for super high-rise buildings. In the next White Paper, remote monitoring and maintenance, and emergency operation of elevators will be examined.

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