The SLOPELIFT - a New Fast Inclined Elevator system, induces no Horizontal Forces on its passengers

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Abstract

The acceleration and deceleration of inclined elevators, are known to induce horizontal forces on its passengers, which are very unpleasant, and cause them to feel unstable. To reduce the ill feeling, the horizontal acceleration is kept low and the elevators are slow and inefficient. To overcome this problem, a new fast inclined elevator system has been developed, where a unique dynamic mechanism brings the horizontal acceleration on the passengers to zero g theoretically, and as low as 0.00g till 0.005g practically. Such horizontal acceleration is not felt by the passengers, and they do not feel that their movement is inclined. The acceleration along the track is kept high, and therefore the system is as fast and efficient as a regular vertical elevator. A laboratory model that has been built, is described and it's measurement results discussed. The dynamic model of the system is demonstrated and the equations of motion are introduced.

1. INTRODUCTION

Inclined elevators for carrying passengers in buildings built on mountain slopes, have been in use for many years. In a few countries there are codes in effect, for this kind of elevators, like part XVII of the American Safety Code for Elevators and Escalators ASME A17.1-1996, to mention one of them. Inclined elevators are used mostly out of necessity, where no other solutions are practical, and are considered not very efficient. The main reason for this attitude is the existence of horizontal forces, that are acting on the passengers whenever the elevator car accelerates or decelerates, which means at least twice in each part of the journey. These horizontal forces cause instability and very inconvenient and annoying feeling to the passengers. To reduce this effect, the designers have to keep these accelerations as low as practically possible, and it ends up with inefficient and often awkward solutions.

For inclined elevators that serve remote villas on mountain slopes, the trip duration is not an important factor, and quite low velocities are acceptable, mainly because these types of elevators are often open to the panorama, and are considered as part of the enjoyment. Up to five floors stepped town houses have also been considered as marginally adequate for the existing inclined elevators solutions. However, elevators that serve multi-story hotels or office buildings, are part of the normal inner traffic, and long waiting and traveling times will seriously harm the satisfaction of the passengers, and therefore the productivity and economy of the building. Not too many hotel or office builders dared to use inclined elevators, because an acceptable solution has not been attainable till now. It is the aim of this study to introduce a fast, highly efficient, inclined elevator system, that can be considered as effective as a regular vertical elevator, with no inconvenience whatsoever to the passengers.

2. THE HORIZONTAL ACCELERATION

Horizontal acceleration function, its rise time (= jerk) and duration, are the main influencing factors of the convenience that the passengers feel. The unpleasant results of horizontal excitation of a car of an inclined elevator, with passengers in it, can be: discomfort, need to maintain balance, anxiety, loss of balance, lateral impact or eventual fall. Horizontal acceleration or deceleration can be caused by normal elevator operation, or by an emergency stop caused by many reasons. Comprehensive studies on this subject have been reported and reviewed by Gibson [1,2] from Otis and now with George W. Gibson & Associates, Inc..

The reported studies deal with regular elevator operation, which will be the main issues of our study, and with the emergency stops. The regular horizontal suggested accelerations are not yet defined in the codes, and for now are left to the discretion of the designers. The issue has been on the agenda of the European inclined elevators code committee recently. The maximal emergency stop is covered by the 1996 edition of the American ASME A17.1 code [3], and they are not questioned in our study. The emergency stops, that are also dealt with in full detail by Gibson, will not be a main issue here, because the results reported by him are the upper limits for the later proposed modifications. The exact deceleration values that will be obtained in an elevator, equipped with the proposed mechanism can only be lower than in one without such mechanism , as will be shown later. The actual horizontal accelerations and retardations, that are in use on inclined elevators for regular travel, are between 0.025g to 0.05g, Such accelerations are both unpleasant and inefficient. Therefore, inclined elevators are used only for special structures, where another feasible solution does not exist.

It is widely accepted and utilized by many manufacturers, that in regular vertical elevators a superior car-riding quality is accomplished during normal elevator operation, by the reduction of stimuli to a ***level below the threshold of passenger perception*** . Contrary to this statement, Gibson in his comprehensive review on inclined elevators [1], relates to experimental and analytical studies that define the passengers comfort as: "A bit uncomfortable" versus " Quite uncomfortable", or "Slight relative movement" of the person, versus "Moderate relative movement", or minor, moderate or major body disturbances due to horizontal acceleration. The cited studies did not refer to the threshold of a person's reaction and are mostly irrelevant, if we want to fulfill the first statement in this paragraph. A few of the studies cited were aimed at escalator traffic, where the passengers start with a horizontal movement in the direction of the acceleration, and are therefore quite different than elevator traffic, where passengers should stand totally unaided. The relevant question that one has to ask the people who will take part in future tests will be: "At what level of acceleration did you start to feel any inconvenience at all? What was your threshold? When did you have to react?". The answers to these questions would have resulted in much much lower acceleration thresholds, than the 0.05g to 0.10g which were mostly measured or cited.

An original study for measuring the threshold of passengers perception of horizontal acceleration and retardation has been performed in the TECHNION in Haifa , by a group of students [4]. A trolley on four bicycle wheels was towed by descending vertical weights that were suspended via rollers and a cable. The jerk was a function of the inertia and friction only, because the weights were loaded without any impact. The people on the trolley were surrounded with a drape, so that they could not see the onset of the motion. The test was performed on students and on very few professors, altogether about 20 people, so that it represented able adults with low statistics only. The general public would be more sensitive. The results were measured with a very sensitive g-meter based on a pendulum and LVDT measuring device, all monitored by a PC, with Keythley A/D interface card and software. The threshold of the detected acceleration by most of the students was within 0.012g to 0.018g with a jerk of around 0.2 g/sec. Therefore, to be on the safe side, the maximum horizontal acceleration value that can be allowed, ***without any response from or effect on the passengers***, has to be around 0.01g with the jerk lower than 0.2 g/sec. Acceleration values in this low order of magnitude were unattainable and impractical till now, and were therefore not considered. As will be described in the next paragraph, it is quite feasible now, to design a fast and efficient inclined elevator system, based on these low acceleration values, so that the passengers may not perceive the onset of travel, nor feel that their travel is inclined.

3. THE TILTING ELEVATOR CAR

The forces acting on a passenger in an elevator car are always a combination from two origins, the earth gravity and the car acceleration. In a regular vertical elevator car, both these acceleration forces are always acting along the vertical axis, which is also the vertical axis of the passengers in the car. We know, based on much experience, that the threshold of human perception of vertical acceleration is around 0.1g in addition or subtraction to gravity. In the previous paragraph the threshold for horizontal acceleration was set as 0.01g, which is one order of magnitude lower. There probably is an interaction between horizontal and vertical accelerations, and their combined influence on a passenger may lower both threshold values. Due to the great difference between both numbers, the combined value will not change much, and therefore we will neglect the influence of one direction on the other, and for now refer to each direction separately.

In an inclined elevator, both accelerations are not acting on the same axis and horizontal acceleration acts on the passengers and on the car. One way to eliminate the acceleration that acts perpendicular to the passenger's body, is to attach the car to the elevator system via a mechanism, that will enable to tilt the car to an angle θ, so that the combined vector of the acting forces will pass along the longitudinal axis of the inclined car, namely vertical to the passenger's body. In such a way there will be no acceleration acting perpendicular to the passenger's body, and he will not feel any disturbance whatsoever. Actually, he may not know that the car's displacement is not vertical but inclined.
The tilting angle θ has to be changed according to the combined instantaneous acceleration in any given moment. When the car will travel in constant speed, the angle θ will be zero. The general arrangement is shown in figure 1.

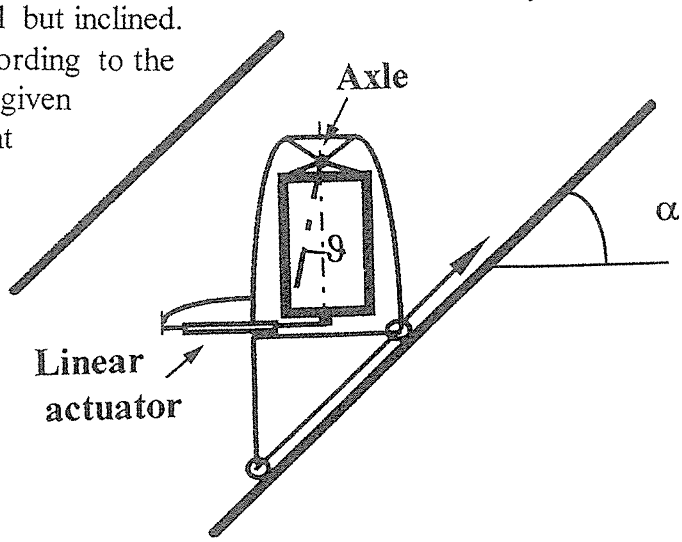


Figure 1: The tilting angle concept of the inclined elevator car, that eliminates the transverse forces on the passengers

The general idea, including the patented realization possibilities, are described in ref. [5;6;7]. The optimal parameters of the mechanism have to be determined analytically and experimentally.

4. THE MAN-MACHINE INTERACTION

One of the most problematic questions in a system like the proposed one, is the location of the appropriate tilting center of the car, relative to the passenger's body. There are at least three different possible points in every passenger's body, that can be considered. These points are: the center of gravity located below the waist, the center of gyration sensing located in the ear , or the ankles that produce the body movement that oppose the disturbances. One can argue that intermediate points can also be used. Another interesting issue is the human sensitivity to difference in inertia forces, acting on different parts of the body. For example, tilting around the person's center of gravity will cause the inertia forces on the head and the ankles be smaller, but with opposite directions. An optimal point for the center of tilting, in an elevator environment, has to be found experimentally.

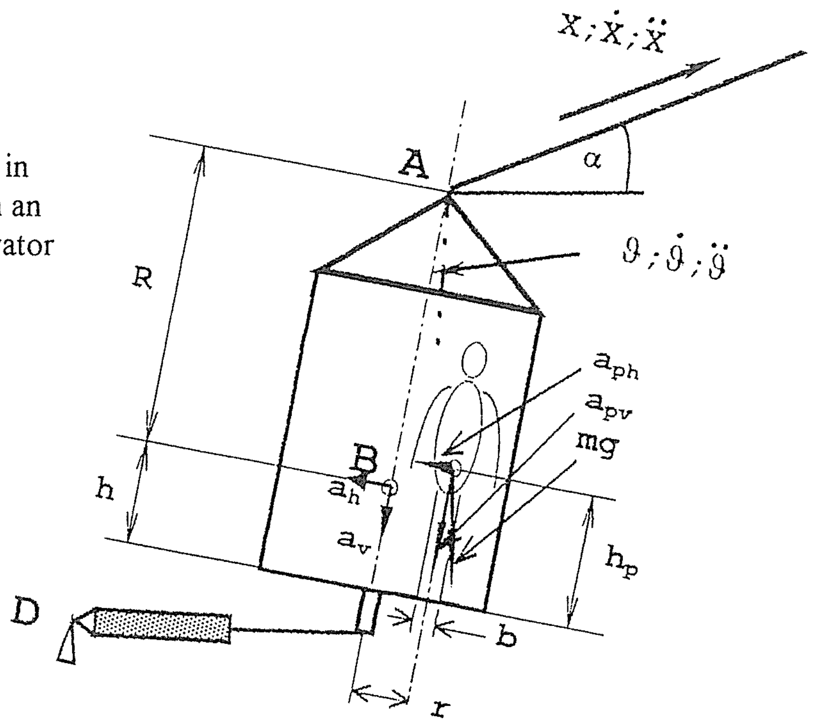
The question of optimal center of tilting or movement of a person, has been investigated by many distinguished scholars, and different answers have been proposed. In our case the question is even more complicated, as there exists a natural large variance between the heights of the passengers, including children, and there is another scatter factor that is caused by the different location of every passenger, as related to the centerline of the elevator car. The model discussed later on is general and covers all the possible locations of the center of tilting. It defines as a feasible solution one that ascertains that, the horizontal acceleration acting on any point of the passenger's body, is as close to zero as possible, and is never higher than the threshold, that has been set to $0.01g$.

5. THE DYNAMIC FUNCTION

When the elevator car is hinged freely on upper hinges, the acceleration and deceleration forces are acting directly on the car, and theoretically there is no need for any inclining mechanism. The car will adapt itself to the consequential acceleration, by rotating to an angle θ, and the passengers will feel only forces that act along their bodies. The problem with this kind of solution is that it is unstable. It will move whenever the passengers are not standing symmetrically in the center of the car, will not be leveled and fixed in stations, will tend to oscillate harmonically as a physical pendulum instead of standing still, after the traction of the motor has been removed near the stations, and generally will hinder the convenience of the passengers. The system could be improved by the use of controlled or by free damping, but even this is not the way to come close to an adequate solution. One needs a forcing mechanism that will bring the tilting angle of the car exactly to the optimal location in any given moment, and keep it fixed there in spite of disturbances. Such a mechanism can operate according to a predetermined function, in open loop, or include a closed loop, feedback control system. There are many possible concepts for such mechanisms, a few will be described in brief later on. Here we will describe the acting dynamic forces on the passengers.

In fig.2 the accelerating inclined elevator is depicted, with one passenger standing at a distance r from the centerline of the elevator. The elevator operates in a shaft with inclination α to the horizon, and tilts around the axis A with a changing angle ϑ. The angle ϑ is attained and constantly changed, as a function of the acceleration along the inclined track, by a mechanism D, located at the lower part of the elevator floor. The control of the mechanism D is robust and does not depend on the number, nor location of the passengers in the elevator car.

Figure 2: A passenger standing in a distance r off the centerline, in an accelerating, tilted, inclined elevator



The controlling function for the angle ϑ of the elevator car, has been calculated in this special case, by bringing the parallel to the car floor acceleration in point B of the car - a_h, to zero, at any inclined acceleration. The perpendicular acceleration in point B - a_v, has been kept close to, but below 0.1g.

The detailed derivation of the equations of motion has been performed elsewhere [6;8] and will be published separately. The resultant accelerations acting on the center of gravity (or on any other point) of the passenger were found to be as follows:

$$a_{ph} = \frac{\partial^2 \vartheta}{\partial t^2}.R + \left(\frac{\partial \vartheta}{\partial t}\right)^2.r + \left(\frac{\partial^2 x}{\partial t^2}\right)\cos(\alpha - \vartheta) + g\sin\vartheta \tag{1}$$

$$a_{pv} = -g\cos\vartheta - \left(\frac{\partial^2 x}{\partial t^2}\right)\sin(\alpha - \vartheta) - \left(\frac{\partial \vartheta}{\partial t}\right)^2.R + \frac{\partial^2 \vartheta}{\partial t^2}.r \tag{2}$$

Here a_{ph} is the acceleration acting perpendicular to the passenger's body, and a_{pv} is the acceleration acting along the passenger's body. As the car control was planed for zero horizontal acceleration for a passenger standing on the centerline of the car, with center of gravity at h, we get from eq. (1):

$$a_h = 0 \Rightarrow \qquad \frac{\partial^2 x}{\partial t^2} = \frac{-\dfrac{\partial^2 \vartheta}{\partial t^2}.R - g\sin\vartheta}{\cos(\alpha - \vartheta)} \qquad (3)$$

This equation describes the angle ϑ and its derivatives, as a function of the inclined acceleration along the track. The solutions for ϑ can be found by numerical simulation, for any value of the inclined acceleration $\ddot{x}$. The regular double-trapezoidal functions of elevator accelerations have to be changed, mainly because of the jerks, and other acceleration functions have to be adapted. Optimization of velocities and accelerations can be made to obtain highly efficient inclined elevator systems. The net traveling time of the inclined elevator, to the adjacent floor of a regular 3 vertical meters high floor building, can be reduced to as low as 4 seconds. This brings the inclined system to efficiency, which is practically similar to regular vertical elevators.

The regular trail slope angles for an inclined elevator system, that serves a modern multi-story hotel or residential building, are within 30^0 to 70^0. These angles are regularly kept constant, but even in a variable angle elevator the proposed system can be fully utilized. Within the above mentioned angles, the constrains of the system can be fully achieved. It might be less efficient in very small inclination angles, due to high tilting angles that will be needed, and not always worthwhile in angles higher than 70^0.

6. THE TILTING MECHANISM

The basic idea for eliminating the horizontal forces on the passengers imply the tilting of the elevator car around a horizontal axis, as a function of the acceleration of the inclined movement. This axis can be fixed or movable, as a function of the mechanism used. The axis can be located above the elevator car, in any height from the elevator floor and even deviated from the elevator vertical centerline, due to the lack of symmetry of the forces acting on the passengers in both directions of travel. The pivot can be arranged by use of fixed bearings in different locations, by guiding rails of different shapes and curvatures, or by different mechanisms, as described in [7]. The most logical and cost effective designs would be with fixed axis, in one of the configurations, as shown in the following figures.

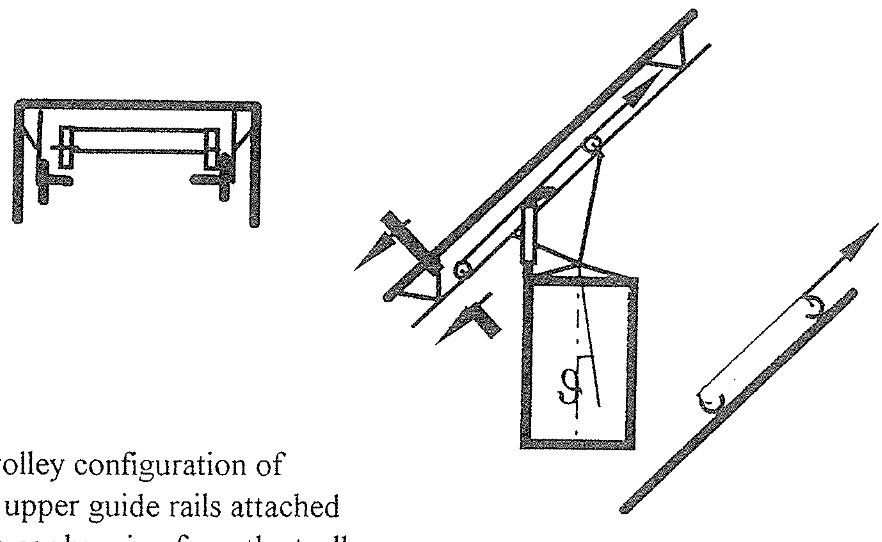


Figure 3: The upper trolley configuration of the SLOPELIFT with upper guide rails attached to the structure, and a car hanging from the trolley

- **The Upper-trolley**: To use rails attached to the topside of the shaft, or to the shaft's walls, and having a hanged trolley moving on the rails. The car will be hanged from a shaft attached to the trolley. This configuration will be rigid sidewise and simple in details. The counterweight will travel on separate rails located on the shaft's floor, for all configurations. This type of configuration is shown in fig. 3.
- **The Lower-trolley**: To use a trolley that inclined elevators regularly use, but to build an upper structure above this trolley, and to hinge the car from that upper structure. This solution will have to be heavier, in order to be rigid to side vibration and excitation. A general arrangement of this type has been shown in fig.1. Here one can see a lower inclined trolley, very similar to the one in regular use in inclined elevators, only with the additional upper structure.
- **The Bottom rails**: Rails curved to a fixed radius, with a center at any height from the car's floor. The car itself will tilt on these rails, back and forth, on wheels. This configuration, shown in fig. 4, has the advantage that it easily enables to locate the center of tilting in any point, including inside the car and at the center of gravity of the averaged passenger.
- **A Bar Mechanism**: The needed effect can be achieved by a special ingenious bar mechanism, attached to the upper or lower trolley, and allowing the hinged motion of the car, without hindering the doors space. This type of mechanism can have some advantages, but might be quite heavy to keep it rigid.

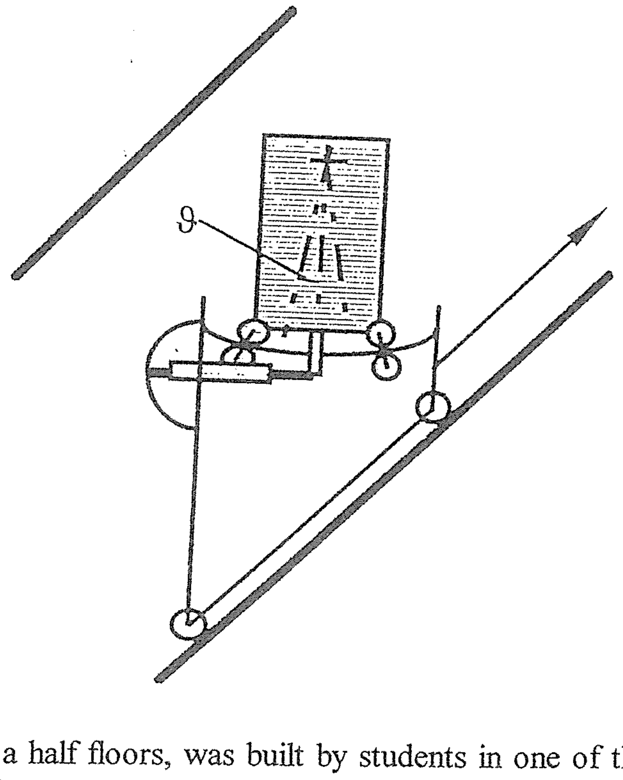


Figure 4: The SLOPELIFT on bottom rails, with the tilting axis inside the car

7. THE MODEL TESTS

A laboratory model, in scale 1:5 of one and a half floors, was built by students in one of the TECHNION laboratories. The inclined motion was carried out with a regular, asynchronous AC motor, regulated with a frequency controller. The tilting motion was carried out with a DC servomotor and a specially designed ball screw actuator. The whole system executed a predetermined tilting angle program in open loop, via closed loop control of both the motors and was operated from one computer. The horizontal acceleration was monitored using a Instruments & Control Inc. model TS2A servo inclinometer made.

A model passenger, made of aluminum, with very slender proportions, was located in different locations of the model car floor. Without the tilting motion, the scale passenger would tip and fall opposite to the direction of motion, immediately on turning on the elevator movement. The g-meter would measure about 0.07g horizontal, when the inclined acceleration was close to 0.1g, with rise time around 1 sec. When the programmed tilting motion was actuated, the g-meter recorded much less than 0.01g (i.e. less than 0.1 m/sec^2). The model passenger remained standing in many of the tests. In a few tests the passenger tilted and fell down in the plane perpendicular to the elevator motion, due to the instability and vibration of the whole model in this plane, a problem that is under improvement now. In one case the passenger remained standing during the whole ascending motion, on a much narrower base (small b/h_p in figure 2) than the one describing a human, that was specially prepared for this purpose. In this case the lateral transverse vibration was absent and clean theoretical accelerations were achieved. The results were compared to analysis done by use of the ADAMS dynamic software [8] with very good conformity. The test results clearly demonstrated that the acceleration on the model, under programmed tilting, was very low indeed, and the theoretical targets and assumptions were validated. In spite of the fact that the model measurements proved the performance of the model SLOPELIFT, a full scale test with passengers in the car, will be needed to verify that the inclined motion is totally not perceived by the passengers.

A full scale horizontal simulation test has also been performed. The g-trolley mentioned in #2 was equipped with a free tilting base, hanging from an upper structure. Students were standing on the tilting base, with drapes around, that concealed the view. The trolley was towed to motion with the same weights mentioned before, only now the base was free to tilt. The students could not distinguish the onset of the motion, and felt it only when the base started to oscillate, after a half of one cycle. The same effect was felt (or more precisely: was not felt) by about ten different people.

8. CONCLUSIONS AND DISCUSSION

- A new concept for an inclined elevator system has been proposed. This concept practically eliminates the horizontal forces on the passengers, and efficient inclined accelerations and velocities can be attained. The proposed concept enables to use long and fast inclined elevators, much the same as regular, modern, vertical elevators, wherever needed.
- The introduction of fast inclined elevators, opens the field for novel architectural solutions of buildings and city planning , including the possibility to cover a whole hillside with long stepped buildings (of 30 or more floors), without the need for making too many in-between roads.
- The safety issues of the proposed concept will be the same as in regular inclined elevators. The highest allowed speed is considered to be reduced to 4 m/sec, and the safety retardation is allowed to be maximum 0.5g. When controlled braking will be allowed, then one might consider to bring the elevator car, at the process of braking, first to the maximal tilting angle ϑ. In this way the horizontal retardation acting on the passengers can be further reduced by a factor of $\cos(\alpha + \vartheta)/\cos\alpha$.
- The open view inclined elevators were introduced out of necessity, because due to the long traveling times, people would be annoyed, and to distract their attention they were exposed to the view. But this is totally unnecessary, because inclined elevators are used in locations where one can see the view from almost every window, passage and balcony, in

each floor. The additional time to look at the view from the elevator is totally unnecessary, instead the elevator efficiency has to be improved, so that people will spend very short time in the elevator. The elevator shaft in an open view elevator is located in such places, that can be much better used for gardens or for more view windows. The SLOPELIFT should be located in closed shafts, that can be placed under the buildings or gardens, and so to add more qualities to the edifice. Here the necessity turns into an advantage.

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