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ANTTI PUSA

EFFECTS OF VELOCITY GRADIENTS ON HUMAN BODY

Master of Science Thesis

Examiner: Prof. Jouni Kivistö-Rahnasto
Supervisor: Dr. Jussi Lähteenmäki

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ABSTRACT

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The number of elevators, escalators and moving walks are increasing each year. Respectively, accident rates, such as losing of balance, are increasing. Escalators and inclined moving walks are considered more hazardous than elevators, as the injuries per machine are significantly higher with escalators. For example, in 2007, the number of injuries per escalators were more than 20 times greater than with injuries per elevators in the USA. Falling accidents are e.g. due to velocity gradients: acceleration and deceleration. It has been estimated that approximately 2,5 % of escalator stops result in passenger fall.

This thesis studies the effects of velocity gradients on the human body with elevator, escalator and moving walk applications. The study is a literature review where accident statistics, the most well-known vertical transportation safety standards and several balance studies are analyzed individually and compared with each other. ASME A17.1, EN 81-20, EN 115 and Japanese codes offer safety instructions and limitations on the effects of velocity gradients. However, the limitations are not unanimous as there is diversity from standard to standard and from machine to machine. When elevator standards were analyzed, surprisingly only the deceleration limitations were comprehensively covered and acceleration limitations could not be found in a similar fashion. Limitations on the velocity gradients of escalators and moving walks were comprehensive altogether.

The balance studies reveal that there are multiple factors affecting the human balance, such as the magnitude of external disturbance, age of a person and whether a person is having an external support or not. Sudden changes and the high magnitudes of velocity gradients, such as emergency braking, can have an undesired effect on the balance and the ride comfort. The deceleration is more challenging for the retention of balance than acceleration. Most older adults aged over 65 years have balance problems when the magnitudes of horizontal deceleration exceed 2 m/s^2. However, younger adults aged under 40 years are able to manage at the magnitudes of 5 m/s^2. The current safety standards limit horizontal deceleration of inclined elevator to 2,46−5,00 m/s^2, from which the highest magnitudes might lead to falling of older passenger.

This paper proposes that elevator safety standards should include both acceleration and deceleration limitations comprehensively. In addition, machine design should utilize new solutions in order to improve passenger safety e.g. for emergency braking. An intelligent braking system shows promising results especially with emergency stop of escalator.

TIIVISTELMÄ

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Hissien, liukuportaiden ja liukukäytävien lukumäärät kasvavat vuosi vuodelta. Vastaavasti kyseisten koneiden onnettomuuksien, kuten kaatumisten ja putoamisten, lukumäärät ovat kasvussa. Liukuportaat ja -käytävät ovat riskialttiimpia kuin hissit, sillä onnettomuuksien määrä konetta kohden on huomattavasti suurempi liukuportailla kuin hisseillä. Esimerkiksi vuonna 2007 Yhdysvalloissa onnettomuuksia tapahtui liukuportaiden lukumäärää kohden yli 20 kertaa enemmän kuin onnettomuuksia hissien lukumäärää kohden. Kaatumis- ja putoamisonnettomuudet johtuvat mm. nopeuden gradienteista: kiihtyvyydestä ja hidastuvuudesta. On arvioitu, että 2,5 % kaikista liukuportaiden pysähtymisistä johtaa matkustajien kaatumiseen.

Tämä opinnäytetyö tutki nopeuden gradienttien vaikutusta hissien, liukuportaiden ja -käytävien matkustajiin. Tutkimus toteutettiin kirjallisuusselvityksenä analysoimalla teollisuuden tilastoja, tunnetuimpia turvallisuusstandardeja ja tasapainotutkimuksia sekä vertailemalla näiden tietoja. ASME A17.1, EN 81-20 ja EN 115 sekä japanilaiset turvallisuusohjeet tarjoavat turvallisuussääntöjä ja -rajoituksia nopeusgradienttien vaikutuksien rajoittamiselle. Standardit eivät kuitenkaan ole yksimielisiä ohjeistuksista, sillä rajoituksien suuruusluokat eriävät standardista ja koneesta riippuen. Hissistandardien vertailussa huomattiin, että hidastuvuuden raja-arvoja esiintyi kattavasti, mutta kiihtyvyyden raja-arvot olivat puutteellisia. Liukuportaiden ja -käytävien tapauksessa sekä kiihtyvyyden että hidastuvuuden raja-arvot olivat kattavat.

Tasapainotutkimuksista ilmenee mm. kuinka ihmisen tasapainolla on monta osatekijää, kuten ulkoisen häiriön voimakkuus, ihmisen ikä ja mahdollisuus käyttää erillistä tukea. Yllättävä tai voimakas nopeusgradientti voi vaikuttaa negatiivisesti matkustajan tasapainoon ja ajomukavuuteen. Tasapainon ylläpitämisessä hidastuvuus koetaan haastavammaksi kuin kiihtyvyys. Tutkimustulosten mukaan yli 65-vuotiailla matkustajilla on hankaluuksia pysyä pystyssä, mikäli vaakatasoinen hidastuvuus on yli 2 m/s^2. Osa alle 40-vuotiaista matkustajista kuitenkin kykenee ylläpitämään tasapainonsa jopa 5 m/s^2 hidastuvuudessa. Nykyiset hidastuvuusrajoitukset rajoittavat vinohissien vaakatasoiset hidastuvuudet 2,46−5,00 m/s^2 väliin. Käytännössä kyseiset hidastuvuudet voivat johtaa vanhempien matkustajien kaatumiseen.

Turvallisuusstandardien tulevissa muutoksissa olisi suotavaa huomioida sekä kiihtyvyys- että hidastuvuusrajoitukset kattavasti. Tämän lisäksi hissiteollisuuden suunnittelun olisi suotavaa hyödyntää uusimpia teknillisiä ratkaisuja matkustajaturvallisuuden parantamiseksi. Esim. älykkäät jarrutusjärjestelmät tarjoavat lupaavia tuloksia liukuportaiden hätäjarrutukseen.

PREFACE

"*No bounce, no play*" is a quotation from Stephen King's book *Dreamcatcher*. This process called Master's Thesis has had both, bounces and plays. There have been times when the project advanced with giant leaps and then there have been times when things seemed to go sideways or even backwards. To my fortune, I've had an awesome network of people helping me play this game of Master's Thesis.

In the beginning, I want to thank my associated professor Kivistö-Rahnasto for all the support and tips he has shared with me. Thanks to him, the initial project was turned into a Master Thesis, which I could take part in. In addition, I want to thank my supervisor Mr. Lähteenmäki and other fine colleagues for welcoming me part of the project, pushing me in the right direction and for the support altogether.

Naturally, I want to thank my friends and family for the cheers and beers. All sports and games require to have supporters and fans. Lastly, I want to thank my fiancée for enduring with me through the whole project. I cannot underline how important our coffee talks have been to me.

To the students who are about to start or in the middle of their Master's Thesis, remember the wise words from *The Shining* by King: "*All work and no play makes Jack a dull boy*". We need to remember that the author needs to have some fun once in a while. It is only a thesis after all.

Tampere, September 20th 2017

Antti Pusa

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineering
BoS	Base of Support
BSLJ	Building Standard Law of Japan
BSLJ-EO	Building Standard Law of Japan - Enforcement Order
CEN	Comité Européen de Normalisation, European Committee for Standardization
CNS	Central Nervous System
CoG	Center of Gravity
CWT	Counterweight
ELA	European Lift Association
Esc	Escalator
HMW	Horizontal Moving Walk
IE	Inclined Elevator
IMW	Inclined Moving Walk
IoT	Internet of Things
ISO	International Organization for Standardization
JEA	Japan Elevator Association
JEAS	Japan Elevator Association Standard
JIS	Japan Industrial Standard
KTI	KONE Technology and Innovation
MOC	Ministry of Construction (Japan)
MR	Magnetorheological
MRL	Machine-room-less
MRT	Metro Rapid Transit (Taiwan)
N/A	Not Available
SIL	Safety Integrity Level
SI-system	Système international d'unités, International System of Units
TR	Technical Report
TS	Technical Specification
Tukes	Turvallisuus- ja kemikaalivirasto, Finnish Safety and Chemicals Agency
TUT	Tampere University of Technology
USA	United States of America
VE	Vertical elevator
WG2	Working Group 2 (from CEN)

a_{av}	average acceleration
a_d	deceleration
α	incline angle
d	displacement
d_{stop}	stopping distance
g	acceleration of gravity
j	jerk
t	time
v	velocity or speed

1. INTRODUCTION

Elevators and escalators are common machines, which are designed to transport people and material from one floor to another safely and easily. In this paper the words “elevator” and “lift” are used to refer to the same machine. Both vertical and inclined elevators are studied for this paper. Moving walks are very similar to escalators. The difference is that moving walks do not have steps and they can also be designed for horizontal transportation. The safety regulations and design parameters are affected by the region where any of these three machines (elevator, escalator or moving walk) are intended to be used or where they are built. For example, American elevators may differ from European or Asian ones with regulations on the velocity gradients, such as acceleration or deceleration. It should also be noted that the liability aspects and legal repercussions associated with elevator, escalator and moving walks accidents vary on each continent.

On a daily basis, several billions of people around the world use previously mentioned machines. Elevators, escalators and moving walks create variable velocity gradients, but their effects on the human body are hardly studied. Different industry standards set different limit values for the machine design. By studying velocity gradients, safety and performance of elevators, escalators and moving walks can be improved.

As the magnitudes of the velocity gradients, such as acceleration or deceleration, with an elevator, an escalator or a moving walk are not so great, they do not have a great effect on human inner organs. However, the velocity gradients have an effect on the balance of a passenger. Because of these machines have potential threat of passenger falling, studying of human balance is important. Human balance in elevator applications requires studying on the effects of vertical velocity gradients. In addition to vertical direction, inclined elevators, escalators and moving walks require studying of horizontal directions as well. Human balance can be studied e.g. by using moveable platforms with varying velocity gradients. In addition, psychological phenomena (e.g. broken escalator) affecting human balance are taken into account in this study.

The purpose of this thesis is to study what effects the velocity gradients have on human body and what kind of legislation current elevator, escalator and moving walk standards and directives set for the industry. The main sources of this paper are engineering articles, most used elevator, escalator and moving walk standards and directives as well as elevator, escalator and moving walk related statistics. The thesis is completed as a literature review and thus study stages can be divided into four main parts. The first two are searching and analyzation of the literature material. Last two are reporting the results and generating development proposals.

2. BACKGROUND AND THEORY

The effects of velocity gradients are mostly studied on the fields, where the magnitudes of the acceleration or the deceleration are great, such as aeronautics. In these fields, velocity gradients might have an effect on human organs. As the magnitudes of acceleration and deceleration with elevator, escalator or moving walk applications are not as high, they do not have a significant effect on human organs, but they might have an effect on balance of a passenger. However, the issued industry has hardly studied the effects of velocity gradients. In this paper “vertical transportation” refers to all three types of the studied machines: elevators (vertical and inclined), escalators and moving walks (horizontal and inclined). By losing one’s balance with any of the machine might lead up to possible injury or even death. Lowering the magnitudes of acceleration and/or the deceleration to minimal is not desired either, as this would result to the impression of a slow machine performance and reduce people flow capacity.

This chapter focuses on opening the theory behind velocity gradients and the components of human balance. In addition, basics of different kind of elevators, escalators and moving walks are described in more detail.

2.1 Velocity gradients

The rate of change of speed or velocity in time is called acceleration, **a**. By using the SI-system, acceleration can be measured with m/s^2. Acceleration occurs either by having change in velocity or change in direction of a motion. There are multiple ways to calculate and measure accelerations. One of the basic calculations is the average acceleration, which gives an approximation of created linear acceleration. Average acceleration can be achieved by using Equation 1. (Young et al. 2008, p. 43−44)

$$\boldsymbol{a_{av}} = \frac{\Delta \boldsymbol{v}}{\Delta t} \tag{1}$$

, where $\Delta \boldsymbol{v}$ is the change in velocity over a period of time Δt.

Acceleration usually refers to speeding up the object. Deceleration on the other hand is the opposite phenomena for the acceleration as it represents the decrease in the speed or the velocity. Therefore, deceleration has the same features as acceleration does. As acceleration and deceleration usually only describe the magnitudes of velocity change, velocity gradients can be considered more informative. Velocity gradients inform how much and in which direction the increase or reduction of the velocity is taking place. (Young et al. 2008, p. 46)

The gradient of displacement with respect to time is velocity, the gradient of velocity with respect to time is acceleration and the gradient of acceleration with respect to time is called jerk, j. In other words, the acceleration is the second gradient of displacement and the third is jerk. Gradients with respect to time are presented with Equations 2−4. As the jerk is the rate change of acceleration, it is a vector measured with m/s^3, or in some cases, presented with standard gravity per seconds (g/s), where 1 g is approximately 9,81 m/s^2. With human transportation machines, such as escalators or trains, the jerk of the machine should be kept low in order to improve the ride quality and maintenance of balance. For example, the maximum jerk in vertical direction for standing train passenger with a hand hold in the United States of America (USA) is 2,94 m/s^3 or 0,3 g/s. (Federal Railroad Administration 1993; Al-Sharif 2012, p. 230) Typical elevator run has vertical jerk of 1,69 m/s^3 or 0,172 g/s (Gibson 1995, p. 65).

$$\boldsymbol{v} = \nabla\boldsymbol{d} = \frac{\partial\boldsymbol{d}}{\partial t} \tag{2}$$

$$\boldsymbol{a} = \nabla\boldsymbol{v} = \nabla\nabla\boldsymbol{d} = \frac{\partial\boldsymbol{v}}{\partial t} \tag{3}$$

$$\boldsymbol{j} = \nabla\boldsymbol{a} = \nabla\nabla\boldsymbol{v} = \nabla\nabla\nabla\boldsymbol{d} = \frac{\partial\boldsymbol{a}}{\partial t} \tag{4}$$

, where d is the displacement of the target object and $\nabla\boldsymbol{d}$ is the gradient of displacement with respect to time.

For this study, the velocity gradient always indicates a derivative over time as represented by Equations 2−4. Velocity gradients are used as they give more information on the direction of the velocity variation (in respect to xyz-coordinates). In addition, the correlation with velocity gradients and jerk is more easily accomplished.

2.2 Human balance

According to Pollock et al. (2000), there is not a single universally accepted definition of the human balance. Balance can be described with mechanical definitions as an equilibrium or with clinical definitions as a postural control. Equilibrium is usually used to define the state of loads acting on an object, where sum of forces or moments are zero and thus object is in equilibrium. Postural control on the other hand is an act of achieving, maintaining or restoring the state of balance during any activity, such as muscle activity or a posture. (Pollock et al. 2000, p. 1) Human postural control requires information from various sources, such as semicircular canals, which are located inside the inner ear. The semicircular canals are filled with endolymph fluid, nerve endings and receptors, which resemble hair cells. When the body position is changed e.g. due to change in magnitude and direction of the head acceleration, the fluid moves the sensory receptors. As the receptors are triggered, they create a nerve impulse to the brain and the cerebellum, which can process the information for the postural control and the muscles. (Martini & Ober 2006, p. 287; Previc & Ercoline 2000, p. 49−50)

Humans can move in three dimensions, which are fore-aft, lateral and vertical by using self-motion movements. Human self-motion perception uses information from the visual, auditory, vestibular, and somatosensory systems with central processing of the brain to understand how various sources individually affect physical motion. (Nesti et al. 2014, p. 303−304) As there are multiple inputs for postural control, various of disturbances can have an effect on human balance. For example, short duration of whole body vibration of 1 m/s^2 with range of 2−20 Hz can result e.g. in disorder, nausea or loss of balance (Klosterhalfen et al. 2008; Ramos et al. 2012). Especially the frequency of two hertz should be avoided, as it is the natural frequency of a typical erect human (Browning 1974, p. 9−10). Long-term whole body vibration is listed as a health risk, as it can cause injuries to the lumbar spine and nervous system (ISO 2631-1 1997, [7.1]). Only the minimal magnitudes of velocity gradients should be allowed at head level to avoid adverse reactions. However, in small amounts and muscle directed, not at head level, the vibration can improve balance due to growth of muscle and bone strength. (Pollock et al. 2010) In addition to external disturbances, internal changes, such as age, are crucial for the balance. When human is born, one cannot stand upright, as muscles of the child and postural control have not yet been grown and developed. Thus, the balance is a learned skill. However, as the human grows old, their muscles, cognitive and sensory skills start to weaken, which in process weakens balance as well.

2.2.1 Postural control

As Newtonian Mechanics state; an inanimate system is in balance when its center of gravity (CoG) and the base of support (BoS) are lined up with the line of gravity and no movement occurs. System is unbalanced when the line of gravity is off from the BoS. Unbalanced system starts to move or fall until it reaches a new BoS and then the balance is achieved again. However, human body has control over its balance while inanimate object does not. When the line of gravity of the human body falls out with the BoS, the human body has an inherent ability to sense the threat to stability and to prevent the falling by using muscles to counteract the force of gravity. With vertebrate animals the vestibular apparatus, which is located inside the inner ear, is used to sense and maintain the balance. (Hine et al. 2016; Pollock et al. 2000, p. 2)

For animals, such as humans, are not inanimate objects, they are required to move in order for them to stay alive. While doing so, they change their CoG and BoS almost constantly. In addition, while moving, the balance must be kept on going to enable the continuation of the movement and to prevent falling from occurring. Here proprioception and neuromuscular feedback plays an important role for postural control (Lephart et al. 1998). In comparison to the four-legged animals, humans stand upright with two legs. Because of standing on two feet, the human body has a relatively high CoG and small BoS in comparison to four-legged animals. With average human, CoG is approximately located in line with the front of the knee and at 54 % of their height (Powell & Palacin 2015, p. 96). By having a high CoG and small BoS creates more complications with the maintenance of stability, as the distance with line of gravity to BoS should be relatively small. (Pollock et al. 2000, p. 2)

Control of the balance can be identified with three broad classes of human activity. These three classes are achieving, maintaining and restoring the state of balance. The identifications are following:

1. Natural and desired movement such as walking or running,
2. Maintaining current posture such as standing or sitting,
3. Reaction to an external interference such as slip or trip.

After the postural control is identified, it can be divided into three strategies. Strategies can be divided as a predictive, a reactive or a combination of the previous two. Predictive postural control might include increased muscle activity as the person is preparing for possible and thus predicted balance disturbance. For example, a situation where a person notices and crosses a slippery ice field. Reactive postural control on the other hand involves unpredicted disturbance such as unnoticeable ice on the road, which is then followed by a muscular response. The last one includes both of these strategies, where the human is preparing for possible disturbance, but is still surprised with the disturbance. (Pollock et al. 2000, p. 2−3) Current posture is maintained by stimulating enough motor units to produce muscle tension needed to maintain the posture and balance. The tension in a skeletal muscle is called muscle tone. Muscle tone helps to prevent sudden changes in the position of bones and joints. Resting the muscle tone stabilizes the positions of joints and bones. On the other hand, if the balance is lost, the elastic nature of muscles also lets skeletal muscles to act as shock absorbers in case of sudden impact. (Martini & Ober 2006)

The response to the postural control strategies are either fixed-support or change in support. In the first case, the BoS remains constant, but the line of gravity is moved. For example, when one is about to lose one’s balance, they might rock their hips or ankles to maintain the balance. Sudden horizontal transition of a standing position is corrected with either ankles or hips. With case of the change in support, the BoS is relocated to intersect with the line of gravity. For example, when one takes an extra step or tries to grasp a railing with a hand. Postural control identifications and strategies are assembled into Figure 1. (Pollock et al. 2000, p. 2−5)

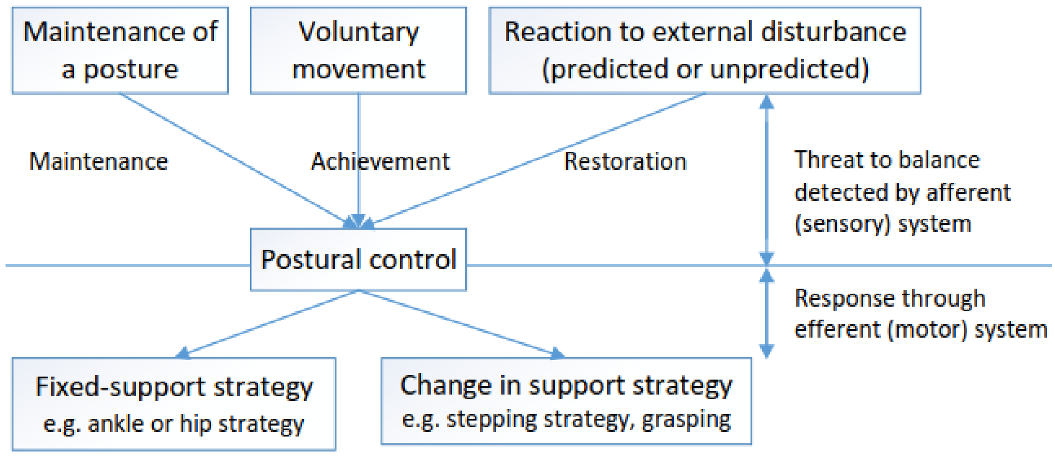

Figure 1: Postural control strategies (Pollock et al. 2000, p. 4)

Postural control strategies are mostly reflex-like responses, which are activated automatically with the sensor stimulus. Balance and postural control are linked with the central nervous system (CNS), which also links up the brain and the spinal cord to integrate information and control the entire body (MNT 2016). As the postural control is part of the CNS, postural control can be considered a motor skill learned by the CNS. This way, likewise to any other motor skill, also postural strategies can be enhanced by training and practice, such as learning to skate. (Pollock et al. 2000, p. 3)

2.2.2 Effect of age to the postural control

The postural control is a motor skill that can be enhanced by training. Unfortunately, motor skills can also weaken if they are not practiced. In addition, after a certain age human body functions start to grow weaker, which affects postural control as well. Lower limb muscles of older adults are not activating as strongly as with young adults. In addition, older muscles have a delay of 10–20 ms when compared with young adults. The changes in dynamic balance can already be found with people of ages 35 to 40 years, where an older person is relying more on the hip movement over ankle movement strategy. (Okada et al. 2001; Tokuno et al. 2010, p. 109) Postural control weakening can happen if any of cognitive, sensory or motor impairment occurs (Pollock et al. 2000, p. 3).

Influence of age on balance and postural control is a widely studied subject. The effects of age have been studied e.g. by studying a participant on a moveable platform. For example, Bugnariu and Sveistrup (2006), Tokuno et al. (2010) as well as Okada et al. (2001) studied postural control differences between young and old adults by using randomly selected healthy participants and moveable platforms. In all of the studies, the young subjects were around their twenties and the older subjects around their seventies. Participants with Bugnariu and Sveistrup as well as Tokuno were an equal number of men and women in each group, but Okada et al. only used men subjects. Each adult stood eyes open, barefoot, erect and with feet around shoulder width apart on the moveable platform.

The platform used by Bugnariu and Sveistrup could be moved with a sinusoidal movement, with 20 cm peak-to-peak values and with variable frequencies, that goes up to 0,61 Hz. They studied both unpredictable and predicable disturbances. The study by Okada et al. used similar platform, but the moveable distance was 15 mm and only the unpredictable changes were studied. In addition, the peak acceleration of moveable platform was set to be 0,78 m/s^2 and peak deceleration 0,10 m/s^2. Tokuno et al. used a long platform capable of creating short, 6 cm, and long, 46 cm, translation with velocity gradients varying with 1,20 m/s^2 and 2,30 m/s^2. (Bugnariu & Sveistrup 2006, p. 73; Okada et al. 2001, p. 11; Tokuno et al. 2010, p. 110)

2.3 Elevators

An elevator is a machine, which is designed to transport people and material from one floor to another through a vertical well serving two or more landing levels. The first modern elevators were already used in the 19th century. Initially the elevator design preferred to use hydraulic power, but by the 1880s, the electrical solutions became more common and finally took over the elevator markets. (Curl & Wilson 2015) However, the hydraulic elevator solutions are not totally forgotten as they can be used for example with the low-rise buildings (Di Tallo 2014).

Elevators are built for different customer requirements and therefore elevator types, features and component solutions vary. The elevator types are decided according to hoist mechanism, building height, building type, elevator location and special uses. The most common hoist mechanisms are either hydraulic or electric traction systems. Building heights are divided into three groups: low-rise buildings with 1−3 floors, mid-rise buildings with 4−11 floors and high-rise buildings with more than 12 floors. Building types are either hospital, residential, agricultural, industrial, commercial or parking buildings. Elevator location inside the building can be for example in the center of the building or on the side of the building. Lastly, special use elevators are designed for certain purposes. Examples of special elevators are firefighter elevators and elevators designed to ease traveling of disabled passengers. (Wit 2007, p. 3−6; Strakosch & Caporale 2010, p. 31, 324)

The assessment for an elevator performance includes multiple factors. Some of these factors are the ride quality (measured by sound and vibrations), energy consumption, door opening/closing time, traffic system efficiency, reliability, requirement for the maintenance and the safety. The safety factor has the most direct effect on the elevator performance, such as limiting the top acceleration or deceleration of the machine. However, the safety can be kept high by improving other factors, such as reliability and requirement for maintenance. (Park & Yang 2010, p. 2 371)

The modern elevator consists of multiple sections and components. In addition to the elevator type selection, national laws and standardization systems of different countries create their own demands for the component selection. Main sections of a modern elevator include a car where people and material can be transported, well where the car can move only in vertical directions, support and guidance railings, lift machinery, such as electric motor, car buffers at the top and the bottom of the well and finally the safety equipment, such as overspeed protection. (Di Tallo 2014) Most of the elevator components and their locations of gearless and machine-room-less (MRL) elevators can be seen in Figure 2.

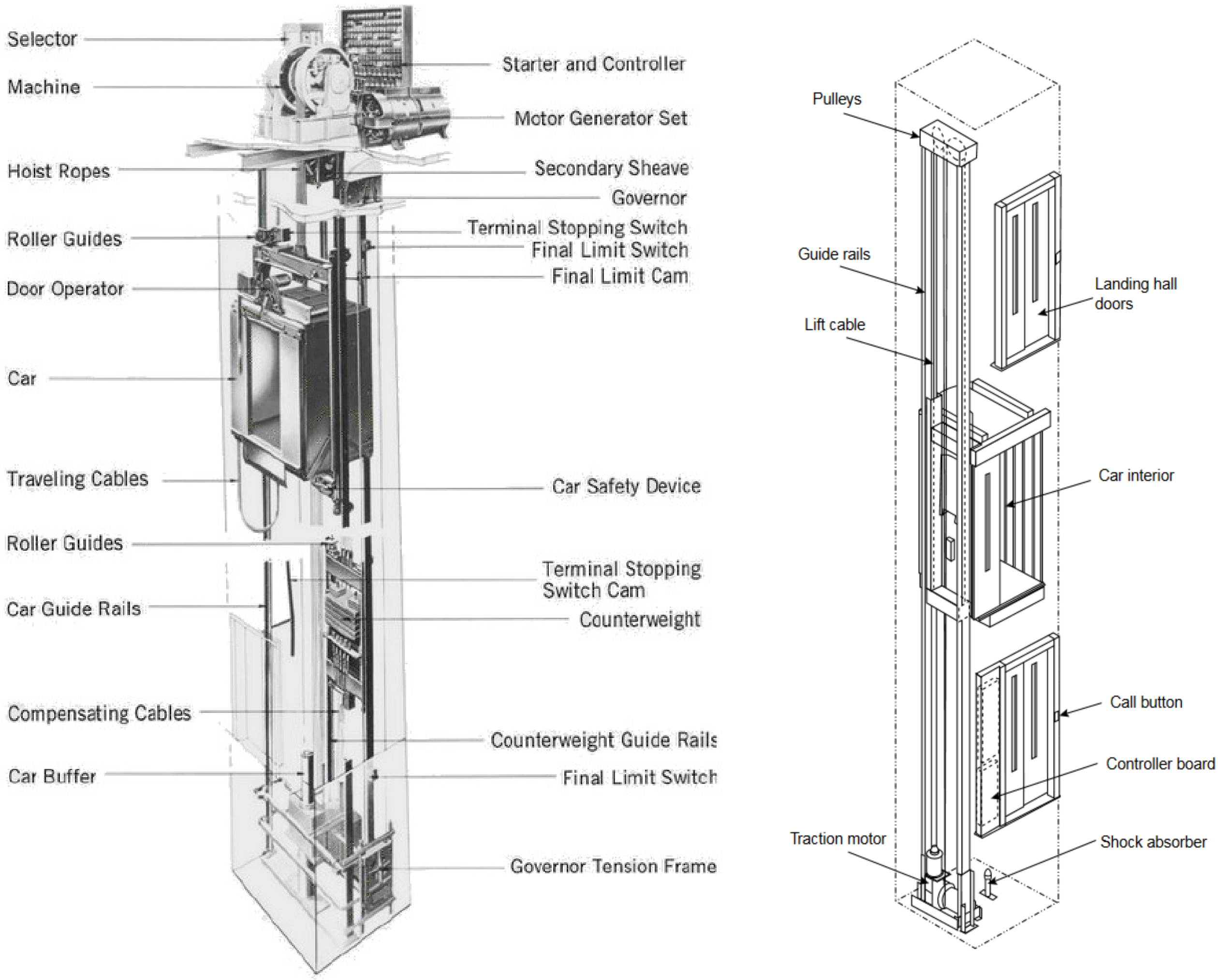

Figure 2: Components of a) gearless electric elevator on left (Strakosch & Caporale 2010, p. 6) b) MRL elevator on right (Mitsubishi electric 1999, p. 20)

An electric traction elevator utilizes electric motor, which is connected to a grooved drive sheave. A hoist rope passes over the drive sheave and then conveys rotating movement of the motor into a vertical movement of the car. The vertical angle of an elevator well must be less than 15° for the machine to be called an elevator. If the angle is more than 15°, the machine is called an inclined elevator. In a typical counterweight elevator, one end of the hoist rope is connected to the elevator car and the other one at the end of a counterweight so that the motor does not need to lift the full weight of the car and its passengers. (Di Tallo 2014)

The velocity gradients with vertical elevators occur either by initiating the transportation and thus encountering acceleration or by initiating the braking and thus encountering deceleration. Vertical elevators naturally only encounter velocity gradients in up- or downward directions if velocity gradients from vibration are neglected. Velocity gradients occurring from vibration are affecting in various directions. In addition to vertical velocity gradients, inclined elevators encounter horizontal velocity gradients, which can be considered more hazardous for passenger balance. Especially the emergency braking of either elevator types can result in a potential hazard with velocity gradients. Emergency braking can be of electrical or mechanical stop. Electrical stop can result e.g. from an actuation of electrical protective device which creates a braking torque with the drive unit, e.g. motor. Mechanical stop on the other hand results namely from the machinery brake, by safety gear or by car exceeding the travel path and thus hitting the buffers. (Gibson 1995, p. 64)

2.3.1 Geared traction, gearless traction and MRL elevators

In addition to elevator type segmentation into a hydraulic and an electric elevator, the electric elevator can be divided by the traction system and by the machine room. From traction systems, there are gearless traction and geared traction systems. From machine rooms, there are elevators with and without machines rooms. Speed is the main difference between gearless and geared traction elevators. Therefore, high-rise buildings generally use gearless traction elevators. However, the geared traction elevators can use smaller motor to turn the sheave, as the gear reduction requires less power. Gearless traction elevators can attain velocities from 2,00 to 10,0 m/s, geared traction systems only from 0,15 to 2,50 m/s and lastly the hydraulic elevators do not usually exceed speed of 1,00 m/s. (Otis 2016; Strakosch & Caporale 2010, p. 10−13, 17)

Gearless traction and MRL elevator components were shown in Figure 2. Geared traction elevators have mostly the same components as the gearless traction elevators have, but there are minor differences with the component sizes and locations. For example, as the top floor components of gearless elevator are slightly bigger than with geared elevator, the location of overspeed governor and secondary sheave differs. Nevertheless, the components and their locations are mostly the same with both geared and gearless elevators. (Strakosch & Caporale 2010, p. 6−7)

In the year of 1996, the introduction of the first MRL elevator revolutionized the design of elevators. The idea behind the MRL system is to remove the machine room from the top of the elevator well altogether by mounting the machinery within the hoistway of an elevator well. By removing machine room, less building space is required. This can also be seen in Figure 2. Machinery of MRL elevator can be mounted within the hoistway, because of more compact component design. Some companies are saving space by creating smaller sheave and other companies by creating more compact hoisting motors for MRL elevators when compared with traditional geared and gearless traction elevators.

In addition, other parts of machinery were redesigned as well. Modern MRL elevators are designed for buildings from two to thirty floors. (KONE 2017; Otis 2016)

2.3.2 High-rise and high-speed elevators

According to Strakosch & Caporale (2010), buildings with more than twelve floors are called high-rise buildings. The height of high-rise building is averagely limited around 300 and 400 meters in Europe. The limitations vary strongly depending on the nation and the city, as there are towers with the heights of more than 800 meters located in the Middle East. The tallest building in the world, Burj Kharlifa, is located in Dubai and has the height of 828 meters (Skyscraper center 2017). By rising the height of a building over twelve floors creates new challenges with the carrying capacity of the soil, construction regulations and environmental aspects, such as wind and seismic factors as well as with elevator design aspects, such as the rope system. By developing the high-rise elevators, transporting people is no longer one of the most significant limit factor for the high-rise buildings. In the modern world, high-rise elevators are required to be faster than standard elevators in order for passenger to travel longer vertical distances, but in acceptable time. (Wit 2007, p. 2−3)

The elevator planning for a high-rise building is essential, for the elevator core is usually the support structure for the entire building. Therefore, traffic flow specialists should be involved with the construction orientation phase of the high-rise building. The specialist should at least conduct the capacity and the waiting time analysis for the construction design. These analyses depend on the function of building, the probable population and peak demand during rush hours. There are no standards for acceptable waiting times and thus these values should be determined on project-by-project basis. In the analyses, the number of elevators per group, nominal elevator speed and acceleration should be taken into consideration. (Wit 2007, p. 3−5)

When building reaches a certain height, it is reasonable to split the building into two or more elevator system zones (e.g. low-rise/high-rise). By splitting the zones, there are more options to choose the access managing system. For example, the passenger traveling to top floors must first travel through a shuttle elevator and then change into a local elevator on the sky lobby. With multiple zones, the elevator group control system should be aided with an artificial intelligence, which understands traffic flow pattern recognition and adaptation to flow management through self-learning. In comparison to low-rise buildings, the margins of high-rise buildings are tight. There is hardly ever opportunity to make subsequent changes after construction is initiated. (Wit 2007, p. 6−8)

2.3.3 Inclined and horizontal elevators

Elevators with inclined angles of between 15° and 75° are called inclined elevators. The inclined angle is in relation to the horizontal direction. Inclined elevators are specially designed for certain buildings such as metro stations, tunnels or hillsides. The idea behind an inclined elevator is to offer accessibility to hard-to-access-areas such as hills. Inclined elevators can be partially enclosed or totally enclosed depending e.g. on the requirements against risk of fire spreading. Inclined elevators are not too common in buildings for they take more room than common vertical elevators does. One of the most famous inclined elevators are located inside the Eiffel tower. (EN 81-22 2014, p. 10, 22; TourEiffel 2017)

The basics, such as components, of inclined and vertical elevators are almost the same. However, the incline angle of elevator well creates new challenges when compared with vertical elevator design, maintenance and installation. For example, with the design of buffers, the overspeed protection or elevator machinery systems the hazards of the horizontal velocity gradients must be taken into consideration. (EN 81-22 2014, p. 6)

Currently, the horizontal elevators are not practical solution for horizontal transportation, for only prototypes exist. However, they might become more common over time. Strakosch and Caporale describe the horizontal elevator to be similar system as a monorail: the horizontal elevator car would be suspended from rails and driven with a traction machines that are similar to normal elevator traction machines. Horizontal elevators could be used similarly like horizontal moving walks in busy locations, such as airport terminals and shopping malls. Horizontal elevator could even work as a bridge over a busy street. Currently there are only a handful of implemented horizontal elevators in the world. One of them can be found from the Disney World. (Strakosch & Caporale 2010, p. 578−580) More recently, ThyssenKrupp have been creating a new elevator design called MULTI. New design does not require ropes as it utilizes linear motors that allow elevator cars to move in both, vertical and horizontal, directions. Switching from vertical to horizontal movement can be achieved with magnetic levitation similar to Transrapid trains. With the new system, several of elevator cars are moving in a single continuous loop and thus elevator doors should open every 15−30 seconds. The first MULTI was unveiled in June 2017 for the East Side Tower, Berlin. (OVG 2017; ThyssenKrupp 2017)

2.4 Escalators

Escalators, or moving stairways, became popular after the 1950s. As only the stair and handrail parts of an escalator are moving in one direction, several people can be transported simultaneously and continuously when compared with the elevator usage. However, the escalators are moving only from certain floor to one on top or at the bottom. Therefore, to reach multiple levels or even multiple directions with escalators, multiple escalators are required. Escalators are mostly used in areas where large flows of people are required to move in a vertical direction. Example of these areas are shopping malls, stores and transportation terminals. Usually the escalators and the elevators are used in combination to provide efficient flow for all range of people from young and healthy to older adults and handicapped people. (Strakosch & Caporale 2010, p. 20)

The elevator only moves vertically up and down, but the escalator also has one-way horizontal movement as well. Horizontal movement creates new challenges e.g. with human balance when compared with the elevator design and usage. Human balance issue comes in order especially if passenger is not expecting the acceleration or the deceleration in the horizontal direction. Reaction to the vertical movement is easier because of human body structure. In addition, the material transportation has their own challenges with escalators, as the escalators are mostly designed for personnel transportation only. Inclined moving walks are more practical for the material transportation as the conveyor belt of an inclined moving walk remains an inclined plane. To make escalators safer for the passengers, handrails are required. Matching acceleration, speed and position of the steps and the handrails is one of the most crucial requirements with escalators. (Strakosch & Caporale 2010, p. 233)

An escalator consists of two machinery spaces, a conveyor system and balustrades. Machine rooms are part of the truss and they are hidden underneath of the landings of the escalator. Machine rooms contain electric motors with sprockets, controllers, brakes, drive unit and safety equipment. Most of the public service escalators contain both operational brake and auxiliary brake. Operational brake works on the high-speed shaft as auxiliary brake respectively works on low speed shaft. Balustrade and conveyor system includes steps, moving handrails and deck boarding components. Most of the escalator components and their locations can be seen in Figure 3. (Al-Sharif 2004, p. 1; Mitsubishi electric 2017; KONE Spares 2016)

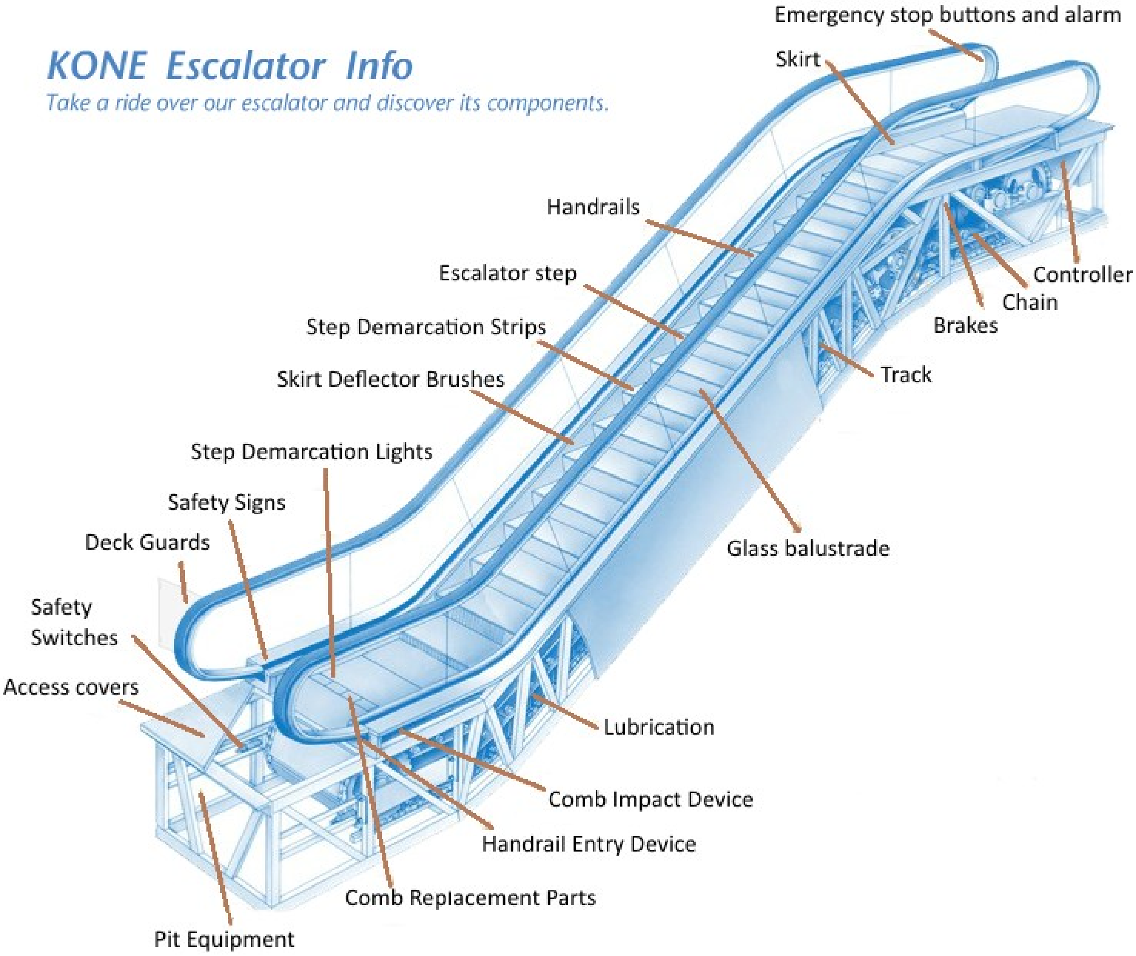

Figure 3: Escalator components (KONE Spares 2016)

In normal use, escalators are running constantly by using unidirectional conveyors. Conveyors are usually moving at constant speed, unless the system goes to or wakes from the sleep mode or the emergency brakes are activated. The movement is created e.g. with AC induction motors so that the incline speed is around 0,50−0,75 m/s at around 30° angle. The maximum elevation depends on the standard family, e.g. EN 115-1 and Japan limits the maximum elevation to six meters. Similarly, the limitation for incline angle and velocity of escalator or inclined moving walks differs slightly depending on the continent and the used standardization. The incline velocity of European and Asian machines can be up to 0,75 m/s when the incline angle is under 30°. These standards however allow incline angle up to 35°, but then the velocity must be kept under 0,50 m/s. The maximum incline angle in America is 30° and the velocity must be kept under 0,50 m/s. (ISO/TR 14799-2 2015, p. 13, 19; Strakosch & Caporale 2010, p. 238, 240)

Velocity gradients of an escalator or a moving walk in relation to the passenger occur when the passenger enters on or departs from conveyor system. In addition, the activation of an emergency brake creates the occurrence of velocity gradients. In the normal use, passengers are not allowed to enter escalator before system is running. Therefore, during the normal use, entering or departing from the escalator are the most crucial moments to affect the balance of a passenger. The magnitude of a velocity gradient is affected by the magnitude of velocity the passenger is moving just before entering. If the velocity of entering passenger and the velocity of the conveyor belt are close, relative small magnitude of velocity gradient occurs. In the case of emergency, system is stopped. Braking system must stop within acceptable distance and without stopping too harshly to avoid passenger falls. The probability of passenger fall is at its greatest when escalator is moving in downward direction and emergency brakes are activated. (Al-Sharif 2007)

In comparison to vertical elevators, escalators transport passenger both in vertical and in horizontal directions, which can affect the balance of a passenger. The escalators can be considered potentially more dangerous than elevators, as there is a possibility for a passenger to fall and hit sharp step edges. In addition, the passenger could fall down the escalator stairs and thus endanger other passengers with a domino (aka. avalanche) effect.

2.5 Moving walks

Similarly to escalators, moving walks are either designed to transport people and material from one floor to another or only in the horizontal direction. Moving walks that go from one floor to another are called inclined moving walks and the rest are called horizontal moving walks. Inclined moving walks are very similar to escalators and thus usually share the same standards and similar components. The difference between an inclined moving walk and an escalator is the conveyor system: escalator's conveyor system turns conveyor belt partly into levelled steps for passengers to stand on. Inclined moving walk's conveyor belt however remains as an inclined plane. The steps of an escalator offer a more practical and natural position for a passenger to stand on, which enhances balance maintenance. On the other hand, a wheelchair or a food cart cannot access the escalator. Food carts can access some of the inclined moving walks if their tires can automatically be locked onto the moving walk. A heavy food cart without locked tires could be difficult to hold on and thus be very dangerous for passengers under the cart. (Strakosch & Caporale 2010, p. 233−239)

Horizontal moving walks are used to guide, ease and fasten the movement in the crowded areas such as airports and metros. These machines are unique in comparison to escalators, elevators and inclined moving walks as horizontal moving walks transport people and material only in the horizontal direction. Horizontal moving walks are designed for distances from 60 to 600 meters (Strakosch & Caporale 2010, p. 233). Transportation beyond 600 meters is more suitable for vehicles such as buses or trams. Despite the name, horizontal moving walks are allowed to have a small ascension or descent. Similarly to escalators, the maximum velocity and horizontal angle of the machine depends on the used standard. American and European standards allow machines to have the maximum angle of 12° and Japanese go up 15°. The velocity restrictions vary between 0,75−0,9 m/s depending on the horizontal angle. (ISO/TR 14799-2 2015, p. 13, 19)

In addition to traditional single-speed moving walks, there are accelerating moving walks as well. The idea behind the accelerating moving walk is to fasten the passenger movement through the walkway that is faster than traditional moving walk. At the entrance, the passenger enters on a conveyor belt that accelerates the passenger to high speed. Just before exiting the moving walk, conveyor belt decelerates to walking speed for passenger to exit safely. Currently, these machines are not widely used, as there are two major problems. First problem issues the mechanical problem of synchronization of handrail and steps. This would require a stretchable handrail, which does not exist or a single speed handrails which would lead to desynchronization of handrails with the conveyor belt. However, ThyssenKrupp's accelerating moving walk, ACCEL, solved this issue by using overlapping pallets, which expand three times their original size during the acceleration. Respectively, the pallets are overlapping during the deceleration. Both handrails and standing pallets use the same idea and thus desynchronization of handrails and standing pallets can be avoided. (Financial Times 2014; Strakosch & Caporale 2010, p. 571−572)

A second problem of accelerating moving walk issues passengers. People tend to move in groups or stack up during rush hours. If passengers do not leave a safe distance from one to another, the deceleration phase of accelerating moving walk might result in bumping among fellow passengers. In addition, some passengers tend to walk, as others tend to stand on the conveyor belt, which also results in similar safety problem. Even though accelerating moving walks are not yet widely used, ASME A17.1 offers some safety regulations for accelerating moving walks. (Strakosch & Caporale 2010, p. 571−572)

2.6 Hazards related to the velocity gradients in vertical transportation

The elevator, escalator and moving walk standards are designed to enhance the product safety for example by listing the most common elevator, escalator and moving walk related hazards. However, elevator, escalator and moving walk related accidents still occur each year. In addition, according to Park and Yang (2010), the same sorts of accidents frequently occur in the vertical transportation industry even though these hazards are listed in the standards. The outcome varies from narrow escapes to lethal cases, which occur to both everyday passengers and the maintenance personnel. The number of elevators are increasing each year, which also is followed by an increasing number of accidents with the machines. For example, South Korea has the quantity of 360 000 working elevators and is ranked ninth in the world for the most elevators. The number of people rescued from elevator accidents had reached the second-highest level of traffic accidents in South Korea, as there were 90 and 97 annual accidents within the years of 2006 and 2007, respectively. Statistics included elevator, escalators and moving walks. (Park & Yang 2010, p. 2 367) In comparison to South Korea, in 2007 Finland had

50 000 working elevators. Between the years of 2006 and 2007, the number for annual accidents in vertical transportation industry were only two and four, respectively. There were no lethal accidents during that time in Finland. Finnish statistics included accident reports from elevators, escalators and moving walks. (Tukes 2008, p. 55)

Greece has the highest number of installed elevators per population in the Europe, as there are approximately 450 000 operating elevators. In the years of 2006 and 2007, Greece reported one and two elevator accidents, respectively. However, the number rocketed up to eight annual accidents for the following two years. Statistics included elevator accidents only. (Zarikas et al. 2013, p. 98)

The higher quantity of elevator accidents in relation to escalator accidents can be reasoned by the overall quantity of elevators in relation to escalators. However, by comparing accident statistics from injuries per machine perspective, the situation changes. For example, between the years of 2009 and 2010 Metropolitan Airport in the USA had 316 fall-related incident reports from which 44 % were resulted from the escalators and only 2 % from the elevators (Howland et al. 2012, p. 134). In the year of 2007, the United States alone had 660 000 elevators and 33 000 escalators from where the injuries per escalator were more than 20 times greater than with elevators (O'Neil et al. 2008, p. 531). In addition, the seriousness of the injuries depends on the machine, e.g. in respect for the height of a fall or impact surface (flat floor of elevator vs. sharp stair edge of escalator). However, the seriousness is always case depended. Between the years of 2011 and 2015, the number for annual vertical transportation accidents in Finland have been between six and nine cases. These numbers include statistics from accidents to maintenance and installation personnel as well as accidents to passengers. Within these five years, there have been only two cases of death, from which the latest one occurred with an escalator. (Tukes 2016, p. 20−21)

Standards categorize the velocity gradients as potential hazards during the operation of elevators, escalators and moving walks. Risks with velocity gradients mostly focus on the loss of balance and possibility to fall. Velocity gradients can be either anticipated or sudden, from where the latter are more dangerous. Anticipated velocity gradients with elevators are e.g. acceleration after the doors are closed or deceleration by following the floor indicator. Sudden velocity gradients can result e.g. from vibration or an emergency stop. However, usually the magnitudes of velocity gradients which are resulted from vibration are low. In normal use, escalators are running constantly and therefore stopping of conveyor system might feel sudden. Consequently, the number of passengers who do not hold on the railing, might be carrying a bag or have weak musculoskeletal structure increases the possibility of a fall during stopping. According to Al-Sharif, approximately 2,5 % of escalator stops result in a passenger fall incident. The severity of a falling accident depends on the height of the fall, on the landing position and on the surface. (Al-Sharif 2004; Gibson 1995, p. 64; Richter et al. 1996, p. 654)

3. MACHINE DESIGN LEGISLATIONS AND STANDARDS

Elevators, escalators and inclined moving walks are used in great heights as well as by great number of people on daily basis. Therefore, safety must be taken into account in each step from design to dismantling of those machines. Guidelines for the safe design, installation and maintenance comes from national regulations and standards. In addition, standards, directives and companies' internal documents are used to define good engineering practices. These are used in order to achieve appropriate, well-documented and safe solutions that fulfill regulations and user requirements (Niknammoghadam 2015, p. 16, 19). Every elevator, escalator or moving walk must be in conformity with the national regulations to be put into service and remain in operation in its life time.

Each country has its own law and legal system. Some countries are part of political or economic unions, such as EU, and their national regulations are aligned with decisions and regulations agreed at the union level. For example, the EU sets regulations and decisions, which directly affect laws in its member states. EU also sets directives, which do not directly affect law of the member state, but give instructions for national legislators of the member state to transpose the technical and legal requirements agreed on the EU level into the national laws. (EUR-Lex 2015; EUR-Lex 2017) On the other hand, standard is a technical documentation that sets the norm and the requirements to ensure materials, products, processes and services are right for their purpose (ISO 2017b). Standards are voluntary on application, however they can be taken as a part of country's legal system to ensure safe and reliable design, installation, maintenance and usage of the technical application.

Elevator, escalator and moving walk standards set the safety requirements for design, construction, maintenance and other aspects in the life time of those equipment. Each country uses standards as a part of their legislative system, which is why it is important to know the technical requirements of the standards relevant to the specific machine. If the machine does not follow the regulatory requirements in any given country, it cannot be put into operation in that country. Therefore, non-conformity to national regulations is the strongest barrier for entering market in any country. Acceptable limits of velocity gradient relevant to elevator, escalator and moving walk are mostly described in the standards.

In addition to standards, regulations may also address the limits of velocity gradients. For example, European directive 2006/42/EC and 2014/33/EU, set regulations for elevators, escalators and moving walks. However, the requirements in the directives define the safety objective to be met without providing a technical solution or specific values. Based on the EU regulatory system, those directives point to the harmonized (recognized by the EU legislator) standards to provide one means of fulfilling the regulatory requirements. For example, Machinery Directive 2006/42/EC in its Annex I section 6.3.1 demands that acceleration or deceleration of escalators and moving walks does not endanger passenger (EUR-Lex 2006; Fraser 2010, p. 322−323). In addition, Lifts directive 2014/33/EU in its Annex I section 3.3 obliges that any safety device must not cause deceleration, which would be harmful to user of the elevator (EUR-Lex 2014). Nevertheless, velocity gradient limit values are not offered. Standards, such as EN 81-20 for elevators, or EN 115-1 for escalators and moving walks describe exact values. Applying those standards provides one means of fulfilling the requirements of 2014/33/EU and 2006/42/EC directives.

Another example is the regulatory system in the USA. Vertical transportation standard ASME A17.1: 2016 Safety Code, sets the limit speed for escalators at 0,50 m/s and maximum deceleration of 0,91 m/s^2 in the downwards direction (ASME A17.1 2016, [6.1.4.1.1] & [6.1.5.3.1]). When the A17.1 standard is adopted by an Authorities Having Jurisdiction, the requirement of the standard becomes a regulatory requirement within that jurisdiction. As the set of standards address the life cycle of the elevators, escalators or moving walks, those standards should be known and applied by persons responsible for design, engineering and manufacture, installation, operation, testing, maintenance, alteration and repair, inspection, administration, insurance and by emergency personal (ASME 2016b; CEN 2016a).

There are some variations in the limit values amongst national standards and therefore it is hard (and sometimes not even possible) to follow all of limitations and instructions from the best-known standards in one single design for elevators or escalators. For example, some of the Russian high-rise subway stations use escalators with the speeds of 1,01 m/s, which is almost twice the speed set by ASME A17.1 (Strakosch & Caporale 2010, p. 239).

3.1 Elevator standards

Considering the technical differences among the regional and national standards, elevator design follows safety regulations from specific area where the elevator is to be installed. In Europe, European Standard EN 81-20: “Safety rules for construction and installation of lifts” describes most of the elevator design safety guidelines and parameters. USA follows American Society of Mechanical Engineering (ASME) A17.1, which describes “Safety Code for Elevators and Escalators”. Standards in other countries are generally based on EN 81-1 (EN 81-20) standard with some national modifications. Several ISO technical reports are comparing standards in order to enhance standard development and harmonization of technical requirements of the national standards. One of these technical reports for elevator standards is called ISO/TR 11701. (ISO/TR 11071-1 2004, p. vi)

The purpose of all vertical transportation safety standards are the same: to address and mitigate related risks by providing prescriptive technical requirements for elevators, escalators and moving walks. Elevator standards set requirements e.g. for velocity gradients, such as maximal limit values for deceleration (aka. retardation), which should not be exceeded. The limit values are normally set for both normal use and emergency cases. The standards are required to be revised over time as new solutions and technical applications are introduced. (ISO/TR 11071-1 2004, p. 21, 23)

3.1.1 European standard (EN 81)

European Committee for Standardization (CEN) is a collaboration among 33 CEN Member countries through their National Standardization Organizations. CEN produces standards and other reference documents used by the industries, consumers, small and medium-sized enterprises and the European legislators. (CEN 2016b) In addition to reference documents, CEN produces safety standards for elevators, escalators and moving walks known as EN 81 series and EN 115 series.

Based on the machine types, what is being transported by machine and the machine environment, the elevator standard EN 81 is divided into multiple volumes. Elevator types are either electric, hydraulic or inclined elevators, elevator transports either people or material and environments are either upcoming or already existing buildings. In total, there are more than twenty parts for the EN 81 standard. EN 81-20 includes both electrical and hydraulic elevators. As electric elevators are the most common elevators, this paper will mostly study and refer to requirements for the electric elevators and their specifications.

EN 81 standard is not updated within a set interval. Revisions are made when required in order to keep the design current and safe in line with continuously developing technology level. EN 81-20 and EN 81-50, have taken over old EN 81-1 and EN 81-2 from September 2017. EN 81-20 sets safety requirements for elevators. EN 81-50 sets the requirements for design, calculations, tests and examination of elevator components. (KONE 2015)

Inclined elevators have their own volume known as EN 81-22 “Electric passenger and goods passenger lifts with inclined travel path”. This standard includes safety rules for the construction and installation of elevators transporting people and material with inclined elevator wells. The standard can be used for example to address the risks related to installation, operation, maintenance, inspection or emergency operation. One of the identified and considered risk is the horizontal component of deceleration in the event of stopping the car. (EN 81-22 2014, p. 6)

3.1.2 American Society of Mechanical Engineering (ASME A17)

As Europeans use EN, American areas mostly utilize standards from American Society of Mechanical Engineering. ASME is a non-profit organization that enables collaboration across all engineering fields in order to create globally standardized solutions. ASME has over 130 000 members from which approximately 2/3 are students. These members are divided into 150 countries. (ASME 2016a)

ASME's elevator, escalator and moving walk standards are the A17 series of standards. The elevator standards include both vertical and inclined elevators. Likewise to EN 81 and EN 115, A17 standard is divided into multiple volumes to make the standard more easy to understand and manage. However, where EN 81 is divided into more than twenty parts, ASME is divided only into seven. Each part includes information on elevators, escalators and moving walks. Volumes are to be used in conjunction with other A17 volumes to ensure safe solutions. An example of these volumes are ASME A17.1 "Safety code for elevators and escalators" as well as A17.2 "Guide for inspection of elevators, escalators and moving walks". A17.1 includes requirements for elevators, escalators, dumbwaiters, moving walks, material lifts and dumbwaiters with automatic transfer devices. A17.2 includes inspection procedures for electric traction and winding drum elevators, hydraulic elevators, inclined elevators and escalators as well as moving walks. (ASME A17.1 2016, p. 1−2; ASME A17.2 2010, p. 1−2)

ASME A17 standard has been in use since 1921. From there on the standard has had multiple revisions to keep it current and to assure the safety of elevator, escalator and moving walk design and usage. New editions are published every third year. Revised parts are usually listed at the start of A17 document similarly to EN 81. The most recent revision for A17.1 is from 2016. According to American National Standards Institute (ANSI), revised A17.1: 2016 enhances elevator safety by underlining design aspects, such as suspension, counterweight and braking designs as well as using suitable materials. Revisions with escalators and moving walks mostly occurred with the geometry of escalator and the right material usage. (ANSI 2016; ISO/TR 14799-2 2015, p. 5)

3.1.3 International organization for Standardization (ISO)

ISO is an international organization, which is designed to share and develop International Standards used by a variety of industries. ISO has a membership of more than 160 national standard bodies in order to ensure reliability, safety and high quality of products and services. The international standards are covering most of the aspects of technology and manufacturing. A few of these aspects are elevators, escalators and moving walks. The modern ISO elevator standard consists of multiple volumes. For example, ISO 4190 "Lift installation" series consists of six parts including elevator classes, control devices and different elevator environments. For another example, ISO offers standard for risk assessment and reduction methodology called ISO 14798. This standard can be used to help with the identification and assessment of identified hazards with the elevators, escalators and moving walks. (ISO 14798 2013; ISO 2017a)

ISO also produces technical specifications (TS) and technical reports (TR), which are designed to aid standard writers with the development of safety requirements. These reports can e.g. compare and comment on other standards and their requirements, or lack of them. For example, ISO/TR 11071 series compares elevator standards and ISO/TR 14799 series compares escalator and moving walk standards. Similarly to standards, technical specifications and technical reports are divided into their own volumes to ease the comprehensibility. (ISO/TR 11071-1 2004 p. vi; ISO/TR 14799-1 2015, p. v)

3.1.4 Japanese codes and standards (JEAS, JIS)

Japan has its own construction codes for vertical transportation. Codes are comprised of the Building Standard Law of Japan (BSLJ), its Enforcement Order (BSLJ-EO), Japanese Industrial Standard (JIS), Japan Elevator Association Standards (JEAS) and several of electrical codes. (ISO/TR 14799-2 2015, p. 5−7) In association to construction codes and standards, Japan also utilizes parts from ISO/TC 178 standard information (JEA 2017b). Requirements for Japanese standards arises from Japanese culture aspects as well as geographical location, where seismic events are common. Japanese culture plays a major part in the elevator and escalator design as in some cases passenger comfort is thought to be more crucial than e.g. the top velocity or the top acceleration of the machine (Kalliomäki 2016).

Japanese Industrial Standard was established by Ministry of International Trade and Industry in 1949. In 2001, the ministry was reorganized to the Ministry of Economy, Trade and Industry (METI 2017). JIS A 4302 issued elevators, escalators and dumbwaiters, as it was published in 1964. Currently, the standard is used to inspect the safety concerning traction type elevators, escalator, moving walks and dumbwaiters. (ISO/TR 14799-2 2015, p. 6−7)

Japan Elevator Association (JEA) is a trade association with 128 member companies to enhance the overall safety, performance and comfort of elevators, escalators and moving walks in Japan. The JEA has a major role for the Japanese elevator, escalator and moving walk markets, as it is the only organization in Japan, which represents the issued industry. In addition to safety enhancement, JEA focuses to develop industry with research activities, to enhance cooperation with related organizations and to set regulations via standard creation and publication. JEA also monitors JIS standards, which apply to elevators, escalators and moving walks in Japanese markets. (JEA 2017a; JEA 2017b)

3.2 Escalator and moving walk standards

Both, ASME A17.1 and JIS, standards include elevator, escalator and moving walk standards within the same volumes. For standards include a lot of information, the content table is not as detailed or user-friendly with ASME and Japanese codes as with EN series. For example, the escalators and moving walks are issued within Part 6 of ASME A17.1: 2016, but the content table does not mention what their subchapters content. However, with EN 115-1, the content table is divided within seven parts and their subchapters.

EN and ISO standards divide machines and their variations into several standard volumes. For example, vertical elevators and inclined elevators have their own volumes in Europe. Escalator and moving walk standards slightly divert from this practice as these machines are included within the same volume. European escalators and moving walks utilize standard known as EN 115 “Safety of escalators and moving walks”. Similarly to the European elevator standards, the escalator and the moving walk standards are divided into multiple parts depending on the environment. There are two parts for the EN 115. The first part includes the construction and installation of a new a machine. The second part issues the rules for the improvement of already existing machine. The standard does not deal with hazards arising from seismic activities, but the standard is still widely used all over the world as the basis of their national standards. (EN 115-1 2010, p. 4−5; ISO/TR 14799-2 2015, p. 4)

ISO 9589 “Escalators – Building dimensions” is a global standard, which similarly to EN 115 and ASME A17.1 sets the minimal safety requirements for escalators and moving walks. According to ISO 22201-2, specification of the safety integrity level (SIL) for escalators or moving walks are required to fulfill at least SIL 1. However, no greater than SIL 3 is required.

4. MATERIAL AND METHODS

This Master's Thesis is carried out as a literature review where the effects of velocity gradients on the human body and the well-known vertical transportation standards are being studied. The main focus from effects of velocity gradients is on the balance of a passenger. As the subject lacks specific information on the velocity gradients from vertical transportation studies, other engineering field studies as well as interdisciplinary studies on similar subjects are to be reviewed and compared in parallel to the found few vertical transportation studies. The collected study results are to be analyzed individually, compared with each other and to be compared with the most well-known vertical transportation standards and directives. This thesis is to answer for the following questions:

1. What are the limit values for the velocity gradients with elevator, escalator and moving walk applications according to the most well-known standards?
2. How standards settled on and justified given limit values?
3. In comparison to the balance related studies, are the velocity gradient limit values set by the standards in alignment and up-to-date?

This chapter focuses on what kind of literature material, such as standards and machine statistics, are used for this study. After the literature materials are shown, study methods and research stages are presented.

4.1 Literature material

For the thesis is a literature review, the literature material is crucial part of the study. As mentioned before, the vertical transportation industry lacks specific and accurate studies on how magnitudes of velocity gradients effect on human body. Therefore, studies from multiple engineering backgrounds must be used in parallel to standards and found vertical transportation studies.

The studied literature materials are divided into different categories. The first category sets the legislation for the machine design and displays the limit values for the velocity gradients. The second category includes studies from varying backgrounds where velocity gradients affects human balance, but not the human intestines. These studies are compared mostly with the normal use of elevator, escalator and moving walk. Thirdly, studies with great magnitudes of velocity gradients are compared with machine's out of ordinary usage, such as emergency braking and accident scenarios. Last category includes vertical transportation statistics, such as accident ratings.

4.1.1 Standards, directives and technical reports

The global elevator, escalator and moving walk design utilizes different directives and standards depending on which continent the machine is being designed and applied in. This thesis studies and refers to a few of the most well-known global elevator, escalator and moving walk standard groups. Backgrounds of chosen standard groups were presented in Chapters 3.1, 3.2 and their subsections. The following volumes/parts from issued standards are analyzed for this study:

- European Lifts Directive 2014/33/EU
- Directive 2006/42/EC on machinery, and amending Directive 95/16/EC
- EN 81-20: 2014 Safety rules for the constructions and installation of lifts – Lifts for the transport of persons and goods – Part 20: Passenger and goods
- EN 81-21: 2009 Safety rules for the constructions and installation of lifts – Lifts for the transport of persons and goods – Part 21: New passenger and goods lifts in existing buildings
- EN 81-22: 2014 Safety rules for the constructions and installation of lifts – Lifts for the transport of persons and goods – Part 22: Electric passenger and goods passenger lifts with inclined travel path
- EN 115-1: 2010 Safety of escalators and moving walks – Part 1: Construction and installation
- EN 115-2: 2010 Safety of escalators and moving walks – Part 2: Rules for the improvement of safety of existing escalators and moving walks
- ASME A17.1: 2016 Safety Code for Elevators and Escalators
- ASME A17.2: 2014 Guide for Inspection of Elevators, Escalators and Moving Walks
- ASME A17.3: 2015 Safety Code for Existing Elevators and Escalators
- ISO 14798: 2013 Lifts (elevators), escalators and moving walks – Risk assessment and reduction methodology
- ISO 18738-1: 2012 Measurement of ride quality – Part 1: Lifts
- ISO 18738-2: 2012 Measurement of ride quality – Part 2: Escalators and moving walks
- ISO 22201-2: 2013 Lifts (elevators), escalators and moving walks − Programmable electronic systems in safety related applications – Part 2: Escalators and moving walks
- ISO 2631-1: 1997 Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements
- ISO 4190-1: 2010 Lift installation – Part 1: Class I, II and VI lifts
- ISO 4190-2: 2001 Lift installation – Part 1: Lifts of class IV
- ISO 9589: 1994 Escalators – Building dimensions
- BSLJ-EO: 2004 – Section 2, Elevator equipment

- JIS A4302: 1992 – Inspection Standard of Elevator, Escalator and Dumbwaiter
- Ministry of Construction (MOC) of Japan: 2000 – Notice No. 1423 & 1424

In addition to the design standards, this thesis also analyzes the following technical specifications and technical reports:

- ISO/TS 22559-1: 2014 Safety requirements for lifts – Part 1: Global essential safety requirements
- ISO/TR 11071-1: 2004 Comparison of worldwide lift safety standards – Part 1: Electric lifts
- ISO/TR 14799-1: 2015 Comparison of worldwide escalator and moving walk safety standards – Part 1: Rule by rule comparison
- ISO/TR 14799-2: 2015 Comparison of worldwide escalator and moving walk safety standards – Part 2: Abbreviated comparison and comments

The technical specifications and reports are not equal to standards and are not intended to replace any existing safety standards. Reports are intended to aid the development of safety requirements among standard writers around the world. (ISO/TR 14799-1 2015, p. v) From the listed standards, EN 81-20, EN 81-22, EN 115-1, ASME A17.1 and Japanese codes are taken in for closer examination. Collected data from chosen standards are presented later on in Chapters 5.3.1 and 5.3.2.

4.1.2 Studies from several engineering fields

In order to compare suitability of regulations for the velocity gradients set by the vertical transportation standards and directives, several velocity gradient related studies must be analyzed. Because issued studies are not common in the vertical transportation industry, studies from varying engineering backgrounds are used in parallel with found vertical transportation studies. The selection of which engineering backgrounds could possibly be used in parallel with vertical transportation studies were completed with the preliminary study for the Master's Thesis. However, before results, or any other data, from other engineering background other than vertical transportation could be used, the study methods of issued study must be analyzed in order to figure out if the data can be used for vertical transportation purposes. For example, studies where passenger of some vertical transport machine is laying down are not suitable for this study. The stages for selection of literature material can also be seen in Figure 4.

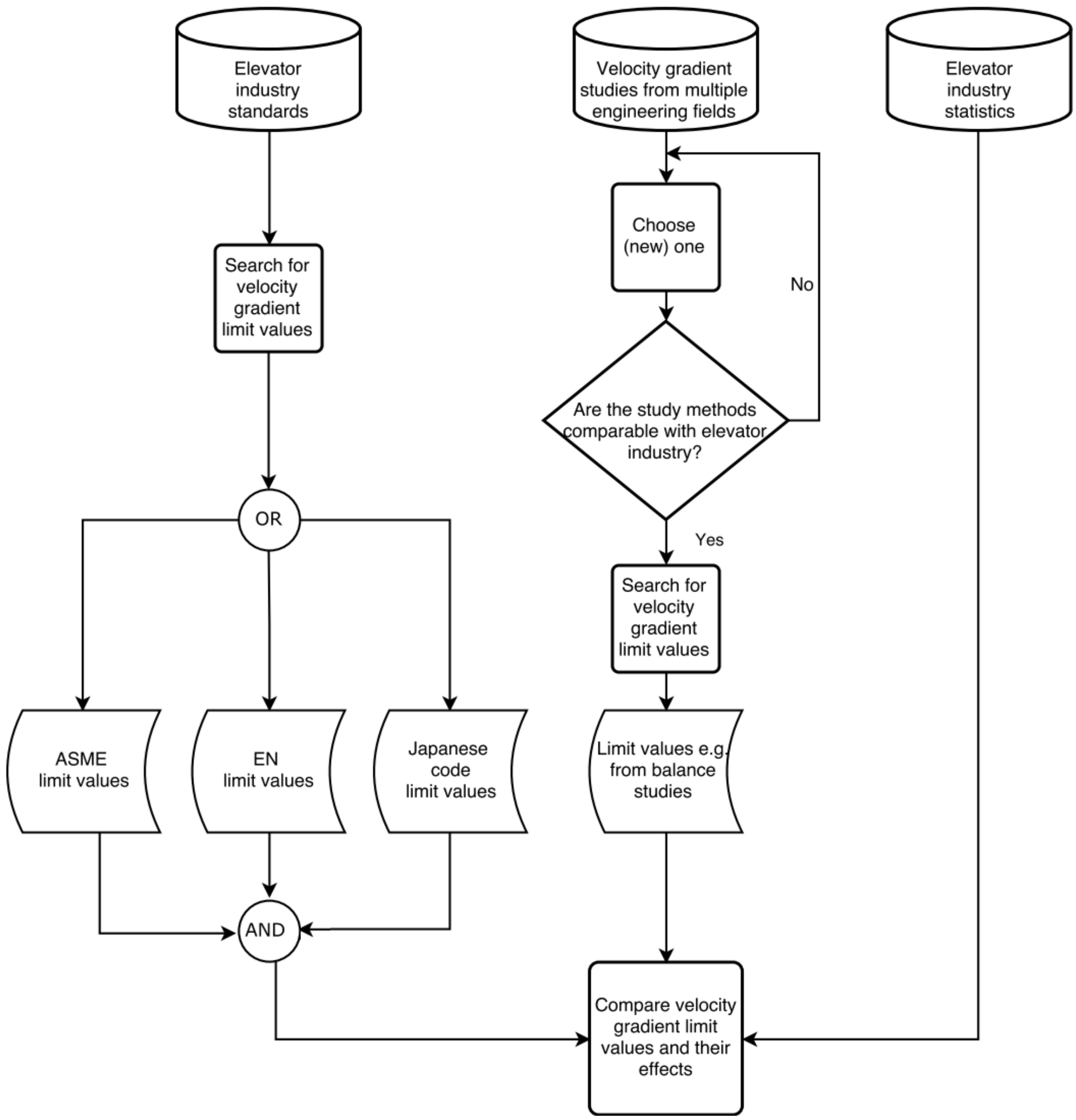

Figure 4: Selection process of literature material

The chosen velocity gradient study backgrounds were vertical transportation, aeronautics, public transports and medical science applications related to studies of velocity gradients. Especially the human balance factor is essential for this thesis, as the magnitudes of velocity gradients in the normal use of an elevator, an escalator or a moving walk are not particularly high. However, the magnitudes of velocity gradients with out-of-ordinary cases, such as emergency braking, should not be underestimated. In association to the balance, also human psychology is to be studied as it has effects to human expectations, ride comfort and possibility to raise the possibility to lose one's balance. For example, wallpaper illusion (described in Chapter 5.1.2) is known to affect the balance of some escalator passengers. Respectively, if the passengers felt scared because of the velocity gradients, which in high magnitudes might feel sudden, the passengers are not likely to use the same machine again in the future.

4.1.3 Vertical transportation statistics

Vertical transportation industry collects various kind of machine data, which can be utilized for example in the R&D and maintenance. At least the data from maintenance requirements and occurring of a failure or an accident are collected. Currently, the technicians gather most of the data manually, but in the near future the elevators will be linked with the internet of things (IoT). With the help of sensors and IoT, machines can gather their own data, store it in the cloud, analyze if the machine requires maintenance and contact maintenance independently. In addition, IoT reports could be used e.g. in order to elaborate causes for accident reports. (IBM 2017)

Statistics on the accident scenarios are collected in order to follow the evolution of the industries as well as their product design, installation, maintenance and dismantling. This thesis utilizes accident and failure statistics involving elevators, escalators and moving walks. The used statistics are collected from multiple nations. For example in Finland, Turvallisuus- ja kemikaalivirasto (Tukes) serves as supervising authority, which gathers announcements and information on close call and accident scenarios from a variety of industries. Similar institutes can be found e.g. in the USA, South Korea, Japan, etc. One of the industries supervised by Tukes is Finnish vertical transportation industry, which include statistics from elevators, escalators and moving walks. In addition to the statistical data, several elevator, escalator and moving walk related accident case studies can be found throughout the internet. For example, the implementation of risk-based inspection for elevator maintenance study by Park & Yang (2010) utilizes South Korean accident and failure statistic data. Alternatively, escalator-related injury study by O'Neil et al. (2008) utilizes data from National Electronic Injury Surveillance System of the United States Consumer Product Safety Commission.

4.2 Study methods

Before the initiation of this Master's Thesis study, the thesis was missing precise study outlining and research questions. Therefore, a pre-study for the Master's Thesis was carried out before the initiation of the Master's Thesis phase. The pre-study was carried out by interviewing engineering experts of vertical transportation industry individually for the purpose of the upcoming Master's Thesis. Interview answers were then compared and analyzed, from where research questions, outlines and timetable for the Master's Thesis were planned. The Master's Thesis was estimated to last for six months.

This Master's Thesis study is carried out as a literature review, which follows research stages shown in the following chapter. As the velocity gradients of elevator, escalator or moving walk applications are hardly studied, the study articles from various engineering fields and origins are used. Study articles are mostly searched and studied from Tampere University of Technology's (TUT) library, from KONE Technology and Innovation's

(KTI) database as well as from the internet by using TUT's subscriptions, internet library and other services.

The chosen literature material for the study subject has been kept, as far as possible close to present-day. Therefore, most of the analyzed articles, studies and books are from the latest of 21st century. In the case of older information being used, the information from chosen source is seen as basic (and unchanged over the years) or hard to come by. In addition, handful of studies that are published before 1990s are analyzed, such as Browning (1974) and Feyrer (1973), as they worked as the foundation for some of the limit values for vertical transportation standards. After the literature materials are chosen, their information and results are analyzed individually and in comparison to other similar studies as well as elevator, escalator or moving walk standards and regulations. The analyzation includes e.g. analyzation of can the results be used and compared with the machine applications or similar studies. After the results are collected, development proposals for elevator, escalator and moving walk design are generated.

4.3 Research stages

This Master's Thesis study can be divided into four main research stages, from which the second stage can be divided into its own sub-sections. Stages are following:

1. Determine the main study questions, restrictions and timetable with the pre-study for the Master's Thesis,
2. Search for the literature material
    a. Search for elevator, escalator and moving walk statistics,
    b. Search for the most well-known elevator, escalator and moving walk standards and directives,
    c. Search for material that studies the effects of velocity gradients on the human body,
3. Analysis and comparison of chosen literature material,
4. Generating development proposals based on the study results.

The pre-study for the Master's Thesis was used to figure out the requirements and borders for the Master's Thesis. In addition, a pre-study was used to familiarize the author with the vertical transportation industry and to search for initial literature material for both studies. After supervisor accepted the pre-study, the Master's Thesis study could be initiated by searching and analyzing more of suitable studies on the subject. In addition to studies from the vertical transportation industry, studies analyzing human balance from aeronautic, public transportation and medical science on the effects of acceleration and deceleration were searched for, as proposed by the pre-study.

Standards and directives for elevators, escalators and moving walks are chosen by their prevalence and purpose. Similarly to standards, studies based on velocity gradients are chosen for machine applications. Therefore, studies that analyze the similar magnitudes of velocity gradients as elevator, escalator or moving walk are chosen. The chosen magnitudes of velocity gradient does not have an effect on human intestines and thus most of the selected studies focus on the human balance.

The chosen vertical transportation standards and studies with various backgrounds are analyzed independently as well as by comparing them with each other. For example, regulations set by ASME, EN and Japanese codes can be compared as they set regulations for the same machines. Before the chosen study results and standard regulations can be put in the comparison, the comparability of chosen study methods and elevator, escalator or moving walk must be considered. For example, can an elevator passenger and a public transport passenger be compared justifiably, as one might be standing and other one might be sitting down? Lastly, development suggestions to improve operation and the safety of elevator, escalator and moving walk applications are generated based on the results.

Qualitative rigor is used in order to analyze the credibility, transferability, dependability and confirmability of the study results. This thesis utilizes mixed-design of qualitative and quantitative approaches. The qualitative approach was used, as the effects of velocity gradients on human body in vertical transportation industry are not widely studied and several of other engineering fields were studied. The quantitative approach on the other hand was in order to study the effects of velocity gradients especially on human balance perspective. (Thomas & Magilvy 2011) The analysis is mostly included within Chapter 6.

5. RESULTS

This thesis studies the effects of velocity gradients on the human body with elevators, escalators and moving walk applications. As there is lack of specific information on the effects of deceleration and acceleration on a human body when travelling with an elevator, an escalator or a moving walk, a new study was required. This paper takes into account effects with the human postural control, effects with the human psychology and occurred accident scenarios, which are affected or caused by velocity gradients. In addition to the effects of velocity gradients, also elevator, escalator and moving walk standards are studied, for they set the limit values for the acceleration and deceleration of studied machines.

In the beginning of this chapter, the hazards of vertical transportation are analyzed by using statistics from various countries and organizations. Afterwards balance related velocity gradient results and limit values for the velocity gradient from well-known standards are collected. Lastly, velocity gradient related study results from varying engineering fields are represented.

5.1 Statistical studies of vertical transportation hazards

In general scope, hazards among elevators, escalators and moving walks are a widely studied area. Especially the statistics on reported accidents from several organizations and countries are used to analyze the development of vertical transportation industry. According to studies by Zarikas et al. (2013) and Park & Yang (2010), most of the elevator injuries occur during the installation or maintenance of the elevator, which usually do not relate in velocity gradients. Some of the safety standards list sudden velocity gradients as one of the potential hazard for elevator passengers. However, these accidents do not occur as commonly with elevators as they do with escalators and inclined moving walks, which can be seen e.g. from the reported accident statistics and from the number of completed escalator and inclined moving walk related fall studies. This is reasonable, as elevators in comparison with escalators do not have as high probability for passengers to fall for great heights, because of the closed elevator car. Nevertheless, a closed car does not rule out the possibility for passengers to lose their balance and fall on the elevator floor due to the velocity gradients. However, these smaller falls might be left unreported if the consequences are not severe.

Injuries with escalators and moving walks can be divided into three main categories: entrapments, falls on a conveyor system and falls from a conveyor system. With most of the entrapment cases, the comb plate is either missing teeth or has a broken one, which allows a small object, such as an open shoelace, to be stuck between the teeth. Entrapment injuries mostly occur with children who are either sitting or playing on a moving escalator or a moving walk. Falling accidents on the other hand are generally associated with older passengers with weaker postural control. Some of these accidents are the result of velocity gradients. (Al-Sharif 2006; Greenberg & Sherman 2005)

5.1.1 Elevators

Most of the elevator, escalator and moving walk accidents occur with the elevators. This is reasonable, as elevators are the most common machines to be found for a vertical transportation. According to TECHNICAL magazine vol. 251 from 2009, Greece had approximately 450 000 of installed elevators, which is the highest number of elevators per population in Europe. In Greece, a total of 41 elevator accidents were reported from the year of 1998 to 2009. The majority of the accidents took place with an unfinished installation of elevators in metropolitan area, where elevators are very common. More precisely, most of the accidents occurred with elevators located in the apartment buildings (43,9 %), hospitals (12,2 %) and public buildings (12,2 %). In addition, an interesting fact is that the most of the accidents occurred for the trained installation and maintenance personnel (65 %) during work hours where the safety and health or the electrical installation regulations were violated. Most of the accidents with regular elevator passengers were due to the violation of machine operating instructions. Approximately 80,5 % of all reported accidents led to heavy injuries or were fatal. (Zarikas et al. 2013, p. 99) The study did not specify the effects of velocity gradients, such as loss of balance, as their own category.

In the years of 2007, South Korea had more than 359 000 installed elevators, from where the calculated elevator accidents per ten thousand elevators were 1,54 and the number of reported accidents were 97. Thus, South Korea reported more than twice as many elevator accidents within a year than Greece had reported within 12 years. The top three appearances of elevator accident types in South Korea were poor components (15,9 %), crushing passenger or worker after opening the landing door with an emergency key (12,4 %) and being jammed or crushed in the gap between the car and the hoist walls (9,2 %). Similarly to results from Greece, South Korean workers disobeying the safety rules resulted in the higher number of accidents (8,0 % of the accidents), as the passenger disobeying the safety rules resulted only in 1,6 % of the accidents. In addition, user carelessness (8,0 %) is worth mentioning as it is close to being within the top three factors. (Park & Yang 2010, p. 2 368) The user carelessness nor passenger disobeying the safety rules did not separate the effects of velocity gradients with the elevator accidents.

Tukes does not specify the appearance of elevator accident types in Finland. However, according to Tapaturmavakuutuskeskus (a Finnish accident insurance company), the majority of the elevator industrial accidents occurred, because of worker's finger or limb got between the elevator door (~40 % of all the accidents). Total of 180 working hazards or potential working hazards were registered in the year of 2013. Most of these work-related accidents led to absences under three days, which allude to mild injury. (Tukes 2016, p. 22) Once again, the effects of velocity gradients are left unmentioned.

5.1.2 Escalators and moving walks

In 2015 European Lift Association (ELA) gathered information from 15 countries for escalator user accidents and from 16 countries for escalator worker accidents. In total 294 escalator user accidents were reported and total of 65 escalator worker accidents were reported. None of fatal accidents were reported. Most of the accidents were user accidents, from which 36 % were caused by slipping on steps, pallets, belt and on landings. In addition, 3 % of user accidents were caused by fall from a landing and 1 % by fall due to stopping distance being too short. Velocity gradients were not reported as their own category, but it is likely that mentioned accidents were at least partly due to the effects of velocity gradients. (ELA 2016)

Approximately 20,3 % of South Korean vertical transportation accidents occur with the escalators and moving walks. The most of the accidents occur among children and older adults. (Park & Yang 2010, p. 2 368) Similarly to South Korean statistics, a major part of Finnish vertical transportation accidents occur with elevators. However, the escalators had a greater number of lethal accidents in Finland with the scope of ten years. (Tukes 2016, p. 20–21) This can be reasoned with the location of a passenger. Elevator passengers are generally located in a closed car, as the escalator and inclined moving walk passengers are located on an open conveyor system and thus have a potential hazard of falling over the railing or down the stairs.

Greenberg & Sherman (2005) analyzed the series of 50 patients, who encountered an escalator related fall injuries and were treated at Cook County Hospital, USA. From the series of accidents, 28 % of the patients felt disturbance in their depth perception, which was caused e.g. by the wallpaper illusion. Wallpaper illusion will be covered later on this paper. In addition to the balance loss due to wallpaper illusion, the majority of patients (64 %) admitted being walking while riding the conveyor system. (Greenberg & Sherman 2005)

Chi et al. (2006) studied escalator-riding accidents in Metro Rapid Transit (MRT) station located in Taipei, Taiwan. In the year of 2000, MRT station alone had 194 escalator riding accidents, from which over 86 % were falling accidents and 6 % were entrapments and cuttings. Over 75 % of the accidents occurred with escalators heading upward, which is reasonable as the most of the MRT station escalators are going up. According to the in-depth investigation, the top three causes for accidents were carrying out other tasks (19,6 %), the loss of balance (13,4 %) and not holding on the handrail (10,3 %). Concerning the loss of balance, mostly women passengers aged over 65 years encountered falling accidents. Especially an emergency stopping results in a sudden exposure to velocity gradients. Seven accidents (3,6 %) were due to emergency stops, which were not part of already issued loss of balance cases. Lastly, three accidents (1,55 %) were reported due to an escalator moving too fast. In addition to previously mentioned age, rushing, shoe types and the victim being alone or with a party affected the occurrence of an accident. The accidents resulted in injuries with multiple body parts, from where the head (29,4 %) was the most common subject for injury. (Chi et al. 2006)

Similarly to Chi et al., Howland et al. (2012) studied escalator accidents in a single area between the years of 2009 and 2010. Howland et al. used statistics and interviews from Metropolitan Airport, United States. From documented 316 falls, 140 were on escalators, 15 on moving walks and 4 on elevators. From the escalator falls, 53 % of the victims were aged over 65 years. Within past years there have been an increase in escalator-related injuries among older adults, which e.g. can be seen from Figure 5. In addition to age, 71 % of escalator falls happened to females. According to the airport fire and rescue personnel, the number of passengers who are carrying bags to and from planes is rising due to changes in airline luggage fees and the removal of skycaps. The rising number of passengers engaged in carrying luggage or using their cellphones results in the increased hazard of balance lose and falling due to not holding on to the railing and not paying attention to the surroundings. (Howland et al. 2012) The study had not separated the influence of velocity gradients, e.g. during emergency braking situations.

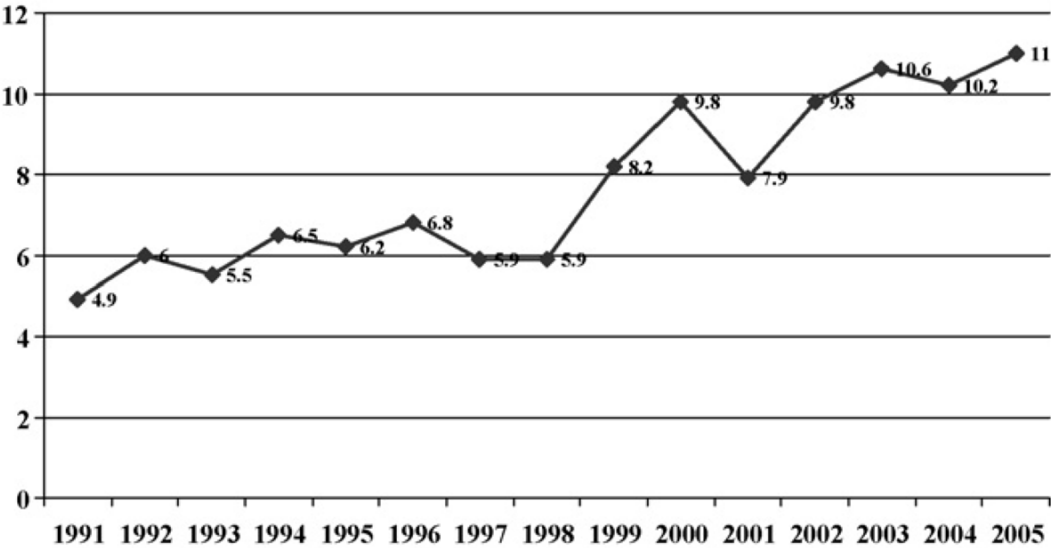

Figure 5: Rate of escalator-related injuries among older adults per 100 000 population by the year, US. (O'Neil et al. 2008, p. 529)

O'Neil et al. (2008) arrived in similar results as Howland et al. did. However, O'Neil et al. studied escalator related injuries only among adults with the age of 65 years or more. The study used data from the National Electronic Injury Surveillance System of the United States Consumer Product Safety Commission between the years of 1991 and 2005. According to the study, there were roughly 40 000 escalator-related injuries with older adults in the USA within the issued time. As can be seen from Figure 5, the rate of escalator-related injuries among older adults rises continuously. The rate is evaluated to keep on rising as the baby-boom generation approaches retirement age. Most of the escalator related injuries took place in public buildings. Following results from other studies, the majority of injuries were seen with females (73 %). Of all the injuries, 85 % were due to slip, trip or a fall and 14 % occurred while entering or departing the escalator. In addition, admitted misstep, loss of balance and fainting were categorized as their own cause for an accident. This category covered 6 % of all injuries. In addition to physical injuries, such as lacerations and fractures, accidents may also cause psychological problems. For example, the fear of falling can limit victim's activities. (O'Neil et al. 2008)

5.2 Human balance and postural control

Aeronautic studies include the great magnitudes of acceleration and deceleration, which have their own effects on a human body, such as effects on the internal organs. As velocity gradients among vertical transportation industry are not as high, the effects on the internal organs can mostly be left out of this paper. However, the internal organs might be damaged in the falling accident cases due to passenger balance loss. In these cases, the organs are not directly damaged by the high velocity gradients from the machine, but rather by the side effect of balance loss and then hitting the ground or an object. Therefore, it is reasonable to study the velocity gradients from an elevator, an escalator or a moving walk mostly in the balance and postural control perspective.

Velocity gradients in elevator applications come into action as the elevator is either initiating the movement by accelerating or ending it by decelerating. With escalator or moving walk applications, velocity gradients can occur in three different scenarios. First and second occur as the passenger either enters or departs from the conveyor system. Especially entering and exiting from the top landing of escalator or inclined moving walk can be hazardous if the passenger moves significantly slower than the conveyor system and passenger is not expecting a change in the velocity. The top gate is one of the most dangerous locations for the passenger, as it is the highest part of the machine and falling from great height is possible. The third velocity gradient can occur if an emergency brake is activated. According to Newton's first law (law of inertia), an object will stay on rest or stay in motion unless it is influenced by an unbalanced force. Therefore, if passenger is influenced e.g. by emergency brake might result in a forward fall when the passenger is facing the direction of the movement. All of these hazards should be taken on account e.g. with handrails. (Bronstein et al. 2009, p. 83)

5.2.1 Effects of age

A human body has a tendency of being able to detect horizontal velocity gradients more easily than vertical ones. With the discrete transitions, the threshold for the detection of a vertical acceleration (0,15 m/s^2) was approximately twice as high as for either direction of horizontal acceleration (0,06 m/s^2). (Previc & Ercoline 2000, p. 54) According to the psychophysical acceleration study by Richerson et al. (2006), standing young adults (aged under 25 years) have significantly lower acceleration detection thresholds when compared with standing older adults (aged over 50 years). Healthy young adults are able to detect whole-body perturbations for the lateral displacements of 2 mm, healthy older adults detect the displacements of 4 mm and older adults with diabetic neuropathy detect the displacements of 8 mm. The studied peak accelerations were approximately at 10 mm/s^2. (Richerson et al. 2006) As young adults are able to detect acceleration more easily, they have more time to prepare for the effect of velocity gradients and thus maintain their balance more easily.

Research by Bugnariu and Sveistrup (2006), described in Chapter 2.2.2, studied the effects of age difference with the postural control and how people react to predictable and sudden changes in their balance. In both, external and self-triggered perturbations, the young adults were more able to maintain their CoG in the central regions of BoS at all frequencies. With the case of old adults, the CoG was located in the extreme regions of the BoS. In addition, the older adults addressed a greater requirement for an external support. Location of CoG in extreme regions and a requirement for external support occurred especially when the platform oscillation frequency was increased. With external triggered perturbations, the young adults were able to shift from a reactive to an anticipatory mechanism within three cycles. In addition, the muscle onset latencies of young adults remained stable over remaining test cycles. Older adults did not have similar results. Older adults used postural muscles primarily in response, but never in anticipation of the upcoming direction change and thus were weaker to resist the effect of velocity gradients. (Bugnariu & Sveistrup 2006, p. 77−79, 82)

In addition to the muscle activity from previous study, Okada et al. (2001) collected data from the movements of hip and knee, ankle angles as well as the acceleration of the head. It is essential to keep the magnitudes of head acceleration low in order to maintain the balance. The study demonstrated how in comparison with young adults, older adults had slower and larger ankle and hip joint movements during recovery from a sudden deceleration of the standing surface. In addition, the central foot pressure displacement with older adults was slower and older adults had a greater extent of acceleration of the head rotation. The hip joint movements and hip strategies were more crucial for the older adults over young adults. Therefore, it can be stated that there is an age-related change in postural control movement patterns from ankle to hip strategy. The change in a postural control movement may occur, because of larger hip movement with the older adults as well as decline in CNS functions due to ageing. (Okada et al. 2001, p. 10, 15−16)

Tokuno et al. (2010) studied age-related differences with short and long translations. Similarly to earlier studies, participants were instructed to recover their balance without stepping. However, with both, short and long translations, stepping almost always occurred at or after the deceleration phase. The comparison of young and old adults resulted in an increased knee and trunk flexion as well as decreased ankle dorsiflexion and displacing CoG forwards. Results were increased during long translations over short translations. According to them, the results imply that reactivity is affected more strongly by aging than by the anticipatory of postural reaction. (Tokuno et al. 2010, p. 111, 115−116)

Previously mentioned studies were completed with balance boards and in laboratory environments. Schubert et al. (2017) studied older bus passengers, who are required to stand with and without support. Participants were exposed to the bus accelerations and decelerations from three different positions: facing in the direction of the movement, facing in the opposite direction and facing sideways of the movement. As expected, the highest ground reaction forces appeared with free standing where up to 200 % of participant body weights were measured. In these scenarios, all participants were forced to take steps in order to maintain the balance regardless of the body direction. Even though additional support removed the need to take steps with this study, average of 80 % of maximal grip strengths were measured when standing in the direction or against the direction of travel. This indicates a close call for taking a step even though having an external support. Thus, even when using external support, occurring forces can surpass passenger forces and lead to the loss of balance. (Schubert et al. 2017) Robert et al. (2007) conducted similar study for young adults, which results are on the table below. Statistical research by Halpern et al. (2005) indicates similar results, as over half of 120 studied non-collision bus injured patients were older than 55 year old (55,8 %). Most of the injured passengers were either standing (55,8 %) or moving (25,0 %) in the bus and injured due to a sudden deceleration or acceleration (51,2 %). (Halpern et al. 2005)

Used velocity gradient values with postural control studies in the horizontal direction are collected in to the Table 1. One of the studies is described later on this paper. The collected velocity gradients are constricted to last at least 10 ms in order to separate studied velocity gradients and velocity gradients resulted from the vibration of the platform.

As can be seen from the Table 1, the velocity gradients vary from study to study. All of the studies used sudden disturbances, as velocity gradients in everyday life are mostly sudden e.g. only a few bus or train passengers are able to pay attention to the effects of upcoming velocity gradients, as the visibility of the vehicle direction is usually restricted or blocked. Most of the studies recorded alternation in balance of participants by participants need to take a step or requiring an additional support for the balance maintenance. Even though in some of the cases the additional support was offered, it does not entirely remove the risk of losing balance. Especially the deceleration phases were seen as problematic scenarios for older adults. The participants, who did not require additional support, were mostly younger adults aged less than 40 years old. Therefore, older adults can be stated as the risk group for the effects of velocity gradients.

Table 1: Collection of studied horizontal velocity gradients in relation to the balance

	Okada et al. 2001	**Tokuno et al. 2010**	**Mihara et al. 2008**	**Schubert et al. 2017**	**Robert et al. 2007**
Top acceleration [m/s^2]	6,18 (for 80 ms)	1,20 (for 300 ms)	5,00	2,45	2,00 & 10,00 (for 400 ms)
Top deceleration [m/s^2]	50,80 (for 10 ms)	2,30 (for 200 ms)	5,00	3,04	N/A
Directions [-]	Anterior	Anterior & rear	Anterior & rear	Anterior, rear & lateral	Anterior
Disturbance [-]	Sudden	Sudden	Anticipated and sudden	Anticipated and sudden	Sudden
Number of participants [-]	8 old + 8 young adults	10 old + 10 young adults	15 young adults	8 old adults	10 young adults
Mean age [years]	69,1 (±3,5) 20,1 (±5,1)	73,0 (±4,6) 28,7 (±0,7)	29,4 (±6,7)	68,1 (±5,2)	25,6 (±2,4)
Note [-]	Without mass of subject the acceleration of platform was 0,78 and deceleration 0,10 m/s^2. For **deceleration, some of the participants required to take steps**.	For **deceleration, most of the participants required to take steps** to maintain balance.	**No additional support** was required in either, anticipated or sudden condition. Participants were **under 40 years old**.	**In acceleration and deceleration** all of the participants **had to take steps** to maintain balance if support was not offered.	**No falling** in any of cases. Only for **high-level perturbation, steps were required** with free standing.

It is hard to say when either the deceleration or acceleration of horizontal plane is safe, as results from Table 1 have a wide range. In order for all of the passengers to be safe, the deceleration should not exceed value of 2,30 m/s^2. For the acceleration, the value of 1,20 m/s^2 did not create problem with older adults. However, value of 2,45 m/s^2 created requirement for steps. Therefore, horizontal acceleration between 1,20−2,45 m/s^2 could be considered safe.

5.2.2 Psychological effects

In addition to postural control being affected by factors, such as visual system, cognitive skills and the age, a human psychology also plays a role for balance maintenance. For example, previous experiences, expectations for upcoming disturbance, environmental context, pathological changes and the level of self-confidence are affecting on the postural control. Brown et al. (2002) studied the differences of anxiety between young and old adults in gait patterns where falling was possible. The results indicate how high anxiety levels alter human gait pattern. In addition, the movement adaptations with older adults were significantly different from with younger adults evidenced with the differences e.g. of joint kinematics. The older adults were slower than young adults were, but had less variability in pitch plane head displacement as environmental constrains modified. The study showed how older adults react to increased postural threat by varying the movement adaptation and slowing down more dramatically than young adults do. (Brown et al. 2002, p. 290, 294)

Similarly to study by Brown et al. (2002), Portegijs et al. (2012) studied psychological effects on the postural control with older adults. Portegijs et al. studied 130 participants aged over 60 years, who had experienced a fall-related hip fracture. Participants were still active and relatively healthy. According to the study, the people who have experienced a traumatic fall-related accident might experience fear of falling even multiple years after the fall. The study found a relationship between balance confidence and balance performance. In addition, the balance confidence influences on the mobility and perceived mobility functions. Older adults who are suffering from the low balance confidence have a greater risk for increased physical disability and thus a greater risk for falling again. (Portegijs et al. 2012) The fear of falling with older adults do not require the adult to be any higher than standing position. Some of the older adults can experience fear of falling even during walking, which was studied by Asai et al. (2017). The study utilized data from a number of 260 active older adults with the mean age of 71,9 years. The fear of falling results e.g. in slower gait speed. The normal walking speeds varied in the range of 1,4±0,2 m/s. (Asai et al. 2017)

The experience and expectations what is going to happen have an effect on the postural control. For example, experienced elevator passengers are automatically prepared for the possibility of an elevator jerk by allowing anticipatory control to compensate body motion in relation to jerk. (Bugnariu & Sveistrup 2006, p. 85). As inclined elevators are not as common as vertical elevators, a new passenger of an inclined elevator might only be prepared for the vertical jerk, but not for the horizontal. In addition, passengers are more easily affected by horizontal velocity gradients, as humans are accustomed to the continuous velocity gradient of gravitation. Therefore, new passengers, such as young children should be instructed about hazards and how to avoid them. Here warning pictures, their location and comprehensibility are essential (Liumin & Wenwei 2012). Generally, the machinery directive 2006/42/EC (1.7.3) demands that machinery must be provided with information for the safe use (EUR-Lex 2006).

The experiences and learned reactions can have an unwanted influence on postural control. The broken escalator paradigm is an example of feed-forward gait adaptation persisting in situations that are known not be appropriate. I.e. a situation where a person enters a non-moving conveyor system, such as broken escalator, might lead to an odd feeling. The odd feeling occurs, as the person knows that the escalator will not move, but the person is still subconsciously prepared for an acceleration by altering CoG forwards. In addition to an odd feeling, a momentary balance loss might occur. Issued adaptation mechanisms are really fast, as a single exposure to phenomena can result in the motor aftereffect. However, the occurrence of the phenomenon depends e.g. on spatial location and how individual identifies an escalator as an escalator and not as traditional stairs. (Bronstein et al. 2009; Fukui et al. 2009)

In addition to a broken escalator phenomena, wallpaper illusion can have an effect on the human balance, as mentioned by patients who encountered an escalator accident (Greenberg & Sherman 2005). The wallpaper illusion is a visual illusion, which occurs when a repetitive or a periodic pattern in a horizontal plane seems to change depth to the nearest fixation. This can result in a disorientation and even the loss of balance. According to Cohn & Lasley (1985), the susceptibility to the visual depth illusions is not reduced due to age. Therefore, as motor control and strength reduces via age, older adults are more susceptible to these falls. (Cohn & Lasley 1985)

5.3 Velocity gradients based on the standards

As stated before, there are not only one, but several safety standards for elevator industries around the world. Each of the most well-known standard families set their own limit values for the differing velocity gradients of an elevator, an escalator and a moving walk. These values differ from standard to standard and from machine to machine. The velocity gradient limit values are set at least for the average retardation or deceleration of the machine in order to ensure the passenger safety. As mentioned in the Table 1, especially the deceleration phase is seen as problematic for older passengers and therefore it must be taken on account. In addition as some of the machines, such as incline elevators, escalators and incline moving walks, have both vertical and horizontal directions, the limit values are set for both directions individually. Individual limit values for vertical and horizontal directions take into account of the human tendency of having a better resistance for the effects of vertical velocity gradients over horizontal ones.

5.3.1 Elevators

It is known that the risk assessment cannot be a punctual science throughout the machine design. Therefore, some assumptions must be made. For example, ISO/TR 11071-1, a technical report that compares elevator safety standards, has an assumption for retardation. According to this assumption, a person riding an elevator is capable of withstanding an average vertical retardation of 9,81 m/s^2, which is the same as the acceleration of gravity (9,81 m/s^2 = 1 *g*). However, higher transient retardations are acceptable. The report admits that the retardation value a person can withstand without an injury or losing of balance naturally varies from a person to person and thus the chosen value is to satisfy the majority of the passengers. The chosen value for a retardation assumption is made empirically. Naturally, as assumptions for limit values were made in the first place, they were based on studies with similar issues. Historically, as the assumption has not been shown to have an unsafe effect on the majority of people, it has been considered functional. (ISO/TR 11071-1 2004, p. 2, 9) Similar assumptions considering retardations are collected into Appendix A.

The table in the Appendix A has a collection of the assumptions of average and maximum retardation from EN 81-1, ASME A17.1 and Japanese codes. The listed retardations for Appendix A from EN 81-1 are the same for EN 81-20. The retardations for downward direction, buffers and overspeed protection for upward direction are used. As can be seen from the Appendix A, the maximal of average retardation altogether is 9,81 m/s^2. Even the retardation of an emergency terminal speed-limiting device shall not excess the maximal magnitude of deceleration (ASME A17.1 2016, [2.25.4.1.4]). The transient retardations can go up to 24,5 m/s^2, but they shall not last longer than 0,04 seconds. However, the maximum peak retardations are limited to 58,8 m/s^2 for buffers with non-linear characteristics (EN 81-20, [5.8.2.1.2.1]).

In a similar fashion to the Appendix A, e.g. the maximal rated speed, the maximal acceleration and deceleration (or retardation) of vertical and inclined elevator set by EN 81-20 and EN 81-22, ASME A17.1 as well as Japanese codes are gathered into the Table 2 below. Some of the decelerations are used in free-fall scenarios as others are used with counterweight attached. Limit values are gathered in situations where the car is travelling downwards with the 125 % of rated load. The category “vertical elevator” refers to the elevators described previously in Chapter 2.3. The table uses the following abbreviations: *VE* stands for a vertical elevator, *IE* for an inclined elevator and *N/A* for not available. Note that *IE* rows for EN 81 divert from parallel rows as EN 81 has a separate standard for inclined elevators, EN 81-22. In case of one cell having two values, the top value is for the vertical direction and the bottom one for the horizontal direction. The sections of referred standards are in the parenthesis.

Table 2: Comparison of limitations with elevators (ASME A17.1 2016; EN 81-20 2014; EN 81-22 2014; ISO/TR 11071-1 2004)

Standard / Machine		EN 81-20: 2014 EN 81-22: 2014	A17.1: 2016	Japanese codes
Top rated speed, v [m/s]	**VE**	N/A	N/A	N/A
	IE	4,00 (1.5)	4,00 (5.1.14.2)	4,00 [III]
Top average acceleration, a_{av} [m/s²]	**VE**	N/A	N/A	N/A
	IE	N/A	N/A	N/A
Top average deceleration, a_d [m/s²]	**VE**	9,81 (5.6.2.1.3)	9,81 (2.24.8.2.2)	9,81 [I]
	IE	9,81 (5.6.8.4) 4,90 (5.6.8.4)	9,81 (2.24.8.2.2) 2,46 (5.1.17.4.1)	9,81 [I] 5,00 [I]
Buffer's top deceleration a_d [m/s²], ≤0,04 s	**VE**	24,5 (5.8.2.2.3)	24,5 (2.22.4.2)	24,5 [II]
	IE	24,5 (5.7.4.1.1) 9,81 (5.7.4.1.1)	24,5 (2.22.4.2) 6,13 (5.1.17.4.3)	24,5 [II] 9,81 [II]
Top stopping distance from unintended movement d_{stop} [m]	**VE**	1,20 (5.6.7.5)	1,22 (2.19.2.2)	N/A
	IE	1,00 (5.6.11.5)	1,22 (5.2.1.19 & 2.19.2.2)	N/A
Incline angle, α [°]	**IE**	15°≤ α ≤ 75° (1.1)	15°≤ α ≤ 70° (1.3)	15°≤ α ≤ 75° [II]

[I] BSL-EO art 129-10 item 2 para. 1

[II] JEAS 517

[III] 2000 MOC Notice No. 1423 item 1

As can be seen from Table 2 some of the limit values and instructions vary from standard to standard. Theoretically, standards do not restrict vertical elevators with the maximal rated speed as the fastest elevators travel with velocities of 20,50 m/s (CNN 2017). However, standards set some limitations to the maximal rated speeds e.g. in order to ensure the safe operation of governor overspeed switches and safety gears. With inclined elevators, all standards set the maximum rated speed for 4,00 m/s. Velocities over 4,00 m/s are out of scope of the standards.

The normal operation of an elevator leads in to the anticipated velocity gradients. Limitations to the maximal acceleration are hard to come by and are only limited for escalators and moving walks with the standards analyzed in the Tables 2 and 4. However, according to EN 81-50, it can be assumed that the maximal acceleration of traction elevators is not greater than 2,50 m/s^2 in the case of electric failure (EN 81-50 2014, [5.8.1]). In addition, the only mention of acceleration magnitudes with the inclined elevators occurs with the Note 1 of F.7.1.1 in EN 81-22; the highest speed of inclined elevator is based on the natural acceleration of 1,50 m/s^2 (EN 81-22 2013, [F.7.1.1]). In the case of an emergency stop e.g. caused by the removal of electrical power, the velocity gradients might be sudden for passengers. For issued situation, ASME A17.1 defines the average horizontal retardation for an inclined elevator to be under 0,98 m/s^2. Retardation peaks exceeding 0,98 m/s^2 are not to last longer than 0,125 seconds. (ASME A17.1 2016, [5.1.20.6])

Emergency stopping can be a result of unintended car movement, which needs to stop within a required stopping distance (d_{stop}) for either direction. Japanese standards have not specified protection requirements against unintended car movements (ISO/TR 11071-1 2004, Table A.9, p. 21).

The velocity gradients resulted from vibrations are not included with the newest revisions of chosen elevator standards (in Table 2), as vibrations are not found at levels which could be considered harmful with the use or the maintenance of an elevator (EN 81-20: 2014, p. 11). However, elevator design requires the use of multiple standards from where vibration is taken on account e.g. with ISO 2631-1: 1997 “Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration”. The standard considers the effects of vibration on human health and comfort from where the approximate limit values for velocity gradients resulted from vibration e.g. in relation to passenger comfort can be found. In addition to ISO 2631-1, directive 2006/42/EC (3.6.3.1) demands that warning must be provided in the case of the whole body being subjected under greater velocity gradient magnitudes than 0,5 m/s^2 resulted from vibration (EUR-Lex 2006). Vibration limit values for passenger comfort from ISO 2631-1 are gathered in the Table 3 below.

Table 3: Indications of passenger reactions to various magnitudes of the whole body vibration (ISO 2631-1: 1997, C.2.3)

Acceleration [m/s^2]	Effect of the whole-body vibration [-]
<0,315	Not uncomfortable
0,315−0,63	A little uncomfortable
0,5−1,00	Fairly uncomfortable
0,80−1,60	Uncomfortable
1,25−2,50	Very uncomfortable
>2,00	Extremely uncomfortable

Naturally, the passenger reactions to vibration differ from passenger to passenger. In addition to passenger's individual tolerance to vibration, reaction to vibration is affected by the duration of transport, in what way the vibration transmits to a passenger (e.g. seated vs. standing passenger) and what the passenger expects to accomplish during the journey. For example, women and children are more likely to feel uncomfortable during whole-body vibration than adult men are. In addition, reading or writing can cause discomfort under the influence of uncomfortable or even little uncomfortable vibration. (CR12349 1996, p. 8; ISO 2631-1 1997, [C.2.1], [C.2.3], [D.2]) However, usually the velocity gradient magnitudes resulted from vibration are low among studied machines and should not cause problems for the maintenance of the balance.

As mentioned before, EN 81-22 already listed the horizontal components of the velocity gradients as a possible risk for passenger safety. The horizontal components of velocity gradients with the inclined elevator cannot be considered the same as with the ones from escalator. This is because an inclined elevator is a closed car, where the vision of the passenger can be blocked, whereas an escalator is an open system where the passenger can react more easily to the movement. The vision is connected to the postural control and therefore the passenger whose vision is blocked is more likely to feel disturbances with the balance. In addition, among elevator passengers only the passengers located next to the car walls can utilize handrails, as among escalator passengers handrails can be utilized regardless of a passenger location.

5.3.2 Escalators and moving walks

As escalators and moving walks are very similar machines, they are usually combined into a single volume of a safety standard or a technical report. Technical report ISO/TR 14799 compares American, European and Japanese escalators and moving walks safety codes. The technical report can be used as a reference material to review individual standards and to help standard users to understand the basis for the requirements. (ISO/TR 14799-2 2015, p. v)

The limitations to escalators and moving walks including the maximum rated speed, incline angle, the maximal magnitudes of acceleration and deceleration set by EN 115-1, A17.1 and Japanese codes are gathered into the Table 4 below by using previously mentioned ISO Technical report and the chosen safety standards. In a similar fashion to Table 2 and previously analyzed elevator standards, the magnitudes of velocity gradients resulted from vibration are not found at the levels that are harmful for the passenger safety during the operation of escalator or either type of moving walks. Therefore, vibrations are left out from Table 4. Table 3 can be applied for escalator and moving walk vibration inspection if required. Table 4 uses the following abbreviations: *Esc* stands for an escalator, *IMW* for an inclined moving walk, *HMW* for a horizontal moving walk and *N/A* for not available. The sections of referred standards are in parentheses.

Table 4: Comparison of limitations with escalators and moving walks (ASME A17.1 2016; EN 115-1 2010; ISO/TR 14799-1 2015, p. 41, 53−54; ISO/TR 14799-2 2015, p. 13, 19, 22)

Standard / Machine		**EN 115-1: 2010**	**A17.1: 2016**	**Japanese Codes**
Top rated speed, v [m/s]	**Esc & IMW**	$v \leq 0,75$ [$\alpha \leq 30°$], $v \leq 0,50$ [$30° \leq \alpha \leq 35°$] (5.2.2 & 5.4.1.2.2)	$v \leq 0,50$ (6.1.4.1.1)	$v \leq 0,75$ ($\alpha \leq 30°$), $v \leq 0,50$ ($30° \leq \alpha \leq 35°$) [I]
	HMW	$v \leq 0,75$ (5.4.1.2.3)	$v \leq 0,90$ [$\alpha \leq 8°$], $v \leq 0,70$ [$8° < \alpha \leq 12°$] (6.2.4.1.1)	$v \leq 0,83$ [$\alpha \leq 8°$], $v \leq 0,75$ [$8° < \alpha \leq 15°$] [I]
Top incline angle, α [°]	**Esc & IMW**	$\alpha \leq 35$ (5.2.2)	$\alpha \leq 30$ (6.1.3.1)	$\alpha \leq 35$ [I]
	HMW	$\alpha \leq 12$ (5.2.2)	$\alpha \leq 12$ (6.2.3.1)	$\alpha \leq 15$ [I]
Top acceleration, a_{av} [m/s^2]	**Esc & IMW**	0,50 (5.12.2.1.2)	0,30 (6.1.4.1.2)	Varying [II]
	HMW	0,50 (5.12.2.1.2)	0,30 (6.2.4.1.2)	Varying [II]
Top deceleration, a_d [m/s^2]	**Esc & IMW**	1,00 (5.4.2.1.3.2)	0,91 (6.1.5.3.1)	1,25 [III]
	HMW	1,00 (5.4.2.1.3.4)	0,91 (6.2.5.3.1)	1,25 [III]
Stopping distances, d_{stop} [m]	**Esc & IMW**	0,40−1,50 [nom. speed 0,75 m/s] (5.4.2.1.3.2)	<0,14 [nom. speed 0,50 m/s] (6.1.5.3.1 & I-11)	0,10−0,60 [IV] $d_{stop}=v^2 / 9000$ [V]
	HMW	0,55−1,70 [nom. speed 0,90 m/s] (5.4.2.1.3.4)	<0,14 [nom. speed 0,50 m/s] (6.2.5.3.1 & I-11)	0,10−0,60 [IV] $d_{stop}=v^2 / 9000$ [III & V]

[I] BSLJ-EO article 129-12 item 1

[II] JEAS 410B 3.2

[III] BSLJ-EO article 129-12 item 5

[IV] JIS A 4302–1992

[V] 2000 MOC Notice No. 1424

As can be seen from Table 4, European and Japanese escalators and inclined moving walks are allowed to have higher magnitudes of velocity, acceleration and incline angle when compared with American escalators and inclined moving walks. When horizontal moving walks are compared, velocity gradients for Japanese and European machines are higher, but the top rated speed of American machine limitation is set to be the highest. When the magnitudes of deceleration for all of the machines are compared, Japanese limit values are notable higher than American and European ones, which are close to the acceleration of the gravity. When stopping distances are compared, European machines have notable longer stopping distances than American and Japanese machines. Even though Figure I-11 from ASME A17.1 is limited to the rated speed of 0,5 m/s and the stopping distance of under 0,14 meters, there are exceptions. According to section 6.2.6.3.9 of ASME A17.1: 2016, the pallet level device will stop the system if the device detects a flaw in the pallet and a sufficient stopping distance is limited to be before the pallet enters the combplate. In addition to comparison between differing standards, European horizontal moving walks are allowed to have a longer stopping distance than escalators or inclined moving walks. This is reasonable, because of horizontal moving walks do not have a similar risk for passenger falling from great heights as escalators and inclined moving walks do.

The peak decelerations and stopping distances are measured on a downward moving escalator during the operation of emergency braking system (EN 115-1 2010, p. 24−25). If the peak deceleration is exceeding the magnitudes mentioned in Table 4, it shall not last longer than 0,125 seconds (ASME A17.1 2016, [6.2.5.3.1]). In addition, the ISO technical report mentions that the limits for moving walk deceleration rates would require a better clarification (ISO/TR 14799-2 2015, p. 23).

5.4 Velocity gradient studies from several engineering fields

The effects of velocity gradients are generally studied with participants who are exposed under long lasting or under high magnitudes of velocity gradients. Standing participants are studied for both cases; with and without external support, such as a handrail. Because of the effects of velocity gradients on the human body are not widely studied subject in the vertical transportation industry, studies from several other engineering fields are used in parallel with found vertical transportation studies. The chosen engineering fields are vertical transportation, aeronautics, public transportation and medical engineering.

It must be noted that the velocity gradients in vertical transportation industry are mostly linear, as the machines are moving from location A to location B in a straight line. Other transports, such as trains or aircrafts, are required to have turns and therefore have both, linear and angular motions, which have their own velocity gradients and effects. The angular velocity gradients are results of centrifugal force, as the vehicle is making a turn. (Previc & Ercoline 2000, p. 23, 26) Angular motions and their velocity gradients are thus mostly left out of this study.

5.4.1 Elevator studies

There are hardly any of elevator related velocity gradient studies carried out in the 21st century. However, in the 1970's Feyrer studied the safety of passengers during an elevator stop e.g. with oil and spring buffers. Studies were carried out by placing four participants in 600 kg elevator with the max speed of 2,0 m/s, one participant in 2 100 kg elevator with the max speed of 0,8 m/s and two participants in 2 000 kg elevator with the max speed of 0,4 m/s. Then participants were exposed to the magnitudes of decelerations. Lastly, the surveys of participant perceptions were carried out. None of the tests led to injuries. (Feyrer 1973)

The results indicated that the rubber spring buffers stop the car with transient oscillations, which lead to unpleasant perceptions among passengers. When oil buffers were used, the initial shock was harder, but the oscillation faded away faster than with rubber buffers. Participants experienced oil buffers loud, but tolerable. When elevator with counterweight was studied, the counterweight created additional oscillation. This was caused by the jumping of the counterweight and then hitting the slack ropes. Then again, the jumping of the counterweight resulted from the impact of the buffers. In addition to oscillation, the jumping of a counterweight caused violent vibration and feeling of sudden weightlessness, which were felt unpleasant by the participants. (Feyrer 1973)

A portion of the test runs are collected in Table 5 below. In some of the cases, the maximum retardation exceeds the indicated values from Table 5, because of the boundaries of oscilloscope were exceeded. The table uses the following abbreviations: *CWT* stands for counterweight and *N/A* for not available.

Table 5: Passenger perception during the operation of the safety gear and buffer tests (Feyrer 1973, p. 4)

Decele-ration type [-]	**Rated load x speed [kg] x [m/s]**	**Braking length* [mm]**	**Average deceleration [m/s²]**	**Maximum deceleration [m/s²]**	**Braking time [s]**	**Number of subjects and their perceptions [-]**
Safety gear	2 100 x 0,8	45	7,1	N/A	N/A	#1: Bearable #2: Uncomfortable
	750 x 2,5	145	19,8	>51	0,13	#1: Unpleasant and very noisy
Spring buffer (rubber)	2 100 x 0,8	46	7,0	17,5	N/A	#1: Bearable #2: Unpleasant
	375 x 1,25	80	9,75	17,0	N/A	#1: Bearable
Oil buffer	600 x 2,0	320	5,5	8,0	0,515	#1−3: Well tolerated, violent vibrations
	750 x 2,5	320	9,8	22,5	0,32	#1: Tolerable, loud, violent vibrations
CWT & spring buffer	2 100 x 0,8	37	8,7 [I]	17	0,16	#1&2: Unpleasant
CWT & oil buffer	750 x 2,50	320	6,9 [I]	19	0,32	#1: Unpleasant

* Buffer stroke or gripping length

[I] Average deceleration of the counterweight

According to Feyrer (1973), the safety regulations limiting the velocity gradients to 9,81 m/s^2 were sufficient for the safety of elevator passengers. Even small overshoots of limit value were seen as acceptable. In addition, Feyrer proposes that the magnitudes of deceleration with elevators moving less than 1,5 m/s could be limited by the durability of the components instead of the safety of the passengers.

Over the years, standard committees, such as the A17 Main Committee, have carried out studies and revisions to improve standard information and instructions as well as passenger safety in general. In the year of 1992, Technical Revision 92-75 was used to study horizontal retardations for both emergency electrical and mechanical stopping of an inclined elevator. As inclined elevators were relatively new machines at the issued time, the study referred to the studies of conveyor systems in U.K., Japanese trains and American buses from where standard revision was built on. (Gibson 1995) Some of these studies are included in more detail later on this paper.

With modern vertical elevators, when vibrations (e.g. from a bump in the rails) are neglected, velocity gradients are generated only in vertical direction by initiating the movement or by retarding and stopping of the car. Most of the modern elevators use electric motors with a variable speed drive system. The drive is a closed loop system, which tries to generate car movement according to the chosen velocity profile. An example of velocity profile with ideal kinematics can be seen from Figure 6, where an elevator moves from one floor to another. First, the elevator is at a halt and initiates the motion with a uniform acceleration until the maximum velocity is reached. As the destination approaches, the machine starts (a uniform) deceleration. Usually, the magnitudes of deceleration are relatively low before the car stops the motion in order to create calm stopping. The velocity profile is usually designed in order to move the load in the minimum possible time without neglecting the passenger safety and comfort. (Al-Sharif 2014, p. 1−4)

In addition to velocity, the velocity profile includes velocity gradients; accelerations, decelerations and jerks. The decision of magnitudes of acceleration and jerk is compromise between the ride comfort and the travel time, as the travel time is prolonged due to transition time of acceleration. However, the magnitudes of acceleration and jerk should not exceed the values set by the standards. According to Al-Sharif (2014), the comfort limit for the velocity gradient is approximately 1 m/s^2 and for the jerk approximately 1 m/s^3. As can be seen from an example of Figure 6, the magnitudes of velocity gradients and jerk are close to the comfort limit, but still under the safety limits set by the standards.

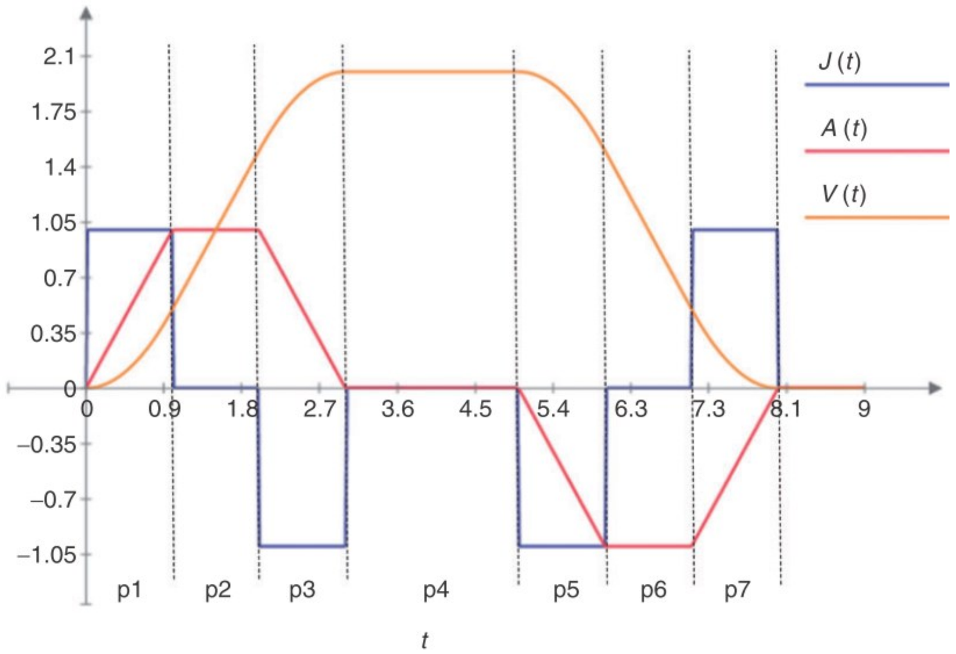

Figure 6: Ideal kinematics of elevator (Gernstenmeyer & Peters 2016, p. 738)

A study by Gernstenmeyer & Peters (2016) offers equations to calculate and control the deceleration of elevators. According to the study, the equations of controlled deceleration can be used in order to control safety distance for multiple cars in a single elevator well. The study took on account the maximum deceleration, e.g. from standards, but did not inspect if the maximum deceleration was safe of not for the passengers.

Great part of elevator studies are focusing on the ride comfort or elevator component reliability and safety. Papers that are studying vertical velocity gradients in relation to the passenger safety are in lesser number.

5.4.2 Escalator and moving walk studies

In the year of 1983, ASME A17.1 was revised to limit the retardation of an escalator into the value of 0,91 m/s^2. The same limitation is still valid today for ASME A17.1: 2016. The revision was based on the U.K. high-speed conveyor study by Browning (1974) where approximately 1 000 different passengers from a variety of people with age ranging from two months old to 85 years old were tested with approximately 18 000 subject runs. The tests were carried out between the years of 1969 and 1972. The work studied the tolerance of pedestrians to the motion of the acceleration and deceleration of a conveyor, passenger ability to transfer between conveyors and the machine safety in general. The study had several results, from which prime results are the following:

1. Small amplitude vibration in the horizontal direction can be effectively damped by the legs of a standing passenger,
2. the balancing reaction uses the natural frequency of around one hertz,
3. large amplitude vibration in a horizontal direction near the natural frequency can impede the maintenance of balance,
4. if the duration of vibration is only a few seconds, high vibrations can be tolerated,
5. the loss of balance depends on the magnitude of velocity gradients and the jerk of the transportation machinery,
6. recommended maximum level for linear velocity gradients, both acceleration and deceleration, are approximately 0,54 m/s^2 (0,055 *g*)
7. the high magnitudes of jerk occurring in less than half a second results in a high possibility for a passenger to lose the balance.

In addition to previous results, a family of acceptance curves for acceleration level in relation to time was compiled. Curves are presented in the Appendix B of this paper. Compiled curves were suggested to be used as the maximum emergency retardation. As can be seen from the Appendix B, the current escalator retardation limitation of 0,91 m/s^2 (just below 0,1 *g*) might result in moderate movement with general public, but not with fit adults. The issued magnitudes of retardation are suggested to be used as emergency deceleration for passengers who might not be using a handle. If all of the passengers are expecting deceleration and thus using handles, the magnitudes of velocity gradients can be as high as 1,96 m/s^2 (or 0,2 *g*). (Browning 1974; Gibson 1995) However, in real world it must be assumed that passengers are not continuously expecting for emergency braking or even using handles. Therefore, previous high velocity gradients can result in accidents in case of emergency braking.

Currently, the stopping requirements from escalator standards are related to the stopping distance with the maximal speed and with differing loads. In the year of 2001, Working Group 2 (WG2) from CEN/TC 10 subcommittee completed a study, where passenger comfort with varying the magnitudes of deceleration was studied. The participants were asked to ride on a downward moving escalator that was stopped during the journey down. Afterwards participants were asked to judge the stopping comfort of the escalator and evaluate a possibility for falling. (Stein & Ludwig 2003) The results are gathered in the Table 6 below.

Table 6: Felt comfort vs. the magnitudes of escalator deceleration (Stein & Ludwig 2003)

Speed of the step band		**Braking distance adjusted [m]**	**Top deceleration [m/s²]**	**Top jerk [m/s³]**	**Felt Comfort [-]**
Nominal [m/s]	**Measured [m/s]**				
0,50	0,475	0,208	0,854	2,6	Comfortable
0,65	0,617	0,300	0,948	2,7	Limit for comfort
0,75	0,710	0,354	1,256	3,6	Uncomfortable
0,75	0,710	0,383	1,013	2,9	Limit for comfort

From the Table 6, the deceleration of 1,00 m/s^2 was seen as suitable for passenger comfort. All cases resulted in an acceptable braking distance and only one case exceeded the magnitude of the deceleration limit of 1 m/s^2, which was also seen with the highest jerk value.

Later on, Al-Sharif (2004) studied an intelligent braking system for public service escalators. A similar system can be used for moving walks as well. The study utilized a new braking system, which would enhance passenger safety during the braking operation by introducing a closed loop feedback braking system. System controls stopping characteristics, such as value of deceleration, jerk and stopping distance. In a similar fashion to study by WG2, participants rode a downward moving escalator that was stopped and then asked to rate the stopping comfort. However, in the study by Al-Sharif, the judging was completed with a scale from one to ten, where one was poor and ten was very good comfort for stopping and safety in general. An escalator was equipped with an intelligent braking system in which braking parameters could be altered. Comfort of a conventional stop was rated as 2/10, inverter stop 9/10 and frictional stop (both brakes are lifted and machine stops under friction) 10/10. As the benchmark of the best and the worst stops were known, tests with several of braking settings were carried out. The maximum magnitudes of deceleration and their comfort levels are collected in Table 7 below. (Al-Sharif 2004)

Table 7: Felt comfort vs. the magnitudes of escalator deceleration (Al-Sharif 2004, p.7)

Stopping distance [m]	Stopping time [s]	Top deceleration [m/s^2]	Felt Comfort, scale 1−10 [-]
0,6	1,5	1,00	5
0,7	1,8	0,50	6
0,8	2,1	0,41	7
0,9	2,4	0,35	8
Inverter stop	N/A	0,18	9
Frictional stop	N/A	0,24	10

Table 7 represents the correlation between deceleration magnitudes and the passenger comfort during the stopping of an escalator. As can be seen, all cases resulted within an acceptable stopping distance when compared with EN 115 limitations, but only the first row was decelerated with the magnitude of deceleration limit value. Even though the rest of cases used more than half times smaller deceleration values, variation in the stopping times were less than one second with the intelligent braking system. By lowering the deceleration values, ride became smoother and thus more comfortable indicated by the felt comfort. In addition to the Table 7, the magnitudes of deceleration and corresponding comfort levels are plotted on a scatter diagram, which can be found from the Appendix C. The diagram shows the relationship between magnitudes of deceleration and the stop quality, as the correlation coefficient of 0,89 was calculated. I.e. most of the comfort variation was caused by the variation in the magnitudes of deceleration. (Al-Sharif 2004)

Later on in the year of 2007, Al-Sharif completed a research with the same setup, where ten subjects rode a downward moving escalator that was stopped with an intelligent braking system. Fifteen tests were carried out. This time the correlation coefficient between the magnitudes of deceleration and the stop quality was 0,913. In comparison with the previous study, this time jerk was studied as well. The risk of falling due to escalator stopping can be reduced by giving the passenger more time to prepare for the deceleration by lowering the magnitudes of the jerk. More time can be achieved e.g. by having a low pre-acceleration-peak jerk, as in this case it takes a longer time for deceleration to reach its maximum value. The correlation coefficient between the pre-acceleration-peak jerk and the value of stopping quality was approximately 0,875 and the correlation coefficient with post-acceleration-peak jerk to stopping quality was approximately 0,663. As the strongest factor for the quality of the stop is the magnitudes of deceleration, the best improvements can be achieved by reducing the value of the maximum deceleration. However, the effect of the maximum jerk should not be neglected. (Al-Sharif 2007)

Al-Sharif (2004) used hydraulic brakes with an intelligent braking system when passenger comfort in escalator stopping was studied. In comparison, similar results can be achieved by using an electrically based intelligent braking system, which was studied by Seaborne et al. (2010). Similarly to hydraulic elevators being overrun by electrical elevators, electrically based intelligent braking systems are taking over the hydraulic based intelligent braking systems. Electrical systems have a faster response and they are cheaper. In addition, the hydraulic based intelligent braking system requires a special controller. (Al-Sharif 2004, p. 2; Seaborne et al. 2010; Al-Sharif 2012)

In addition to previously mentioned studies, simulation models on passenger kinematics are used to study passenger falls on escalators. Al-Sharif et al. (2012) built and verified a Matlab model that calculates the maximum value of the deceleration for decreasing the risk of passenger fall caused by a sudden escalator stop. According to the study, the decelerations of 1,36±0,2 m/s^2 leads to a passenger to fall. Therefore, the study proposes escalators to limit the maximal deceleration of a stopping escalator at 1,16 m/s^2. (Al-Sharif et al. 2012)

5.4.3 Aeronautics

A human body can survive surprisingly high magnitudes of velocity gradients resulted e.g. from riding a stationary transportation machine or a mobile vehicle, a crashing of such machine or simply by falling. Even though a human can survive a high level of velocity gradients, exposure should be avoided, as it might have undesired effects on human wellbeing. In the 1950s, Stapp J.P. studied the effects of deceleration forces of high magnitudes on a man in order to understand stresses associated with aircraft ejections and later on with the car crashes. For the study, several volunteer human subjects were tied on a chair and exposed to velocity gradients with the magnitudes of higher than 30 *g*'s (>294 m/s^2) in several different impact directions. The highest recorded magnitude of a velocity gradient covered deceleration of almost 83 *g*'s (~814 m/s^2) that was measured on the chest. Subjects left without irreversible injuries, but suffered the compression of soft tissue, pain and later on stiffness for several days. (Chandler 2003, p. 7−10)

The high magnitudes of velocity gradients do not only result in physical injuries, such as the previously mentioned compression of soft tissue, but can lead in a loss of consciousness as well. The level when the subject loses consciousness depends e.g. on the orientation and features of an individual. Rudnjanin et al. (2006) studied the loss of consciousness by accelerating 2 192 aircraft pilots in a vertical direction. Studied pilots were divided by their anticipated tolerance to the loss of consciousness from air academy pilots to high performance combat pilots. Only eleven subjects (0,50 %) experienced the loss of consciousness during the tests. Nine subjects lost their consciousness with velocity gradients of 5,5 *g* (53,94 m/s^2), one at 6,0 *g* (58,84 m/s^2) and the last one at 7,0 *g* (68,65 m/s^2). All of the loss of the consciousness occurred without warning symptoms, such as the loss of peripheral vision. (Rudnjanin et al. 2006) The loss of consciousness does not occur instantly. Whinnery & Forster (2013) studied 888 centrifuge induced tests. The earliest occurrence of the loss of consciousness between 5,5−7,0 *g* required the exposure of five seconds, as the latest occurrence required more than 90 seconds (Whinnery & Forster 2013, p. 4).

Predicting the perception of the vertical self-motion is essential in the field of vehicle simulation and in a clinical assessment of balance disorders. Nesti et al. (2014) studied human sensitivity to vertical self-motion by seating participants into a CyberMotion Simulator chair, shifting the simulator with varying velocity gradient amplitudes and asking which movement was stronger in relation to acceleration, velocity and covered distance. The velocity gradient amplitudes varied between 0 and 2 m/s^2. Nesti et al. noticed that the amplitudes of velocity gradients could be higher for upward than downward motions. In addition, humans are less sensitive to vertical motion in comparison to horizontal motion. Nesti et al. speculated that the greater sensitivity to a downward self-motion and increased sensitivity with the higher velocity gradients are results from the human perception of vertical movement as it modulates around the gravity as well as from the human tendency of avoiding falling. (Nesti et al. 2014, p. 305, 309−311)

In a similar fashion to Nesti et al., MacNeilage (2010) seated ten subjects aged 19−34 years old on a 6-degree-of-freedom motion platform and studied the otolith organs. The research studied the direction of movement in the head coordinates, the direction of movement in the world coordinates and the body orientation. Participants were exposed to varying velocity gradients with the peak magnitude of 1,13 m/s^2. For the identification of greater magnitude of velocity gradients, velocity gradients around 0,3 m/s^2 were used. According to the results from the elevation heading and coarse direction tasks, similar results from the previous studies of lower threshold for the horizontal than the vertical plane were found. In addition, the vestibular heading estimate depends on the body orientation and on the direction in the head coordinates. This indicates that the performance is affected by how the gravitational velocity gradient vector and the generated velocity gradient vectors are oriented in respect for the head. Lastly, the world-centric direction was the only factor that had at least modest influence on the performance of identification of greater magnitude of velocity gradient tasks. (MacNeilage et al. 2010)

5.4.4 Public transportation

Each day millions of people around the world are traveling on the railroads e.g. with trains and metros. Similarly to elevators, escalators and moving walks, velocity gradients from trains and metros are limited to ensure a passenger safety for both, sitting and standing passengers. In the year of 1960, New Tokaido Line studied braking retardation and the magnitudes of jerk associated with the Japanese trains by using forty male volunteers. The suitable limit values to prevent standing passenger falls were specified for situation, where volunteers were standing laterally in the moving direction and usage of hand straps were allowed, but not demanded. According to the study, the allowable horizontal retardations ranged between 1,67 and 1,96 m/s^2 where participants were using hand straps. (Matsui 1962; Gibson 1995, p. 66−67) According to the Federal Railroad Administration of the USA, the maximum longitudinal acceleration in issued situation is 1,96 m/s^2 and the maximum jerk is 2,94 m/s^3 (Federal Railroad Administration 1993). Horng et al. estimated the peak of acceleration and deceleration of a modern MRT metro to be around 1,18 m/s^2, which is notable lower than either of previously mentioned values (Horng et al. 2015, p. 919). The engineers from TÜV Bayern engineering office support the horizontal retardation limitation proposed in the previous study by Matsui (1962). In addition, the engineers mentioned that transports should prefer long-jerk durations over one second or lower, as the shorter duration tend to result in falling, as the passenger tend not to have enough time to react to the excitation. (Gibson 1995, p. 67)

A study by Powell & Palacin (2015) gathered several of papers studying the limits of maximum longitudinal acceleration with railroad vehicles. In the 1950s, the British Railways studied lateral accelerations due to track curvature. Horizontal velocity gradient magnitudes over 1,18 m/s^2 were defined as uncomfortable for standing passengers. Later on similar studies were conducted in Japanese railroads e.g. by Hiroaki (1995), whose results are presented in Figure 7. As the magnitudes of velocity gradients varied among different studies and nations, Powell and Palacin noted that studies could only provide a general scope for acceptable levels of velocity gradients. In addition to several studies, Powell and Palacin gathered the examples of maximum accelerations from British railroad vehicles. The maximum velocity gradient for the traction varied between 0,37−1,30 m/s^2, for service braking between 0,7−1,5 m/s^2 and for an emergency braking between 0,70−3,00 m/s^2. (Powell & Palacin 2015)

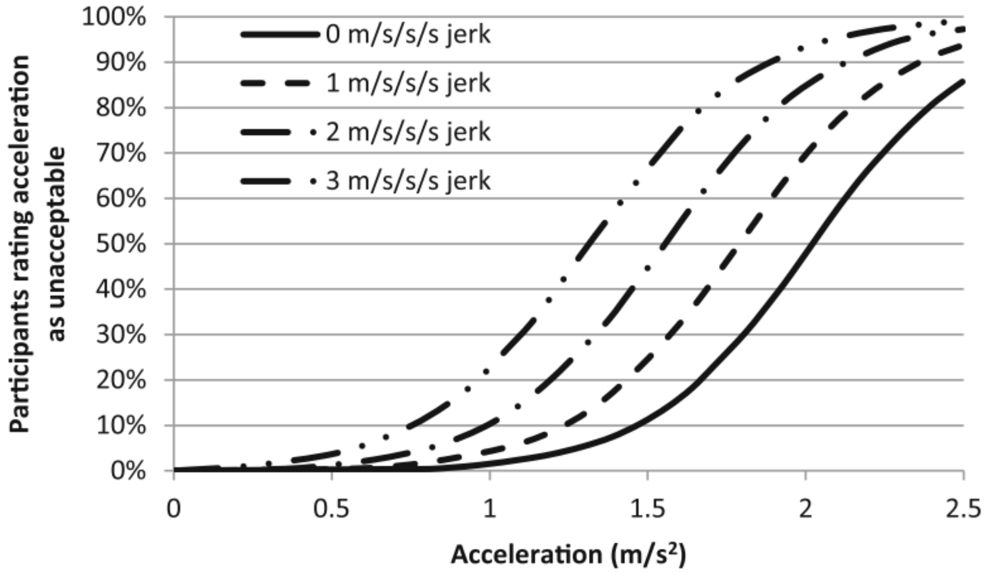

Figure 7: Acceptability of velocity gradients with railroads (Hiroaki 1995)

As can be seen from Figure 7, the greatest magnitude for an emergency brake deceleration of over 2,50 m/s^2 is easily considered unacceptable according to study by Hiroaki (1995). More recently, Verriest et al. (2010) studied the kinematics of young and healthy standing passengers under an emergency braking where the top magnitudes of velocity gradients were around 3,50 m/s^2. Passengers without support and facing rearward had the most trouble maintaining their balance, as none of ten participants could resist the motion. When free-standing participants were facing forwards, 30 % of the participants were able to maintain their balance. However, this required very large steps and good physical condition. When leaning against a buttock rest was studied, 70 % of supported passengers facing forwards were able to stop the motion. (Verriest et al. 2010) According to Hirshfeld, unsupported passengers facing forward and sideward would lose their balance averagely at 1,62 m/s^2 (1,27 m/s^2 if only facing forward), overhead strap supported passengers at 2,26 m/s^2 and vertical grab rail supported passengers at 2,65 m/s^2 (Hirshfeld 1932).

The modern airport terminals can be huge buildings where people might be required to travel for long distances. In addition to moving walks, some airport terminals have automated trolley cars transporting people in horizontal directions. The vehicles are designed to carry up to fifty people. Cars are limited to accelerate and decelerate at about 0,98 m/s^2 during the normal usage. In the case of an emergency, the deceleration is raised up to 2,94 m/s^2. The emergency deceleration limit is rather severe and might cause balance loss if a passenger is not sitting or holding onto something. (Strakosch & Caporale 2010, p. 574, 578) In relation to trolley cars and moving walks, Otis studied horizontal retardations by using emergency braking stops with New York buses in the 1970s. The typical hard stop was achieved with horizontal retardation of 2,45 m/s^2. According to the study, the magnitudes of horizontal retardation would have caused standing passengers to fall unless passengers were not holding onto handholds or poles or were supported by other passengers. (Gibson 1995, p. 67)

The most commonly experienced horizontal velocity gradients with public transports are in buses, railroads and aircrafts. The Shock and Vibration Handbook gathered the approximate magnitudes and durations of issued velocity gradients, which are presented in the Table 8 below. In addition to the magnitudes and durations of velocity gradients from the handbook, the magnitudes of the jerk are calculated for the table.

Table 8: Common horizontal velocity gradients in public transits (Harris & Crede 1976, t. 44.5; Gibson 1995, p. 67; CDRA 1993)

Transport [-]			**Magnitude [m/s²]**	**Duration [s]**	**Jerk [m/s³]**
US bus & railroad vehicles	Normal acceleration and retardation		0,98−1,96	5,0	0,2−0,4
	Emergency stop	from 110 km/h	3,92	2,5	1,57
		from 40−50 km/h	2,45	2,5	0,98
Colorado funicular		Standing passenger	1,18	N/A	N/A
		Sitting passenger	2,16	N/A	N/A
Ordinary aircraft			4,90	≥10	≤0,49

As can be seen from the Table 8, the highest magnitudes of velocity gradients and similarly the longest durations occur with aircrafts. In order for aircrafts to take off, they require long-lasting accelerations of usually more than 10 seconds, which are not common with non-aviation transports (Previc & Ercoline 2000, p. 41). Because of the long velocity gradient duration, the magnitudes of a jerk are tolerable. However, the aircraft pilots and passengers are required to sit down and in addition wear a seatbelt e.g. during take-off and landing. In the normal use of buses and railroad vehicles, the magnitudes of velocity gradients are hardly within the range where a passenger can maintain their balance with the help of external support, such as handholds. In addition, unsupported standing passengers would most likely lose their balance. Especially older adults would most likely fall. In the case of an emergency stop, regardless of having external support or not, a standing passenger would most likely fall. This is inevitable for the emergency stop in a high velocity, as the magnitudes of velocity gradients are over 150 % higher than with low velocities. In addition, the magnitudes of jerk are two and four times higher than the proposed jerk value of 0,5 m/s^3 by De Graaf & Van Weperen (1997).

5.4.5 Medical engineering

Mihara et al. (2008) studied the human balance by disturbing standing participants on a moveable platform to disturbances. The prefrontal cortex was imaged with neuroimages in order to study its role in the human balance. Fifteen healthy participants with age-range of 25 to 47 years old were disturbed with predicable and sudden disturbances in horizontal directions. The used platform was displaced for 4 cm with peak acceleration of 5 m/s^2. During the experiments, all of the participants were able to maintain their balance without the need of an external support in both test; anticipated and sudden perturbations. According to Mihara et al., the ankle strategy was sufficient for the maintenance of balance. The cortex receives multiple inputs from auditory, somatosensory, visual and vestibular system, which can be used to enhance the activation of postural control. By having input of knowing the perturbation is approaching, participants could allocate attentional resources to maintain the postural balance. (Mihara et al. 2008)

De Graaf & Van Weperen (1997) studied the maximal magnitudes of velocity gradients at which participants could maintain their standing balance as well as compared these results with similar, but older study by Jongkees & Groen (1942) and measured the magnitudes of velocity gradients from the public transports. First, 22 participants, aged from 26 to 63 years old, were exposed to sudden acceleration magnitudes varying in steps of 0,1 m/s^2 over range from 0,3 to 1,6 m/s^2 by using a conveyor belt that accelerated for a distance of 45 cm. The participants were standing unsupported and with the heels of their feet together. Secondly, the velocity gradients of public trams, buses and metros were measured and compared with previously measured values. Thirdly, the effects of the jerk were studied by exposing ten new participants to the acceleration of 1,0 m/s^2 and to the varying magnitudes of jerk from 1 to 10 m/s^3. The results of the first phase are collected in the Table 9 below.

Table 9: Group means for the maximal magnitudes of accelerations for maintaining the balance (De Graaf & Van Weperen 1997, p. 114)

Study [-]	**Forward [m/s^2]**	**Sideward [m/s^2]**	**Backward [m/s^2]**
Jongkees & Groen (1942)	0,48	0,33	0,76
De Graaf & Van Weperen (1997)	0,54	0,45	0,61

As can be seen from the table, the sideward direction proved to be the hardest for balance maintenance, as the feet were together. However, as the participants were allowed to have their feet further apart and not completely in line, resistance to a movement in the sideward direction could be improved to twice higher acceleration levels (mean of 0,93 m/s^2). When these results were compared with the velocity gradient magnitudes of public transports, none of the tested participants could maintain their balance without external support, because the initial accelerations of transports generally varied between 1 and 2 m/s^2. Lastly, as the effects of the jerk were studied, 35 % of the participants could not stand properly even during the lowest jerk level of 1 m/s^3. Therefore, the jerk magnitudes between 0,5 and 0,6 m/s^3 were proposed for longitudinal velocity gradients with un-supported standing passengers. (De Graaf & Van Weperen 1997)

As mentioned earlier in this thesis, the maintenance of the balance is harder with high CoG and small BoS, such as a passenger wearing high heeled shoes. A research by Nagata et al. (1996) studied the tolerance to horizontal velocity gradients with participants wearing various heel heights. Participants with the high heels (the height of 89 mm) encountered the loss of balance with 38 % smaller magnitudes of forward acceleration than the participants with lower heels (the height of 12 mm). The loss of balance, because of high heels, can also be seen e.g. from the escalator-riding accidental statistics at MRT station. (Chi et al. 2006; Nagata et al. 1996)

Horng et al. (2015) found out that the horizontal acceleration magnitudes over 0,98 m/s^2 affects human visual acuity by decreasing the human vision. The human visual system generates the base for the spatial reference system and feeds the information about body movements for CNS (Smetanin et al. 2004). The magnitudes under 0,98 m/s^2 did not have significant effect on the dynamic vision. Especially the forward directed acceleration to a person standing on a moveable platform decreased both vision and stereopsis significantly when the magnitude of forward directed acceleration was over 0,98 m/s^2. Lateral acceleration had similar, but not as strong effect. In addition, participants complained about ocular strains during most of the tests. (Horng et al. 2015)

Where Horng et al. studied the effects of horizontal velocity gradients, Mueller et al. (2016) studied vertical velocity gradients and their correlation to human ability to detect the vertical velocity gradients. According to Mueller et al., the detection varies depending on the direction of movement (up or down) and the extent over the stimulation is made. The detection is better for downward motion, as upward motion gives greater support for the human body. A greater extent of stimulation easies the detection as well. In addition, the detection seems to be the same regardless of the velocity gradient being an acceleration or a deceleration. (Mueller et al. 2016)

6. DISCUSSION

As the effects of velocity gradients on the human body with an elevator, an escalator and a moving walk applications are hardly studied, accurate and exact data are hard to come by. In addition to hard-to-find data, different standards on the same subject give variable limitations to machine design. Therefore, studies based on similar issues, such as the studies of human balance with moveable platforms, are used to refer to machinery applications. This chapter focuses on the question of are the located study results from differing backgrounds compatible with vertical transportation industry and how this study has reached its goals. First, the usability and comparability of used statistics are analyzed. Afterwards the chosen vertical transportation standards and study results are being compared. Lastly, generated development proposals for the vertical transportation industry and contributions of this thesis are presented.

6.1 Comparability of used statistics

This study utilizes several of vertical transportation statistics and the studies analyzing similar statistics from around the world. The statistics are chosen in order to cover information from several continents where the chosen vertical transportation standards are used. Some of the statistics cover information from an entire country, as others only from a specific organization or from a building, such as MRT station described in Chapter 5.1.2. Thus the extent of used statistics fluctuates from dozen to thousands of records. Most of the utilized statistics are issuing the occurrence of vertical transportation accidents in order for this paper to study the development of vertical transportation industry and the effects of velocity gradients on human body.

According to the study by Park and Yang (2010), the same sorts of accidents frequently occur in vertical transportation industry. Regardless of the country, statistics support this statement, as the majority of the elevator accidents occur with trained installation and maintenance personnel who one way or another violate the safety instructions during working hours. The high number of violation of safety instructions was surprising for the author. The number one elevator accident appears to be being crushed or stuck e.g. between the elevator doors. Elevator accidents related to velocity gradients are not that common and therefore they are usually included in with other accident types e.g. user carelessness. Where elevators are relatively safe when velocity gradients are considered, the same conclusion cannot be said for escalators and inclined moving walks. Accidents with escalators and moving walks tend to occur with either children being entrapped or older adults falling. When velocity gradients are considered, escalators and inclined moving walks are clearly more hazardous according to the statistics and the number of produced escalator fall studies. This is an anticipated result, as elevators are closed systems, which only utilize movement in the vertical dimension. The risk group for the effects of velocity gradients are passengers with weaker postural control, such as older adults and especially elderly women (Chi et al. 2006; O'Neil et al. 2008; Howland et al. 2012).

When qualitative rigor of this thesis is analyzed, the utilized statistical data can only be considered indicative and not completely accurate. The statistical data on occurred vertical transportation hazards are never all-inclusive, as it is unknown how many accidents or narrow escape situations are left unreported. For example, Zarikas et al. mention that before the year of 2005 the data collection of elevator accidents in Greece was very poor (Zarikas et al. 2013, p. 94). This can also be seen by comparing the number of reported accidents in Greece and South Korea, as South Korea had reported more accidents within a year than Greece in twelve years. In addition to unreported data, the sample size and time period of used statistics are important factors when statistics are analyzed and compared. Statistics with a higher sample size and a longer time period can be considered more accurate than statistics with a lower sample size or a lower time period. However, when is the sample size or time period big enough, is debatable. For this thesis, the sample size of used statistics were sufficient and dependable, for statistics were only used as directional. Lastly, because of the statistics from several of countries are used, documentation style differs and varies qualitative rigor slightly. For example, none of studies or statistics of the reported elevator accidents clarified velocity gradients as separate reason for accidents, but several of escalator and moving walk studies and statistics did. In addition, some countries favored to include the elevator, escalator and moving walk accidents as a single category and some separated elevator accidents from escalator and moving walk accidents.

6.2 Comparison of vertical transportation standards

First two research questions reflected the current limitations of velocity gradients according to the safety standards and how standards have settled on these limitations. Generally, the standards do not inform on which studies the guidelines are based on. However, some technical papers, such as Elevator World, issue the development of standards. According to Gibson (1995), the revision of escalator braking for ASME A17.1: 1983 was based on the study by Browning (1974). In addition, according to Feyrer (1973), the limitation of vertical deceleration is based on the jumping of the counterweight. As only two references to justification of two guidelines were found, it is impossible to answer accurately for the second research question within this thesis.

Nevertheless, the chosen vertical transportation standards, ASME A17.1, EN 81 & 115 as well as Japanese codes, can be considered up to date and comparable with each other. Each standard is updated within a set period interval, such as three years for ASME A17.1. Naturally, if there is nothing to be revisited within the period, then the revision is moved for the next period. The standard revision ensures the effects of the most current technical solutions and new findings as well as revisions on other standard revisions. For ISO, a worldwide federation of national standards, produces technical reports comparing vertical transportation safety standards, the comparison of chosen safety standards can be considered justified for this paper as well.

Even though some of the limit values and safety instructions are varying from one standard to other, the majority of guidelines are within the same area with all three standards. When velocity gradients are considered, especially the limitation to the vertical component of elevator deceleration is seen to be unanimous with all three safety standards where no elevator should exceed an average deceleration of 9,81 m/s^2 or transient deceleration of 24,5 m/s^2. According to Feyrer (1973), the limitation of the vertical velocity gradient to the value of acceleration of gravity originates from the safety and ride quality perspectives. If the vertical velocity gradient exceeds the acceleration of gravity, jumping of the counterweight might occur due to the use of safety gear or the buffer impact. Jumping of the counterweight might result in unpleasant elevator ride or in the worst case damage the ropes, which might lead to severe accident. The limitation became more common in the 1970s and is currently widely used by several of the safety standards. (Feyrer 1973, p. 1−2)

With inclined elevators the horizontal component of deceleration is approximately twice smaller for ASME A17.1 than with EN 81-22 or Japanese codes with both, average and transient decelerations. When escalator and moving walk deceleration limitations are considered, none of the safety standards are in direct consensus for the velocity gradients. However, the variety between the limit values are within ±0,17 m/s^2, which can be considered insignificant for passenger balance, as most of the balance studies are suggesting human to lose balance with higher magnitudes than the highest limitation of 1,25 m/s^2.

As seen from several of the balance studies, the human balance is more easily affected by the deceleration than the acceleration. Therefore, it is not surprising that all of the safety standards are limiting elevator deceleration comprehensively. However, the lack of elevator acceleration limitations was a surprising result. The same cannot be said for the escalator and moving walk limitations as the values for both, acceleration and deceleration, were provided. However, it is surprising that the velocity gradient limitations are more extensive for escalators and moving walks than elevators, especially as the elevator passengers are exposed more frequently and under higher magnitudes of velocity gradients than escalator or moving walk passengers.

According to Schiffner (2004), emergency stops with an electrical safety device are the most common emergency stops with elevators, but nevertheless they are only occasional. Regardless of small frequency, safety standards and designers should take into account the combined effects of safety equipment e.g. during emergency braking. In some cases several safety equipment might overlap and create new hazardous situations. For example, situation where several braking systems would engage simultaneously, e.g. because of the power failure, and create higher magnitudes of velocity gradients than anticipated by the standards.

The standards divide velocity gradients into two sections depending on the duration of velocity gradient. The sections are durations under and over 0,04 seconds. As mentioned by Tokuno et al. (2010), longer velocity gradient intervals create greater differences in postural control with standing young and older adults. In addition, the UK Defence Standard 00-25 supports the importance of duration of velocity gradient to the human safety. Velocity gradients with short durations of under a second create impact like disturbances and longer durations create sustained velocity gradients. These are also represented in the Figure 8. (Defence Standard 1992, p. 9, 14)

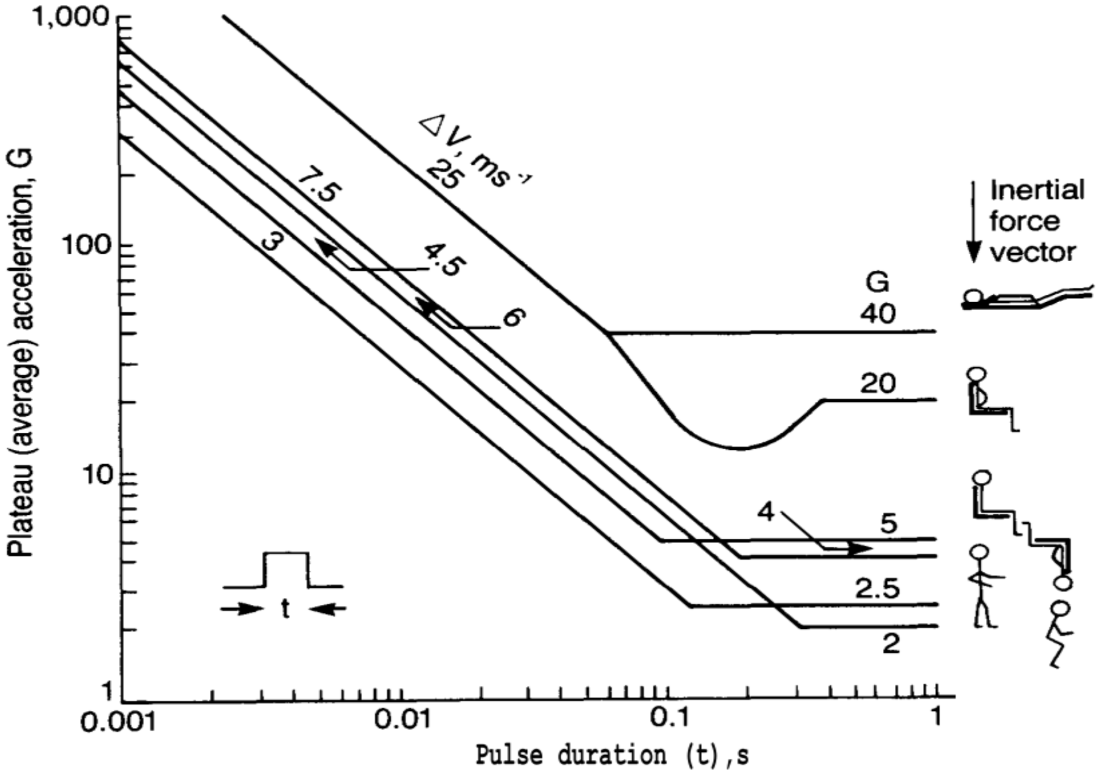

Figure 8: Human tolerance to vertical velocity gradients under various conditions of body restraint (Defence Standard 1992, p. 14)

According to Figure 8, an upright standing human can withstand a vertical velocity gradient pulse of over 98,1 m/s^2 (>10 *g*) lasting for 0,01 seconds or a pulse of 24,5 m/s^2 (2,5 *g*) lasting over 0,1 seconds without an injury. However, the figure or the Defence Standard does not mention anything about the balance maintenance. Even though the safety standards of vertical transportation industry divide velocity gradient durations only in two sections, the segmentation is sufficient. The used boundary value of 0,04 seconds is functional, as the human tolerance to a vertical velocity gradient is close to constant onwards from the chosen boundary value. (Defence Standard 1992, p. 9, 14)

6.3 Comparison of vertical transportation standards to the statistics and the other engineering field studies

A human perception of position, motion and its magnitudes are in respect for the gravitational vertical and a surface of the Earth by using sensory inputs for the CNS. Therefore, when various, long-lasting and significant alterations to perception of orientation are made, such as in flight, vestibular information is no longer reliable for the detection of the magnitude or the direction of the gravitation. (Previc & Ercoline 2000, p. 82) For this reason, and the fact that the magnitudes of velocity gradients in vertical transportation industry are not particularly high, study results with the high magnitudes of velocity gradients are not directly comparable or transferable with the applications of elevators, escalators or moving walks. In addition, several of study results where participants were seated on a chair, such as Nesti et al. (2014), cannot be compared with balance analyzation. However, other results from aeronautic studies, such as human being less sensitive to vertical than horizontal motion or the limits of human body are comparable and transferable with this thesis. Similarly to accident statistics, results from aeronautic studies were used as directional and therefore were sufficient for this thesis.

When the magnitudes of velocity gradients are small, standing passengers of elevator, escalator and moving walk should be able to maintain their balance with ankle strategy. With higher magnitudes, or passengers with a weaker postural control, body position must be changed by using hip strategy. With even higher magnitudes, one or more steps might be required in order to prevent falling. This is called stepping strategy. Alternatively, additional support, such as handrails, could be provided in order to improve passenger maintenance of balance. However, support only works up to certain point with magnitudes of velocity gradients. As passenger room is limited with escalator and inclined moving walk applications, only the first two strategies are acceptable. In addition, handrails are offered with these machines. Even though elevators have room for one or two steps, passengers should not be required to rely on stepping strategy in order to maintain the balance. In addition, only passengers located next to car walls can utilize external supports. Therefore, to avoid possible balance loss with any of machines, only the low magnitudes of velocity gradients and jerks should be pursued. By having low jerk, the effects of velocity gradients are not as sudden. At what levels, passenger requires to change postural control strategy or possibly end up falling, depends on number of factors, such as the physical and mental capability of individual, CoG orientation to BoS (standing/sitting, facing towards/sideways in relation to movement, supported/unsupported) and the magnitude and orientation of external disturbances. In general, children and older adults have weaker postural control and therefore are more easily affected by the velocity gradients.

Escalator and moving walk passengers are instructed to stand still and hold on to the handrails during the entire travel time. However, as seen from the escalator fall studies, several passengers are walking during the journey. In addition, over 50 % of the passengers tend to not hold on the handrails (Ferrario & Hubbard 1993). Human mental factors can have an effect on maintenance of the balance. The older adults tend to have higher anxiety levels than younger adults when environmental constraints occur, such as during the use of escalator. Therefore, the tendency of people walking on escalators can be narrowed to passengers with better postural control. (Brown et al. 2002; Howland et al. 2012) Nevertheless of walking passengers having better postural control, walking passengers are in greater danger for falling or bumping into other passengers during an emergency stop. Therefore, walking should be avoided, e.g. with narrow conveyor pathways where passengers could not fit side by side.

In normal use, landings of escalator and moving walk are hazardous locations for loss of balance. The balance loss can occur if passenger moves significantly slower than conveyer belt does. According to Asai et al. (2017), the walking speed of older adults varies in the range of 1,4±0,2 m/s. It can be assumed that younger adults are at least capable of similar velocities. The maximum velocities of escalators and moving walks are in between 0,5−0,90 m/s. Therefore, older adults should be able to alter their velocities to match velocity of conveyor belt and minimize effects of velocity gradients.

The research by Al-Sharif (2004) is based on the European escalator standard, EN 115. As the stopping distances with EN 115 are significantly higher than with American or Japanese standards, the magnitudes of deceleration could be kept low. However, similar results could not be accomplished if the stopping distances from American or Japanese standards were used. The variation among stopping distances is a surprising result. Nevertheless, an intelligent braking system with a well-designed velocity curve could improve passenger safety even with sudden situations, such as an emergency stop. In addition, the Matlab simulation model created by Al-Sharif et al. (2012) is extensive as it utilizes a safety margin, which takes into account e.g. frail passengers and passengers with carryings. On the other hand, the model does not include the effect of the passenger holding onto the handrail, which weakens the dependability of a simulation model. However, by excluding the effects of handrails offers safer limitations on the deceleration values as only a proportion of passengers are actually utilizing the handrails.

As seen in Table 1, Tokuno et al. (2010) studied the smallest magnitudes of velocity gradients with young and old adults. Even though the magnitudes of velocity gradients were relatively low, most of the older adults had to take steps with horizontal decelerations of 2,30 m/s^2. Horizontal acceleration of 1,20 m/s^2 did not create similar requirement. According to Mihara et al. (2008) young adults on the other hand were able to maintain their balance in both, acceleration and deceleration, of 5,00 m/s^2. However, according to Jongkees & Groen (1942) a standing human could encounter the loss of balance during the horizontal acceleration of 0,33−0,76 m/s^2 depending e.g. on the body and leg orientation. Therefore, it is hard to say accurately when human might encounter the loss of balance due to the effects of horizontal velocity gradients.

All of the studies listed in Table 1 used sudden disturbances, which can be compared with the horizontal component of a sudden emergency stop of escalator, moving walk and inclined elevator. When velocity gradients from Tables 1 and 4 are compared, the top acceleration of escalator or moving walk can be considered safe, especially as an external support is provided. For the maximum deceleration of escalators or moving walks, values of Table 4 are approximately twice smaller than the one used by Tokuno et al. (2010) and the fact that passengers are able to use external support from handrails, the current maximal decelerations can be considered safe for the majority of passengers.

According to Feyrer (1973) and Figure 8, current vertical velocity deceleration limitations are safe for elevator passengers. Horizontal acceleration of inclined elevators could be limited in similar fashion to public transports, somewhere between 1−2 m/s^2. Similarly to vertical deceleration, the maximal vertical acceleration could be limited to 9,81 m/s^2. This would ensure that passengers traveling down will not lead to the loss of floor support, as the machine would accelerate faster than the acceleration of gravity.

When horizontal velocity gradients from Tables 1 and 2 are compared, it is likely that emergency stop with inclined elevator would result in stepping strategy or falling of older passenger. Because of the inclined elevators currently have from two to five times greater magnitudes of average horizontal deceleration limitation when compared with escalators or moving walks, the equipment and deceleration limitation to inclined elevators may need to be re-evaluated. For the comparison and credibility, during a normal operation of public transport, such as bus or train, the magnitudes of velocity gradients are between 1−2 m/s^2. Therefore, the limitation of the maximum horizontal deceleration with inclined elevators from current values to approximately 2 m/s^2 is recommended. With current limitations most likely only passengers aged under 40 years could maintain their balance with hip strategy during maximal braking.

Most of the study results (marked with * and ∆) and velocity gradient limitations from the safety standards (marked with □, ◊ and ☆) are collected in Figure 9. Study results and standard limitations are marked on their own columns. The figure utilizes the same abbreviations, as Tables 2 and 4. As can be seen from the figure, the top left corner is empty. In addition, horizontal studies are more common than vertical ones and elevator standards limit only deceleration comprehensively. Therefore, a new vertical acceleration research is proposed in Chapter 6.4.2.

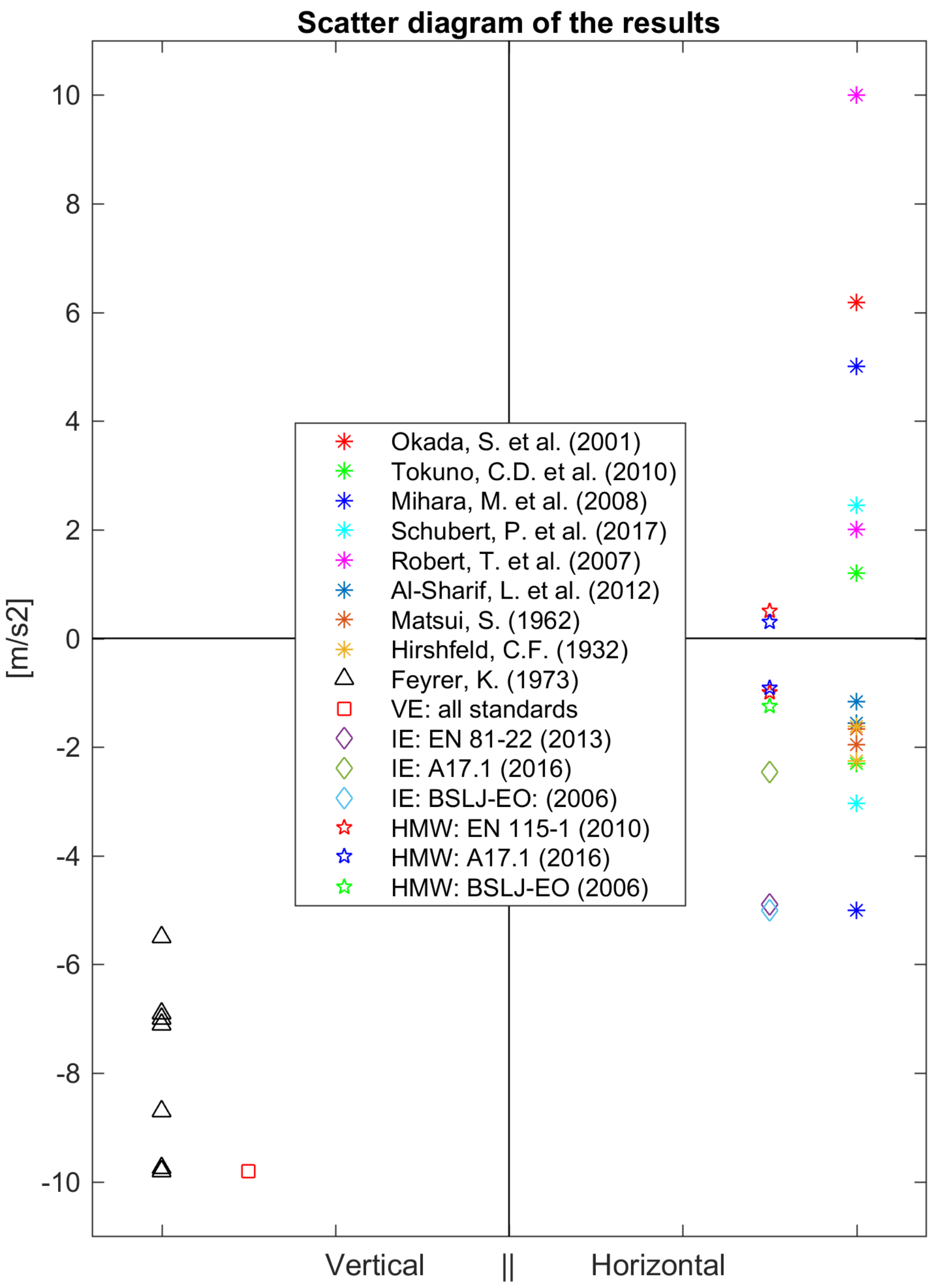

Figure 9: Collection of the study results and the safety standard limitations

One aim of this thesis was to study the current customs of velocity gradients and passenger safety in vertical transportation industry. This was achieved by analyzing the safety standards and papers studying e.g. passenger balance. The chosen safety standards are sufficient for this study, as they provide extensive view of the current situation where safety customs for velocity gradient limitations are not totally in unanimity for all portions of velocity gradients. Only the deceleration is comprehensively limited for elevators and the acceleration is secondary. The limitations are more comprehensive with escalators and moving walks than with elevators and thus would require better clarification. Balance studies are providing support for the most of current safety standard limitations issuing the effects of velocity gradients on human body. The only exception among limitations was the horizontal limitations with inclined elevators as they might result in the loss of balance with older passengers during emergency braking. The balance researches studying effects of vertical velocity gradients with standing passengers are in lesser number and thus should be studied more in the future work.

Most of the studies, which were analyzed in this thesis, included only healthy adults. Therefore, the transferability of study results to general public is not all-inclusive. In the real life studied machines are used by people from all demographic groups. It is known that diseases, such as Alzheimer's or higher level gait disorders have negative effect on postural control due to slower reaction time and due to weakening brain cells which affect motoric control (Demain et al. 2014; Gago et al. 2016). For this paper, people suffering from weakened postural control are not separately observed, but it is recommended that passengers with weaker postural control should be encouraged to use elevators over escalators and moving walks (Chi et al. 2006).

6.4 Development proposals

The development proposals are divided into two segments: accident triangular and research plan for evaluating the limits of vertical acceleration. The first segment offers development proposals in order to reduce the effects of velocity gradients with general improvements. The second segment offers a research plan in order to study the effects of vertical acceleration with elevators.

6.4.1 Accident triangle

The main purpose of safety standards for elevators, escalators and moving walks is to provide principles and guidance for addressing safety when designing those machines. According to the escalator passenger accident triangular model proposed by Al-Sharif (2006), escalator accidents are caused by one or several factors from the triangular model. The model is divided in three major parts, which are escalator design, passenger behavior and management. By understanding and affecting these factors, most of the accidents could be prevented. The model can be seen illustrated from Appendix D. (Al-Sharif 2006) The same model can also be used for elevator and moving walk design.

Passengers of elevator, escalator or moving walk are general public. They can be healthy adults or more vulnerable part of the population, such as children aged under 10 years, older adults aged over 65 years or people suffering from balance disorder illnesses. As there is a proven difference in a postural control of young and old adults (seen e.g. in the study by Okada et al. 2001), the velocity gradients of vertical transportation should be kept relatively low. However, very low velocity gradients may have an undesirable effect on the machine performance. Therefore, designers have a challenge of ensuring the performance level for the intended use of the machine while considering the vulnerability of the passengers exposed to the velocity gradients. For example, a high-acceleration elevator may need to be designed in order to satisfy the high machine performance requirements for high-rise buildings, fire-fighting elevators or evacuation elevators.

Generally, passengers are not aware of the level of velocity gradients that they may be exposed to when using elevators, escalators or moving walks, especially in the case of emergency stop. Therefore, warnings could be used to inform and instruct the passengers accordingly. For example, the proposed high-acceleration elevators could be marked clearly in order to let passengers brace for the high velocity gradients. This could be accomplished e.g. with picture-warning signs by following instructions from study by Liumin & Wenwei (2012). Warning signs and instructions rise passenger short-term awareness, which is a factor of passenger behavior.

Warning and instructive signs should be utilized in similar fashion with other machines as well. Several papers studying escalator or moving walk related accidents propose enhancement and increasing of symbols describing risk behaviors. For example, symbols indicating risk of using cell phones, carrying multiple bags or awareness of possible velocity gradients on escalators and moving walks. In addition, the major risk group for the escalator related accidents are passengers, especially women, aged over 65 years. A study by Chi et al. (2006) proposed women older 65 years to utilize elevators instead of escalators or inclined moving walks. (Chi et al. 2006; O'Neil et al. 2008; Howland et al. 2012; Liumin & Wenwei 2012) In addition to warning signs, the passengers could be informed e.g. with voice commands. Hokki & Yoichi propose a voice-promoting device, which reminds passengers to pay attention for the change of velocity with passenger conveyors (Hokki & Yoichi 2011).

Machine design covers one third of the accident triangular. To enhance the safety with elevator velocity gradients, the braking system could be improved. For example, during emergency stops, the safety gear creates high magnitudes of deceleration. The damping coefficient of the safety gear could be affected e.g. with magnetorheological (MR) fluid dampers proposed by Nagano et al. (2012). The proposed safety gear would change the damping coefficient in order to produce reliable and soft braking characteristics. (Nagano et al. 2012) Similar enhancement could be achieved with escalators and moving walks by using an intelligent braking system proposed by Al-Sharif. Instead of using conventional open loop braking, proposed closed-loop braking system could control the speed during deceleration by adjusting the braking effort according to feedback information and the reference curve. The reference curve should be designed in order to achieve set stopping distance with a comfort magnitude of deceleration. With electrical components, the proposed system is capable of lowering the maximum deceleration value with light loaded stop to 0,50 m/s^2. With issued deceleration levels, the level of stopping comfort was 6/10, as a conventional stop was evaluated 1/10. For an upward direction, the magnitudes are always around maximum allowed deceleration values of 1,00 m/s^2 as the risk for falling is smaller. (Al-Sharif 2004; Seaborne et al. 2010)

Several industries are collecting user feedback to enhance system development according to the user preferences. User feedback could be collected from the passengers of elevators, escalators and moving walks as well e.g. by using smartphone application. Where studies using human subjects are utilizing ten to twenty participants in average, crowdsourcing can utilize data from hundreds or even thousands of users. For example, Yang et al. (2013) conducted a global crowdsourcing study by using an Android smartphone application, which calculates moving distance, the velocity and velocity gradients of an elevator. Within 53 days, the application was installed in 230 smartphones and collected 1 056 files of acceleration data from around the world. The data was then used to build a robust elevator recognition algorithm. (Yang et al. 2013) In a similar fashion, application collecting feedback from elevators, escalators or moving walks could be generated. For the development of velocity gradients, the application could be allocated to only measure velocity gradients and enquire passenger experience e.g. in similar fashion to a rating system used by Al-Sharif (2004). Respectively, vertical transportation machine itself could collect data e.g. with the help of IoT. Data could be saved in a black box (located in cloud) in similar fashion to black box of an airplane. In the case of an accident, the data could easily be accessed for incident reports.

The final section of accident triangular issues the management, such as maintenance and inspection. Maintenance problems e.g. lack of maintenance or violation of safety rules by maintenance personal are one of the largest factors for the occurrence of elevator accidents. If accidents are caused by the velocity gradients, they should be stated in the accident reports. To focus and ease the development of safety with velocity gradients, the accident reports should be more specific. Accident reports should include in more detail about what happened, personal characteristics of the victim including involved products, such as shoes or clothes, the accurate location of the accident, possible medical treatments and a victim activity that might have led to the accident. In order to maintain velocity gradients within desired values and ensure a safe operation of the machine, a proper maintenance is crucial for all of the systems.

6.4.2 Research plan to evaluate the limits of vertical acceleration

The effects of vertical acceleration might affect balance of elevator passengers if the magnitudes of acceleration are high enough. Currently, the elevator standards do not limit the magnitude of acceleration, even though the acceleration of escalators and moving walks are limited by their standards. The objective of this research plan is to find boundary limits for the acceleration of elevator in relation to the safety of standing passengers.

Research will be carried out by finding heterogeneous group (both genders and all age groups) of 25 participants who are familiar with elevators and asking them to ride the test equipment. Before tests can begin, the participants are asked to sign Inform Consent Form in order to take part in research, as required by Intel International Rules and Guidelines. After each test run, participants will be asked to scale the felt safety level from 1 to 10, where 1 is unsafe and 10 is safe. Ratings and corresponding test settings will be recorded by using table from Appendix E. The magnitudes of acceleration will start from a safe region of 1,00 m/s^2, which participants are asked to rate as 10 for a reference. From here on the acceleration increases +0,25 m/s^2 with every test run, until the participant rate the level of felt safety with 1 or encounter the loss of balance.

Preliminary, the jerk will be set to constant value of 1 m/s^3. When participants rate the level of felt safety between 1−2, jerk will be lowered to 0,5 m/s^3 and no other changes will be made. Afterwards participants are asked to ride the equipment and rate the ride again. For research records, the lowered magnitudes of jerk will be marked with double stars (**). If participants rate level of felt safety with 1, the tests will end. Otherwise the acceleration can be increased as before, but the jerk will remain at 0,5 m/s^3.

According to Feyrer (1973), the limitation of vertical deceleration to 9,81 m/s^2 might originate from jumping of the counterweight. Therefore, the limitation of acceleration should be studied with number of elevators. For example, the comparison of traction elevators with and without a counterweight in relation to passenger safety during acceleration should be studied.

The acceleration of the elevator will be measured from three locations: the acceleration measured from the machinery (measure angular acceleration from where the acceleration of the car can be calculated), from counterweight (if one is used) and from the car itself. The reliability of measured acceleration data is weakened e.g. by the measurement noise. Therefore, either Savitzky–Golay or Butterworth filter will be used to reduce the noise. The tuning of the filter can be completed with instructions from the study by Pulecchi et al. (2010). In addition, according to the study by Feyrer (1973) the vibration of the car increases with higher magnitudes of velocity gradients. Therefore, vibration of the car will be measured and evaluated with limits from ISO 2631-1: 1997 (C.2.3) in order to see if the vibrations are within acceptable regions. In addition to evaluating results with

ISO 2631-1, the acceleration and passenger rating results will be plotted by the level of felt safety in relation to the acceleration of the car (in similar fashion to Appendix C).

The acceleration of the car is the most relevant data. Thus, this data will be compared with the rest of the measurements. The data analyzation will be carried out by using the analysis of variance (ANOVA) with system configurations. Level of significance will be set at $P < 0{,}05$.

6.5 Scientific and practical contribution of this thesis

As mentioned at the beginning of this thesis, the effects of velocity gradients on human body are hardly studied on with vertical transportation applications. This thesis is one of a few papers that collects and studies information from the global safety standards, from a number of incident statistics and from studies with differing backgrounds. Even though this paper does not offer new empirical data on the subject, the paper collects data from several of studies with varying backgrounds, e.g. from vertical transportation and medical engineering.

The results of this thesis indicate that the passenger safety among the elevator, escalator and moving walk design is widely taken into account e.g. with standards. However, the global number of reported vertical transportation accidents seem to be rising as the quantity of machines increases. The increase can be due of improved quality of reporting as well. Especially the accident rates of passengers with weaker postural control, such as older adults, have been rising within the past 15 years. Therefore, standard organizations should investigate the possible relevance of the reported accidents to the velocity gradients and, if required, to update their safety guidelines to cover the effects on passengers comprehensively. In addition, the vertical transportation companies should collect data on passenger experience e.g. with mobile applications.

In addition to the collected study results, this thesis offers new development proposals based on the collected information. Results and proposals from this thesis could be used e.g. by standard organizations and vertical transportation companies in order to develop the safety of passengers with the elevator, escalator and moving walk applications. In addition, potential new empirical research studying the balance of an elevator, escalator or moving walk passengers could utilize this thesis as a source information for a new study.

7. CONCLUSION

The human balance is a widely studied subject. An up-right standing person has significantly higher center of gravity (CoG) and smaller base of support (BoS) when compared with a person who is either sitting or lying. A person with a high CoG and small BoS is more vulnerable to external disturbances than a person with low CoG and large BoS. The high CoG and small BoS might lead in the change of a postural control strategy or, in the worst case, in a fall. In addition, the postural control is affected by external and internal factors. External factors are e.g. handrails and sudden or anticipated disturbances. Internal factors are e.g. muscular strength and the age of a person. Because of these multiple factors, it is hard to say accurately when human might encounter the loss of balance due to the effects of velocity gradients.

Elevators, escalators and moving walks provide the essential means of access to the built environment and due to rapid urbanization around the World, their number and usage are increasing each year. Elevators, escalators and moving walks are used by the general public from all age and demographic groups. Therefore, manufactures are continuously investigating ways to improve the safe use of those equipment. Study on the effects of velocity gradients on human body may provide such opportunity. Sudden changes or high magnitudes of velocity gradients, such as acceleration or deceleration, can have undesired effect on the balance of passengers and the ride comfort. In addition to velocity gradients, the jerk affects balance of passengers and ride quality. By using relatively low magnitudes of a jerk, passengers have more time to react to the changes in the velocity gradient.

The aim of this paper was to study the effects of velocity gradients to the human body with elevator, escalator and moving walk applications by using the most well-known safety standards and several balance studies. Safety codes and standards from Europe, America and Japan were used to map the current global limitations to velocity gradients with the studied machines. There was diversity from standard to standard and from machine to machine when safety instructions and machinery limitations were studied. When elevator standards were analyzed, surprisingly only the deceleration limitations were covered comprehensively and accurate acceleration limitations could not be found. However, when escalator and moving walk standards were studied both acceleration and deceleration limitations were provided.

The human body is less sensitive to vertical motion of the floor than horizontal motion. When vertical motions, such as motion of elevator, are compared the amplitudes of velocity gradients can be higher for an upward than a downward motion, for the floor creates greater support for the human body during an upward motion. For horizontal floor motions, such as motion of moving walk, the balance depends strongly on the leg orientation and usage of handrails. If legs are tightly together passenger should face the movement. Then again, if the legs are widely apart passenger body should face the sideward direction in relation to the motion. In addition, shoes with high heels rise the CoG and thus increase the possibility for the loss of balance.

When the current velocity gradient limitations from safety standards for escalators and moving walks were compared with the analyzed balance studies, it was found out that both, acceleration and deceleration, limitations from the safety standards were safe for the passengers. However, according to ISO/TR 14799-2 (2015), the deceleration limitations to escalators and moving walks should be specified more clearly.

With elevators, the safety standards did not provide similar amount of acceleration limitations. Therefore, this paper proposes forthcoming elevator safety standard revisions to consider the review of acceleration limit values comprehensively with further studies. Limiting the horizontal acceleration between 1−2 m/s^2 might be sufficient for passenger balance, but would require further study for the machine performance level. The vertical acceleration can be higher than a horizontal one, but should not exceed value of 9,81 m/s^2, as this might lead to feeling of loss of floor support with downward moving elevator. However, the effects of vertical acceleration on elevator passenger should be studied in more detail e.g. with proposed study plan.

All of the studied vertical elevator standards limit the vertical deceleration to value of 9,81 m/s^2. Some of the passengers could tolerate even higher magnitudes than the current safety limitation requires. Nevertheless, higher magnitudes of velocity gradients would most likely result in a low ride quality among the majority of passengers, because of loud noises and violent vibrations. Therefore, current vertical deceleration limitations are considered sufficient.

The current standards limit horizontal deceleration of inclined elevators between the magnitudes of 2,46−5,00 m/s^2 depending on the standard. According to the balance studies, emergency stop with corresponding values of horizontal deceleration would most likely result in stepping strategy or may result in fall of an older passenger. In addition, horizontal velocity gradients with public transports, such as bus or train, generally utilize the magnitudes of 1−2 m/s^2. Therefore, limitation of the maximum horizontal deceleration with inclined elevators from current values to approximately 2 m/s^2 is recommended.

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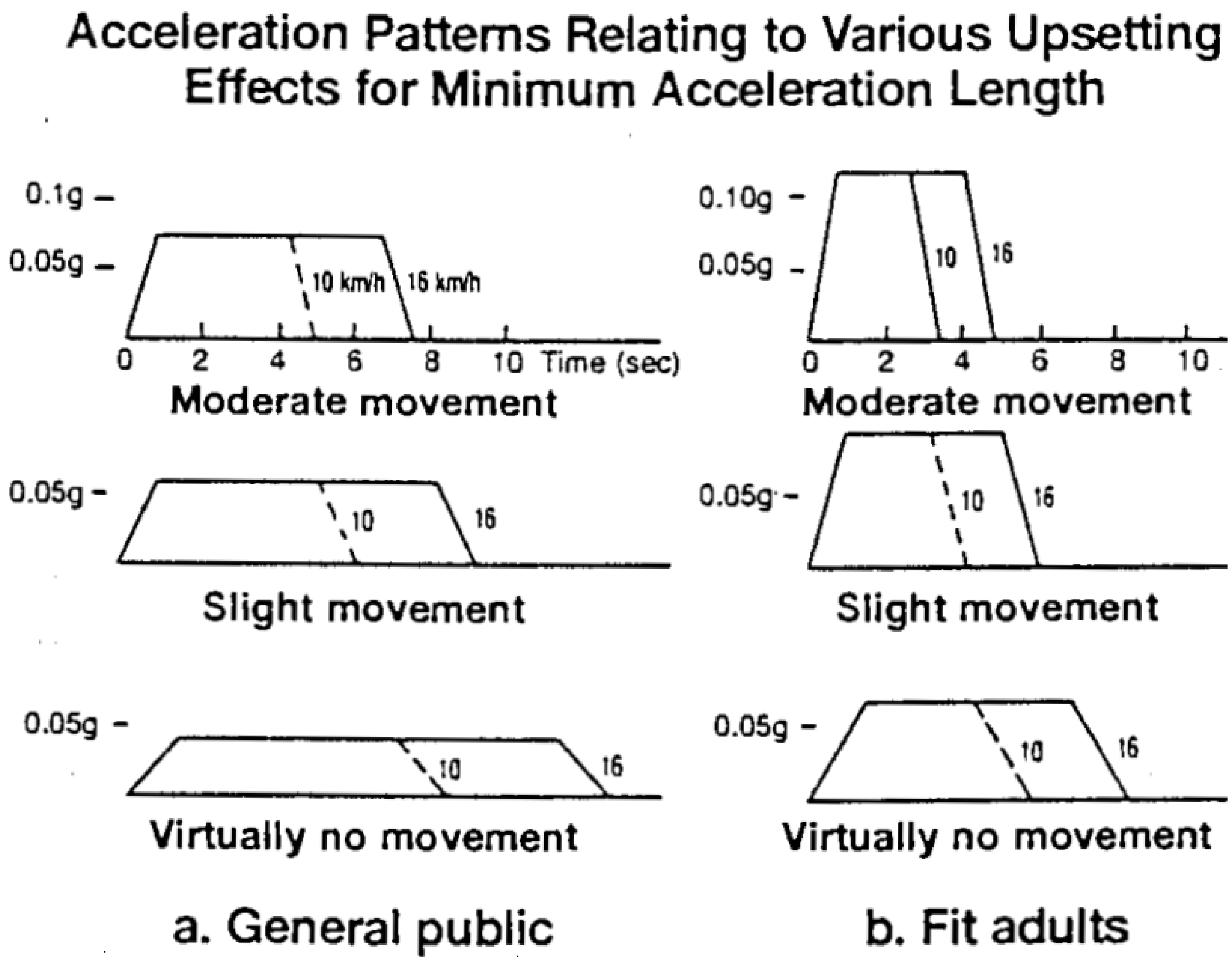
APPENDIX A: ASSUMPTION OF ELEVATOR RETARDATION (ISO/TR 11071-1 2004, P. 10)

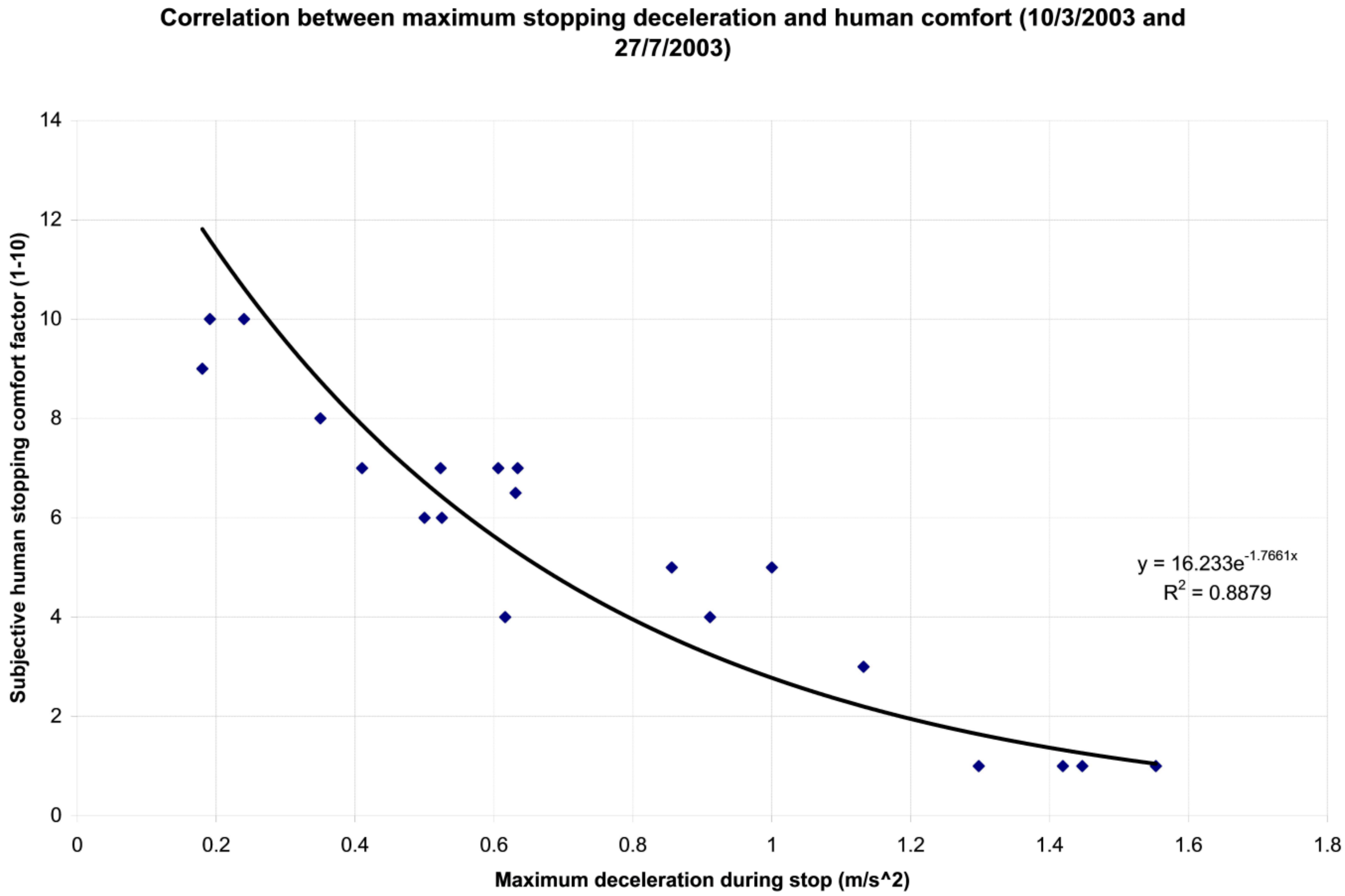
Assumption	EN 81-1:1998	A17.1-2000/ B44-00	AS1735-1:2001	AS1735-2:2001	Japan
Average retardation [a f]					
Safety gear for downwards direction	$0{,}2g$ to $1g$ [g] (9.8.4) [b]	$1g$ [h] (2.17.8.2) [b]	$0{,}2g$ to $1g$ [g] (9.8.4) [b]	$1g$ [h]	$1g$ & $0{,}5g$ [d e] (BSL-EO Art 129.10 item 1 para. 1)
Buffers	$1g$ [c] (10.4.3.3)	$1g$ [c] (2.22.4.2)	$1g$ [c] (10.4.3.3)	$1g$	$1g$ & $0{,}5g$ [d] (BSL-EO Art 129.10 item 1 para. 1)
Device for "up" overspeed protection	$\leqslant 1g$ (9.10.3)	$\leqslant 1g$ [2.19.3.2 e)]	$\leqslant 1g$ (9.10.3)	No spec	No spec
Maximum retardation					
Safety gear	No spec	No spec	No spec	$2{,}5g$ for 0,04 s	No spec
Device for "up" overspeed protection	No spec (9.10.3)	No spec	No spec (9.10.3)	No spec	No spec
Buffer duration	$> 2{,}5g$ $\leqslant$ 0,04 s (10.4.3.3)	$> 2{,}5g$ $\leqslant$ 0,04 s (2.22.4.2)	$> 2{,}5g$ $\leqslant$ 0,04 s (10.4.3.3)	$> 2{,}5g$ $\leqslant$ 0,04 s (9.6.3)	$> 2{,}5g$ $\leqslant$ 0,04 s (JEAS 517)

a Average retardation levels exceeding $1g$ can occur with a lightly loaded car during safety or buffer application.
b For progressive safety gears only (applicable to CEN).
c At 115 % of nominal speed (applicable to CEN).
d $1g$ in vertical direction, over $0{,}5g$ in horizontal direction. No spec for instantaneous gear or spring buffer (applicable to Japan).
e Stopping distance for gradual-type safety is stipulated in JIS A 4302. The value is calculated based on the stopping distance and the speed of actuation of the safety gear (applicable to Japan).
f $1g = 9{,}81\ m/s^2$.
g Retardation in free-fall situation.
h Retardation with counterweight attached.

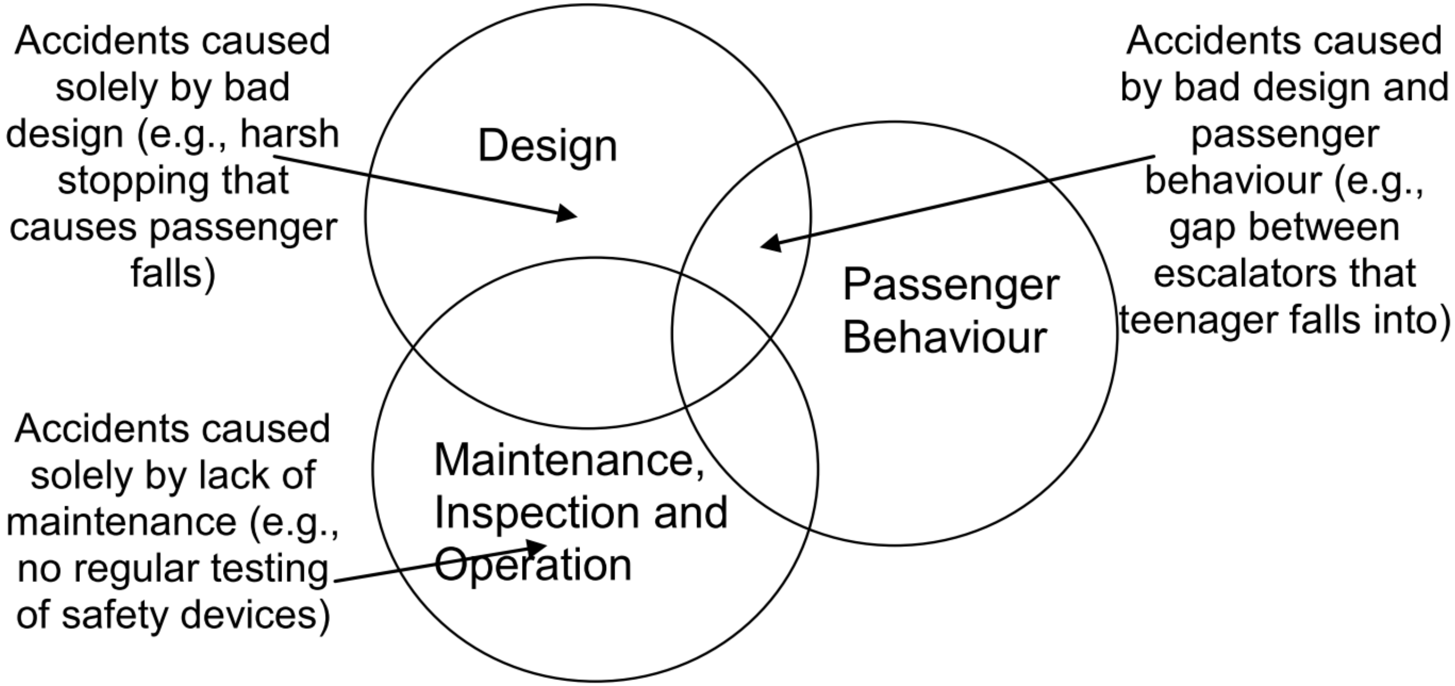
APPENDIX B: RELATION OF CONVEYOR ACCELERATION TO PASSENGER BALANCE (BROWNING 1974)



APPENDIX C: COMFORT DECELERATION MAGNITUDES OF ESCALATOR STOP (AL-SHARIF 2004)



APPENDIX D: PASSENGER ACCIDENT MODEL (AL-SHARIF 2006, P. 2)



APPENDIX E: RESEARCH RECORD FOR THE RESEARCH PLAN

Number of participants:	Date:
Location:	Researchers:

Passenger age [-]	**Elevator type [-]**	**Direction, up/down [-]**	**Angular acceleration of the motor [rad/s²]**	**Acceleration of the car [m/s²]**	**Acceleration of the counter-weight [m/s²]**	**Vibration**		**Level of felt safety, scale 1−10* [-]**
						[m/s²]	**[Hz]**	

*) 1 is unsafe (and ends the tests if test run is marked with **). 10 is as safe as acceleration of 1,00 m/s^2.

**) Jerk is at 0,5 m/s^3. Otherwise jerk is at 1,0 m/s^3.