SOME DETAILS ABOUT THE DEVELOPMENT OF ACCELERATION LIMITS FOR AMUSEMENT RIDES

Matthias Rohde

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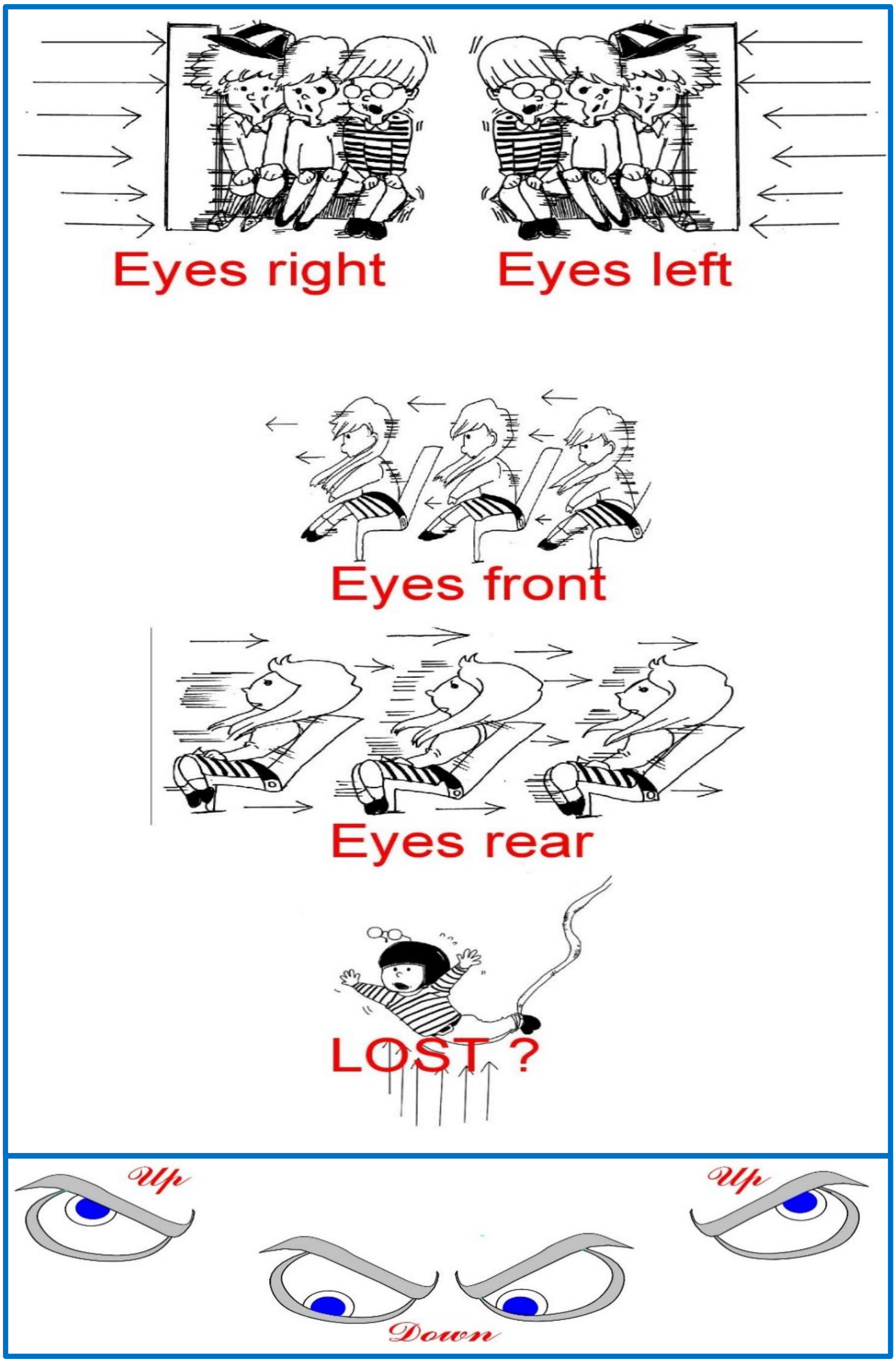

Dedicated to my wife Brigitte supporting me in all situations of our life

SOME DETAILS ABOUT THE DEVELOPMENT OF ACCELERATION LIMITS FOR AMUSEMENT RIDES

Contents

1 Introduction

More than one billion people are attending amusement parks every year, where they expect to be kept safe while enjoying themselves.
Limits for accelerations on humans were not defined in the first code for Design and Construction of Temporary Structures – DIN 4112 in 1938.

Further research and experience over the last 25 years has allowed acceleration limits to be defined more precisely. With an agreement between the American (ASTM International) and European Standard (CEN) Institutions it was possible to harmonize the two standards. The Harmonization continues with task groups organized by IAAPA. In addition, ISO TC254 "Safety of Amusement Rides and Amusement Devices" finally adopted most of the EN/ASTM regulations.

The patron acceleration limits were established via a close collaboration of the design/engineers and biomechanical experts. The goal of the limits was the ensure patron safety.

The Standards must be written in a clear and decisive manner in such a way that, if all institutions involved follow the rules, all Amusement Rides are safe. Vague information can lead to misinterpretation and discussions with the inspection bodies with the loss of time and money … and safety.

Most of the generation of biomechanical specialists and engineers who wrote the G-Force chapter have retired, and documentation of their discussions, studies, and "whys" behind the existing (and non-existing) requirements is severely lacking. This yields a risk that important information and history will be lost for current and future generations. This paper strives to fill this gap by describing the theory and experience between the limits. As always, there are possibly some background information missing. This paper is written as a "living" document and the author is happy to get feedback as much as possible, so he can cover more open questions.[1]

This document summarizes the minimum acceleration limits of ASTM International F2291-23b and CEN EN 13814-2019 only. Other national ntandards are not included. Some of them have more detailed information and they will be discussed partially only.

Up until the end of the 20th century the only Standard DIN 4112 [1] "Temporary Buildings", editions were in 1938, 1960 and 1983. The author remembers that this felt like a paradise to be asked to design according to DIN 4112 only. There was no harmonization needed. Just do it!

But the rides grew to be longer, faster, more thrilling, and a simple DIN 4112 was not enough anymore. Approximately at the beginning of the 21st century ASTM International published in F2291 the first limits of acceleration and CEN with EN 13814 [2] in Europe together with the guidelines of the operation of temporary buildings [3]. A brief historical summary can be found in [22], [23] and [26].

Today some National Standards are published in countries such as Russia (GOST R52170) [6], Australia (AS3511) [7] and China [18]; in 2010 Canada adopted the ASTM-regulations. EN 13814 has been revised and was published in May 2019.

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[1] Prof. em. Dr.-Ing. Matthias Rohde, Germany; E-Mail: Matthias.Rohde@outlook.com

The relatively late development of the Standards in the field of the amusement industry is astonishing, considering that more than one billion people are using the facilities of the parks every year, trusting in their safety.

The amusement park Industry is relatively young and there is huge competition between companies. Nowadays, to attract more customers slogans, read “higher, faster, further…”. This means, in terms of the maintenance expenditure, on one hand there is a significant increase in financial costs for each park and on the other hand, a high responsibility for the engineers. Before starting the fabrication, the engineers need to estimate and ensure the safety of the ride. In this case safety means, to design safe foundations, support structure, vehicles as well as developing restraint systems and limit accelerations to an amount the Patrons can tolerate.

A Standard can only reflect part of the progress (state of art) and a new revision normally is issued in Europe every 10-20 years. This gives all engineers the chance to work with one Standard without need to double-check new requirements. Only the ASTM International is adapting annually, having two meetings a year. However, this leads to a high workload for the participating experts.

Amusement Rides require a different approach. In this case the questions which should be asked are, “how hazardous are the effects of the rides on the health of a Patron?” and “how much acceleration can Patrons withstand without any effect on their health?”. It is not a part of a Standard to judge if these accelerations are still felt as fun for everybody. The standards cannot base their limits on tests of young and healthy people. All Patrons must be safe, elderly people, children, tired Patrons etc.

Other influences for example are jerk (=change of the acceleration with the time) and the phenomenon of the motion sickness. Basic research explains the problems, but the standards do not specify limits because they are not treated as safety risk for the Patrons and there is an insufficient data base.

In literature e.g. the space agency’s NASA (USA) or Roscosmos (USSR/Russia) [8], research can be found where studies were made on well-trained, healthy people. The data can only be partially used by the Amusement Industry. For the Amusement Industry, a more appropriate data set is Amusement Rides. Therefore, it follows that patron acceleration limits shall be investigated and defined by taking existing Amusement Rides and comparing possible safety concerns, with the ride characteristics. The conclusions of these investigations shall than be validated by biomechanical experts.

Biomedical experts are necessary to understand the physical effects on the human body. For instance, due to vertical acceleration the blood will be forced downwards, instantaneously decreasing the blood flow to the brain - effects like this are of importance.

In studies, factors such as complaints or incidents must be included and compared as these results are frequent. But the Revision of EN 13814 in 2019 defined the limits in the appendix I as informative. The reason is that EN harmonized with ASTM the F2291 limits. This was an important step, because all manufacturers deliver their products all over the world and need the same basic requirements. The CEN committee was happy to harmonize as over the years the limits were found service proven, but without the research reports EN defined them as informative.

In the past years the G-force task group (including two participants from Europe) did extensive research and studied mainly on the facilities in Amusement Parks such as Disney, Universal and Six Flags. On these rides all data/measurements were available. For legal reasons, results were treated confidentially and are only partially published [9-11].

It should be mentioned that the ASTM International and the CEN committee agreed on a harmonization. The focus of this article is the updated and revised state of knowledge and standards regarding the limits of accelerations on Amusement Rides.

Note: On June 9, 2022, it was announced that ASTM International and CEN have agreed to extend and expand a Technical Cooperation Agreement from 2019.

Personally, the author tried summarizing and explain the G-force basics. Please, if something is not mentioned or not enough explained, contact the author. This is a “living” text and open questions should be answered and added.

February 2024

Matthias Rohde

ASTM INTERNATIONAL

VERBAND DER DEUTSCHEN VERGNÜGUNGS ANLAGENHERSTELLER E.V.

2 Political Background

A standard must be introduced by the national building authorities. In addition, further regulations may have to be observed, such as a venue ordinance or regulations on how regularly a system must be inspected.

In most European countries, for example, EN 13814 - 2004 was introduced promptly, whereas in Germany it was only introduced around 10 years later. This is also currently the case in Germany again, where EN 13814-2019 has still not been introduced by the building authorities.

In the USA, not all states have adopted ASTM F2291.

For an engineer, the question always arises as to which version is the current one to be used, even if the standard is not officially introduced. Basically, a standard is "state of the art" and should be considered as this. From a legal point of view, the designer can deviate from a standard, but he must prove safety by means of expert certifications including a possible proof with tests.

Not everything can be standardized. Some regulations are still missing due to a lack of experience. One example is acceleration events of less than 0.2 s, which is a duration too fast for a human's neuromuscular system to react. (This will be discussed in Chapter 8)

3 Terminology

Both F2291 and EN have a section for further Definitions of Terms Specific to the Standards. Her are to terms which are used in the paper.

- Impact force those forces with a duration less than 0.20 s (=200 ms)
- Impact acceleration those accelerations with duration less than 0.20 s
- Sustained acceleration Event: Those accelerations with duration greater than or equal to 0.20 s [4, 3.1.2]. (see also [23] defining this as 1.0 s]
- Sustained Events are events lasting 0.20 s or greater
- Jerk / Onset at a specific time window of 0.10 s (100ms) determined by finding the slope (acceleration/time) of the best linear fit using the least squares centered at that specific time (Chapter 7.3)
  Note: The EN decided to use jerk only and in this summary “Jerk” is normally used.
- Delta-v (Δv) is a function of the change in velocity undergone by the ride vehicle over short periods of time (that is 0.20 s or less). A method is described in F2291-Annex X11.
- Average acceleration is Delta-v (Δv) divided by the duration of the sub-event and is thus a single metric which incorporates both, Δv and duration for impact events.
- Sub-event is the acceleration-time graph with the duration of the applicable isoacceleration. (see figures in appendix X21-X2.4 of F2291)
- Design risk analysis is a technique used to identify the potential failure modes in a product. These failure modes could be related to (but not limited to) product

performance, life, reliability, durability, cost, manufacturability and maintainability

- Design Risk Assessment: Identification of hazards arising from your design followed by an assess how serious the risks are and a decision what to do to eliminate or reduce these risks.
- Isoacceleration: The data should be 'sliced' and assessed at multiple values of constant acceleration (increments between values no greater than 0.1 g). these slices are called isoacceleration.
- Butterworth low pass filter is a type of signal processing filter designed to have a frequency response that is as flat as possible in the passband. It was first described in 1930 by the British engineer and physicist Stephen Butterworth in his paper entitled "On the Theory of Filter Amplifiers". [20]
  The filter is used to post-process the accelerations as measured according to F2137.
- Push-Pull Effect: A possible visual light loss after exposure of negative $-G_z$ (eyes up) for 5 or more seconds followed by a positive G_z (eyes down).
- CEN French: Comité Européen de Normalisation; European Committee for Standardization is officially recognized as a European standards body by the European Union, European Free Trade Association and the United Kingdom
- ASTM International, formerly known as "American Society for Testing and Materials", is an international standards organization that develops and publishes voluntary consensus technical standards

4 Coordinate system and measurements

Internationally, the Cartesian coordinate system is being used to visualize specific drawings of the theme park industry, as shown in figure 4.1.
This is different to the coordinate system of other standards (for example DIN 1080, having the Z-axis defined as being positive upwards).
The updated version of the EN has adapted to the ASTM definition. The orthogonal coordinate system relates to the Patron. The Z-axis is directed upwards and is defined as lining up parallel to the spine. Approaches to define the direction by using a connection line between two defined vertebrae exist [8], which is very hard to generalize and describe.

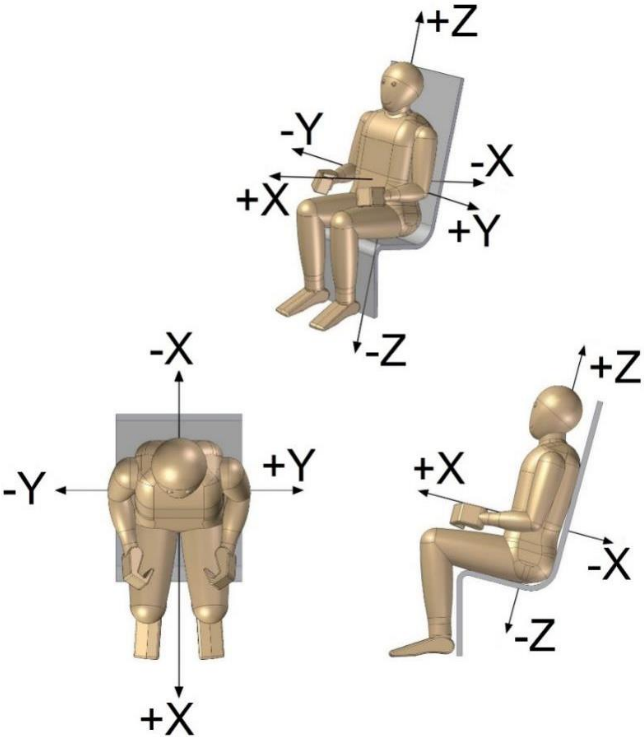


Figure 4.1 Body – Coordinate system

The tolerance has been set at a relatively generous +/-5°, also preventing unnecessary discussions about possible interpretations. Figure 4.2 is illustrating two examples of unusual positions.
A definition of positive rotations can be found in chapter 7.6.2

Note: The values as measured are based on the seat angle (see figure 5.1) and the x-axis is not aligned with the driving direction.

Figure 4.2 Example of an unusual seating position (Photo: Vekoma)

5 Measuring the Dynamic Characteristics

5.1 Overview

The first approach known by the author was by RWTüV in Germany. This body of work was published in 1994 was most influential and helpful in the development of the ASTM G-Force standard [22]. The first Standard to measure the accelerations was published by ASTM as F2137-01, with further input from many international experts an improved Standard was published as F2137-02. Since then, it is the only internationally accepted standard for Amusement Rides. [22, 23]. Some not harmonized variations were published in the appendix of DIN 4112/A1-2006 and EN 13814-2004.

The accelerations are related to the Body-Coordinate system as shown in Figure 4.1 are measured on the seat. EN has adapted to the American Standard ASTM International F2137 [5], except for the position of the accelerometers. As part of the harmonization between the ASTM and EN the tests are referred to in both standards as ASTM F2137. They are called “Standardized Amusement Ride Characterization Test“, SARC Test in short. These tests also include the specific requirements of the EN and ISO. The reason for the different locations and its influence of the measured values is discussed in chapter 9.

5.2 Measuring with the Requirements of the F2137 Standard

An example of the experimental arrangement taking a triaxial accelerometer is illustrated in Figure 5.1.

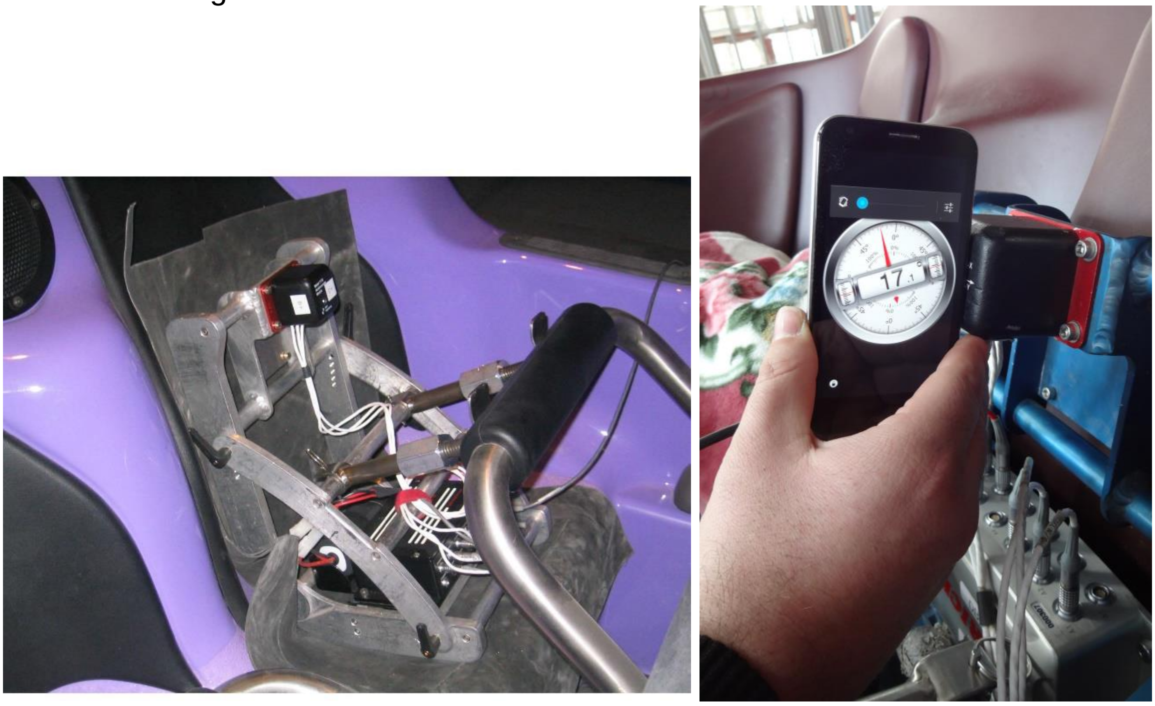


Figure 5.1 Device to measure the acceleration on the seat (Photo: Rohde/Vekoma)

It should be mentioned that the data are measured with a high sample rate and stored. The filter can be applied during post processing. As example, visualizing different filter frequencies at a specific excerpt is shown in Figure 5.2.

Note: The filters are not defined in F2137 and are mentioned in the design Standards F2291 or EN 13814. It has been agreed to recommend the post-process with a 4-pole, single pass, Butterworth low pass filter using a corner frequency (Fn) of 5 Hz. This filter was developed for acoustic systems. As all filters may be problematic in some areas this filter showed a minimum of side effects.[20]

Obviously, a seat dampens already possible impacts from rails and the measurement is only a proof whether the design assumptions of the acceleration correspond to the reality.

Note: The accelerations taken via the methods in F2137 should not be used for analysis of structures.

EN and ASTM International have agreed on the following filters:

- Review on the acceleration exerted on a patron: 5 Hz.
  Following the expertise of medical professionals, the human nervous system will not react to accelerations of a frequency above 5 Hz.
  Note: The EN Committee has agreed to change in EN 13814-2019 the filter from

10 Hz to 5 Hz from “low-pass with edge steepness min. 6dB per Octave” to “Butterworth”. (EN 13814-2019; I.2.1)

- Review on the Restraint Systems: 1 Hz;

  The type of restraint system is chosen based on the design. The 1 Hz filter smoothens the graph and peaks will not lead to unnecessary higher restraint areas, plus the allowance of a tolerance of +/-0,05 g.

  Note: The lines of the restraint diagram have a thickness of 2*0,05 = 0,10 g. Under this review, the engineer must still consider extreme situations. This also concerns a variety of positions in a vehicle (front, middle, back), emergency stops, as well as various train speeds due to abrasion, temperature or humidity. Note: F2291 added the filter of 1 Hz to validate the type of restraint. (F2291 X1.2)

Figure 5.2 illustrates the data filtered with 1 Hz which is close to the design without showing impact peaks.

Data filtered at 5 Hz (Filter recommended for the Acceleration limits) reflects the experience of the Patrons.

The filter at 20 Hz is only partially reflecting the impact imposed to the structure. Also factors such as dampening due to the seat, natural frequencies or the distance from the origin of the impact (wheel) have to be taken into account.

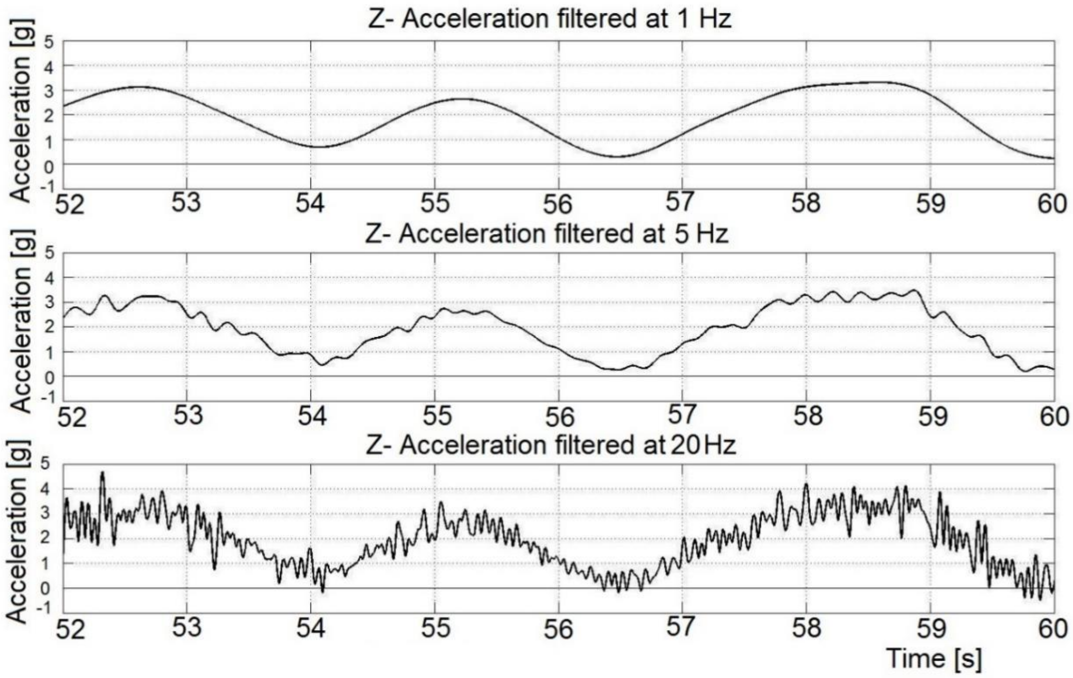


Figure 5.2 Excerpt of a measurement with various filters (from Vekoma)

5.3 Test Protocol Evaluation

SARC testing shall be carried out per F2137 as empirical tests validating the patron accelerations expected on an amusement ride. These tests shall measure accelerations that are reasonably expected to be experienced by the patrons including normal operation, E-stop conditions, etc.

F2137 12.1.1 Testing Ballast Weight specifies a loading condition to represent an approximatively averagely weight vehicle.

Note: It should be reflected here that the trains can often be occupied by heavy people. This usually increases the speed and acceleration of many systems. Similarly, offset loading or lighter loading conditions may exist that impact the accelerations induced on the patron. The question should at least be asked in the report and, if necessary, assessed by the designer/engineer and validated via empirical testing.

Test documentation shall include all information required for testing to be repeatable (i.e. temperature, humidity, weather, height and angle of measurement device relative to seat, loading condition, etc. – see *ASTM F2137 Section 11*). Factors that may influence repeatability (such as running a train "cold") should be avoided as much as reasonable (such as by running the train a few times prior to taking the measurements – see *ASTM F2137 10.3*).

The tests are carried out as proof of the design for the amusement rides. However, below please find a few indications as to how the evaluation should take place.

This chapter aims to sensitize all parties involved as Manufacturer, Designer, Owner, Operator and Inspector.

5.3.1 External conditions and boundary conditions

- The vehicles should have made a few runs before the measurement. At least 3 runs are usual.
  The chassis uses, among other things, grease that only measures speed at a certain temperature

- External humidity, temperature and rain should also be noted. Furthermore, the angle of the seat = spine to vertical axis must be noted. The travel time should also be recorded for each measurement.

- The measuring instruments should be described and the requirements of F2137 should be met.

- The applicable standards such as F2291/EN 13814 must be listed for the assessment.

- The vehicles should be loaded. Today it is common to load dummies weighing around 75 kg.

- It should be reflected here that the trains can often be occupied by heavy people. This usually increases the speed and acceleration of many systems. The question should at least be asked in the report and, if necessary, assessed by the designer/engineer.

- Especially in roller coasters, the speed and acceleration in the front or rear vehicle are different.

- It is therefore common practice to carry out and assess the measurements in the front, middle and rear of the vehicle.

- To do this, some experiments are necessary and must be documented, for example charging states, different cars, E-Stop situations, etc.

- The measurements are normally carried out at the beginning of the season or before the facility opens. Experience has shown that the system has not yet fully run in at this point. Travel time is often shortened during the summer months.

The designer or engineer should assess the shortened travel time in terms of acceleration or braking distances.

Note: Defining testing beyond what is already in F2137. It is new business that is in discussion in the Acceleration Task Group.

5.3.2 Evaluation

All Evaluations must be carried out on all tests, full / empty or front / middle / rear car etc.

- Restraint Rose

  The so called „Restraint Rose” should fit into the Restraint Determination Diagram. The Restraint Category has been already determined during the design phase. In this case Area 3 was determined and the Evaluation would even allow Area 2. (figure 5.3)

  The Restraint Determination Diagram will be explained in Chapter 6.

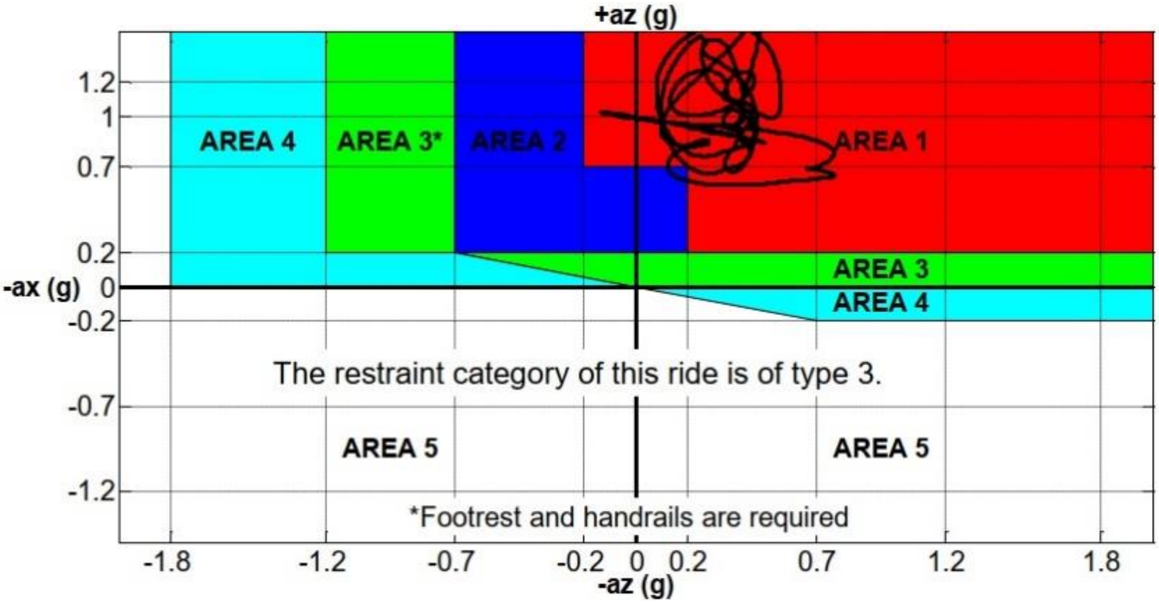


Figure 5.3 Restraint Rose and Restraint Determination Diagram (from Vekoma)

– Limit Acceleration
  The Accelerations must be evaluated with the time-acceleration diagrams, as shown in figure 5.2. This helps only partially, as longer accelerations are evaluated as well. The method is described with an example in chapter 7.2.5 and the plots are shown in figures 5.4 and 5.5

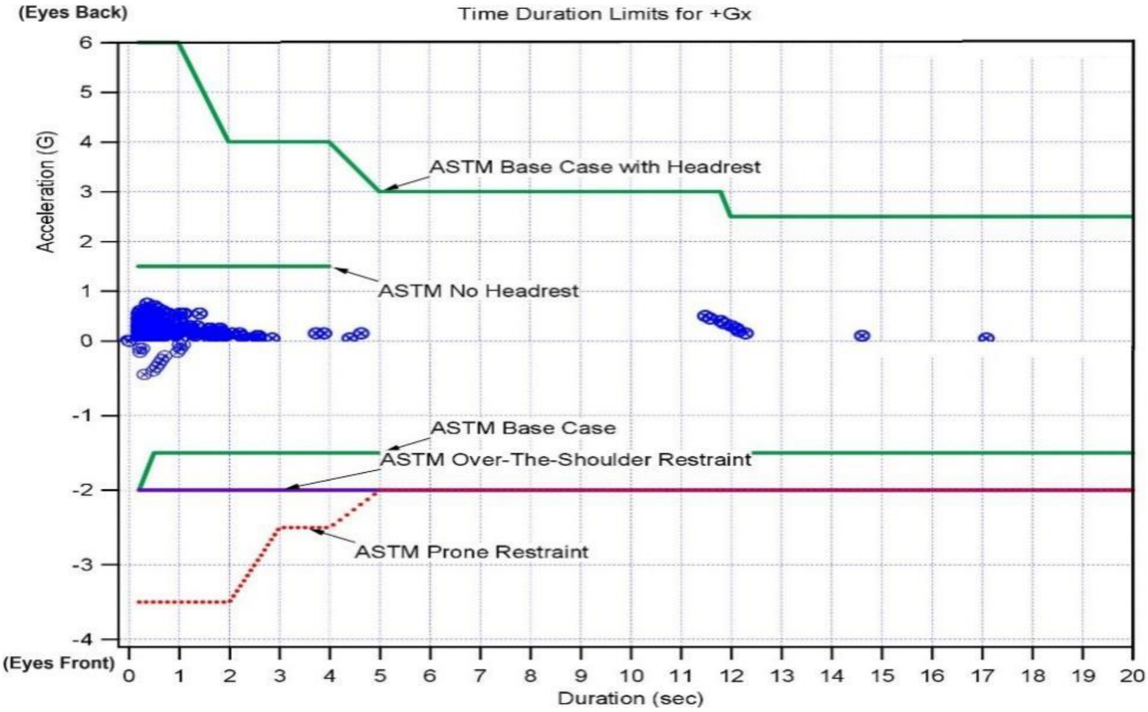


Figure 5.4 Evaluation Accelerations in x (eyes front/rear)

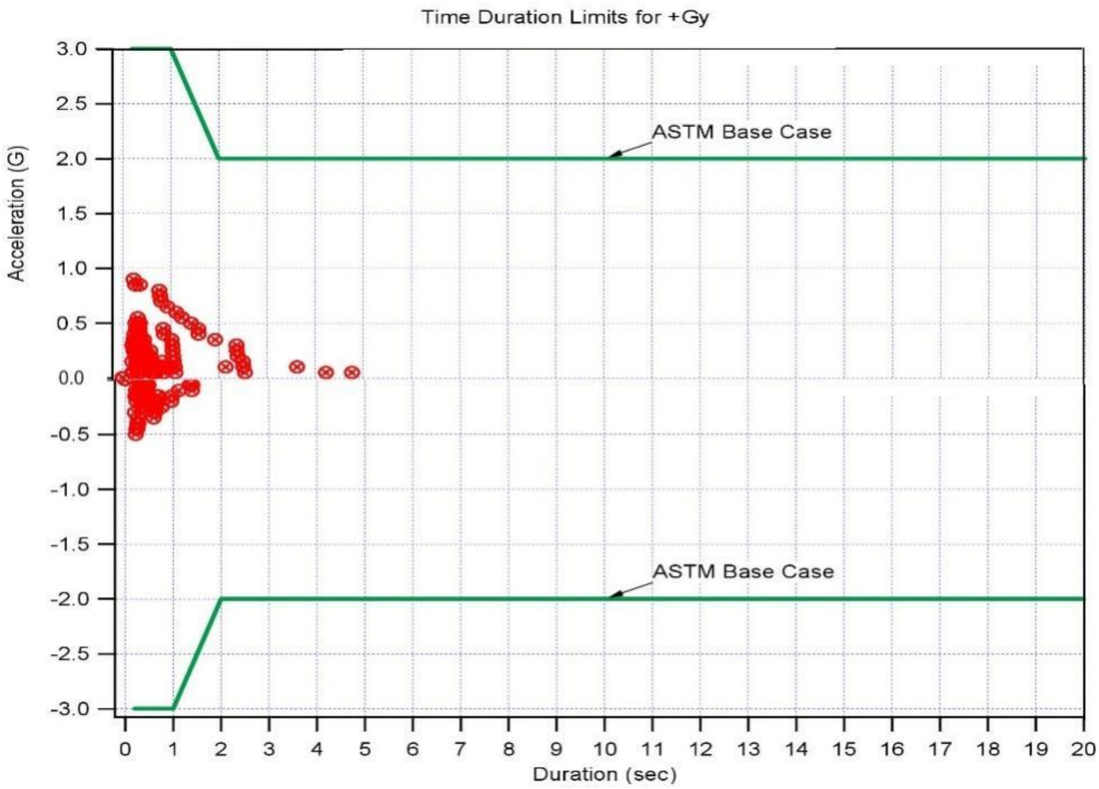


Figure 5.5 Evaluation Accelerations in y (eyes left/right)

– Combinations

All requirements of the “eggs” must be fulfilled. It is sufficient if the 3-d graph does not show values over 1.0 (see formula (4), chapter 7.2.6.2 and figure 7.17

- Reversals in x and y (chapter 7.3.2)
  It may be sufficient if all peak values are below the 50% values of figures 6 and 7 of F2291

- Transitions in z
  There are two requirements which the inspector needs to examine, the push-Pull-Effect in Chapter 7.3.3.1 and the sustained transition in Chapter 7.3.3.2. Both reflect the terms in F2291 7.1.7

5.3.3 Design check

The designer should double-check the data as measured with his assumptions. Discrepancies shall be addressed and corrected.
The designer should also double-check to ride-time versus the projected ride-time. Normally the rides are slower than projected and the accelerations are different. The designer should judge whether the measurements are appropriate.

6 Restraint devices

Restraint and containment systems are used in combination to keep patrons inside the amusement ride or device. In consideration of accelerations, the human body is not rigid and can shift depending on the direction and intensity of the acceleration. Restraints and containment devices shall keep patrons secured inside the system during these events. For higher accelerations or intense accelerations, restraints would be designed in a way to control the rigid points of a human body. For example, a lap bar restraint would be designed in a way where the full range of patrons accepted on the ride would be constrained to a z-shaped positioning of the lower limbs.

Restraints and containment systems take into consideration the accelerations in a particular direction. For example, higher accelerations in $+a_x$ (eyes back) will utilize the design of a seat back and headrest. Higher lateral accelerations +/- a_y (side-to-side) may require additional padding to react from unexpected motion (see 7.2.6.1 and 9). In general, it can be noted that if the possibility of being ejected out of the seat increases, the safety requirements on the restraint system also increases.

Figure 6.1 shows criteria for the choice of an appropriate restraint system for use with respect to accelerations. Other factors, like unwanted self-ejection, may warrant the use of a higher-class restraint or modification of overall containment system. The different criteria are subdivided into so called “Areas”. This is harmonized between EN13814 and ASTM F2291.
Some accidents as on the ICON in Orlando/Florida lead to a deep investigation. Therefore, soon the restraint chapter of both Standards will be adapted.

Note: Lateral accelerations are not considered in the Restraint Rose.

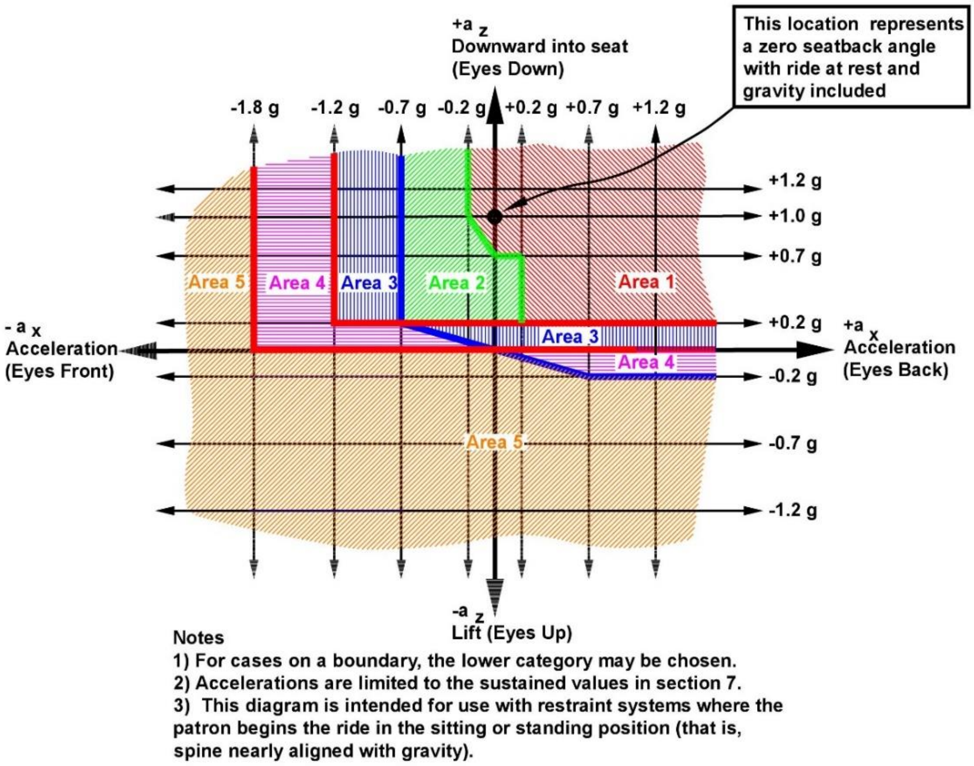


Figure 6.1 Passenger restraint diagram aka “Restraint Rose”

7 Limit accelerations

7.1 General

All Limits described are based on the normal operation and cases reasonably expected to be experienced by riders, such as E-Stop conditions. This does not include incidents such as a coaster getting stuck in a loop or a train hitting a previous train. These incidents should be examined with the Design Risk Analysis DRA.

Steady-state values in acceleration graphs as described in this chapter are valid for exposures up to 90 s unless otherwise indicated. Longer exposures are not addressed by this standard.

Impact events are not addressed in the existing F2291 Patron Acceleration limits. However, these impact events may influence the human health. Current research related to impact events on existing amusement rides is under review and is discussed in chapter 8.

In both ASTM and EN, limits for the rotational accelerations are not explicitly stated. The rotational accelerations normally occur in combination with the linear a_x, a_y or a_z accelerations. It is possible to transform these rotational accelerations into the a_x, a_y or a_z – linear accelerations and combine them (see chapter 7.5.2).

In the design phase, all 6 accelerations (linear a_x, a_y and a_z such as rotation $\dot{\varphi}_x$, $\dot{\varphi}_y$ and $\dot{\varphi}_z$) are known and should be taken into the design analysis. This is currently not the case with the measurements. It is therefore essential to keep this in mind when evaluating the tests.

The G-Force Task Group recommends that an amusement ride should not be ridden several times in a row without a break period. This rest duration can be accomplished by the rider exiting the ride and waiting in the queue before riding again.

7.2 Limit accelerations

7.2.1 Normative Regulations

The Figures 7.1, 7.2 and 7.4 illustrate the limits of acceleration in x, y and z direction in relation to the time of exposure. In EN the acceleration components are referred as adm. a_y, adm. a_x and adm. a_z and to be more understandable with the words “eyes up, right, down etc.”

Note: Europeans use a decimal comma rather than a decimal dot. 2,4 g is equivalent to 2.4 g.

In contrast with ASTM, notes in EN standards are usually incorporated under the figures. According to a decision of the F24 committee, this practice will be harmonized, and in the future ASTM will also have the notes under the figures.

For children or riders with a height less than 1,20 m (48"), the defined acceleration limits may not apply. For rides that include patrons with a height less than 1,20 m (48"), the design/engineer must consider the biodynamic effects on the patrons to determine if the stated acceleration limits are appropriate or if more restricted limits are necessary. See Chapter 7.5.

In the subsequent figures, the positive directions of acceleration (a_x, a_y or a_z) are defined in accordance with the patron coordinate system as follows:

- $+a_z$ presses the body into the seat downward, described as "eyes down";
- $-a_z$ lifts the body out of the seat, described as "eyes up";
- $+a_y$ presses the body sideward to the right, described as "eyes right";
- $-a_y$ presses the body sideward to the left, described as "eyes left";
- $+a_x$ presses the body into the seat backward, described as "eyes back";
- $-a_x$ pushes the body out of the seat forward, described as "eyes front".

7.2.2 Lateral Accelerations (left/right)

7.2.2.1 Sustained acceleration duration limits in y-direction

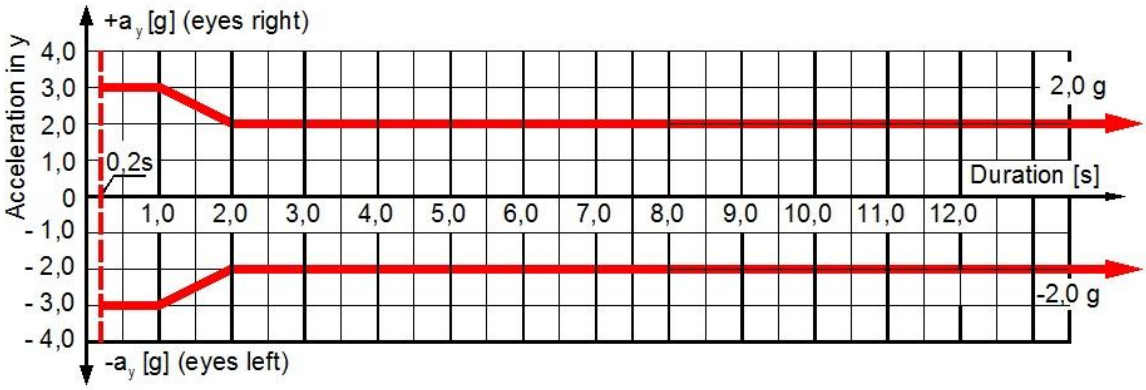


Figure 7.1 Acceleration-Duration Limits for the Acceleration in the y-direction (Eyes Right and Eyes Left)

7.2.2.2 Bench Seats

For amusement rides and devices with bench seats (for example, without individual patron retention or seat dividers) and sustained lateral accelerations greater than 0.7 g in only one direction, patron seating order shall be from smaller to larger patron in the direction of the load). Normally this situation should be already addressed in the design phase of the amusement ride during the risk analysis and its assessment. The patron seating order instruction is self-explanatory and must be included in the operation manual.

The lateral acceleration limit of 0.7 g describes a minimum requirement, but it is strongly dependent on the friction coefficient of the patron containment system. The specific friction characteristics of the containment system should be considered and the lateral acceleration limit of 0.7 g be reduced if needed.

Note: Considerations of lateral acceleration has already lead to many discussions with inspectors during the Site Acceptance Tests (SAT). Inspectors have asked for a reduction of vehicle speed along with the reduction lateral acceleration. It is recommended that lateral acceleration characteristics be clarified during the design phase. One possibility is to prove with the experience of existing rides (proven system).

7.2.2.3 Head and Whiplash

Jerks in the planar direction (lateral and longitudinal) seem to be critical to the incidence of whiplash-related complaints. Investigations done in on a portable roller coaster showed critical accelerations for whiplash to be associated with event duration Δt even smaller than 0.2 s. According to the U.S. Customer Product Safety Commission (CPSC), neck sprain is one of the most treated injuries in emergency rooms. Whiplash-related complaints have also has been problematic for amusement rides in the past [25]. Given the number of investigations conducted on existing amusement rides and the involvement of biomechanical experts, this risk could have been mitigated. For further discussion, refer to Chapters7.2.3.2, 8 and 9.

7.2.3 Longitudinal Accelerations (front/back)

7.2.3.1 Sustained acceleration duration limits in x-direction

Figure 7.2 Acceleration-Duration Limits for the Acceleration in the X-Direction (Eyes Front and Eyes Back)

Notes (in F2291-23b still in the Figure):

+a_x (G_x):

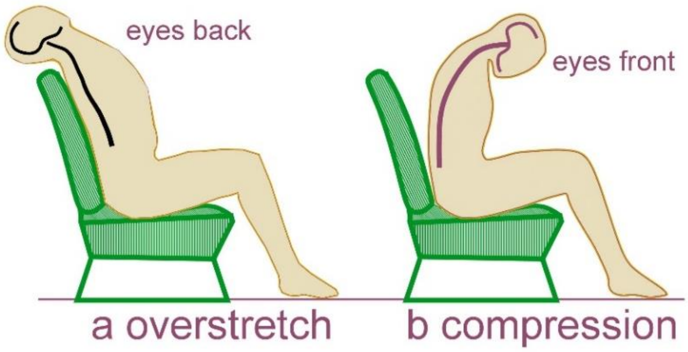
1) Must have headrest above 1.5 g unless onset rate is less than 5.0 g/s; then 2.0 g is permissible.
   For no headrest case the max. duration of above 1.5 g is 4 seconds
2) Design and operating procedures must assure patron is in contact and supported by appropriate backrest and headrest.

- a_x (G_x): “Prone” Restraint:

3) Upper torso restraint must minimize patron forward motion.
4) Upper torso limits may be increased to Prone Limits providing the onset is less than 15 g/s and the restraint is appropriately padded.
5) Prone Restraint assumes body is supported by appropriately padded restraint.

7.2.3.2 Whiplash injuries

Investigations of whiplash injuries have been carried out on a portable roller coaster in Germany. [17] The detailed circumstances of this study are described in Chapter 7.3.



Other whiplash incidents have been documented in research from the automotive industry. These automotive incidents were almost exclusively accidents that involved excessive impacts with higher accelerations than could be applied on amusement rides in normal operational mode.

Figure 7.3 Cervical Spine Whiplash Injury Mechanism [17]

Note a: Retroflexion with hyperextension of the cervical spine and hyperextension of the soft tissues of the neck
Note b: Anti-flexion with compression of the mobile segment and the soft tissues of the neck
Figure 7.3 illustrates body movements as a result of acceleration in the longitudinal direction. The critical initiator of the acceleration is a sudden, unpredictable impact from behind. This literally means "Impact" = Jerk. This type of impact acceleration does not happen on amusement devices in normal operation circumstances. However, historically longitudinal acceleration levels were a major consideration when entering loops or curves. (see Chapter 9).

As noted in F2291, the maximum positive acceleration shown in Figure 7.2 (6 g) is only permitted if a corresponding headrest is included in the patron containment system. More detailed information on this can be found in Chapter 7.2.6.

In general, a whiplash injury can be summarized as follows:

- Damage occurs in the soft tissues of the neck with relative movement of the head in the longitudinal direction ($+a_x$; eyes back) and with inadequate neck protection.
- The damage is caused by a shearing mechanism known as the whiplash phenomenon.
- The moment of surprise prevents reactionary muscular defense (Figure 7.3 Note a:).
- Countermovement with compression of the mobile segment and the soft parts of the neck (Figure 7.3, b:).
- Pre-existing cervical vertebrae damage leads to an increased risk of injury.

$+a_x$ (G_x):
For positive accelerations (eyes back) a headrest is not necessary, but the limit is used similar to the base case with over the shoulder restraint with a_x = +2.0 g with a max. duration of 4 s. If the jerk exceeds 5.0 g/s only a_x = 1.5 g is permissible.

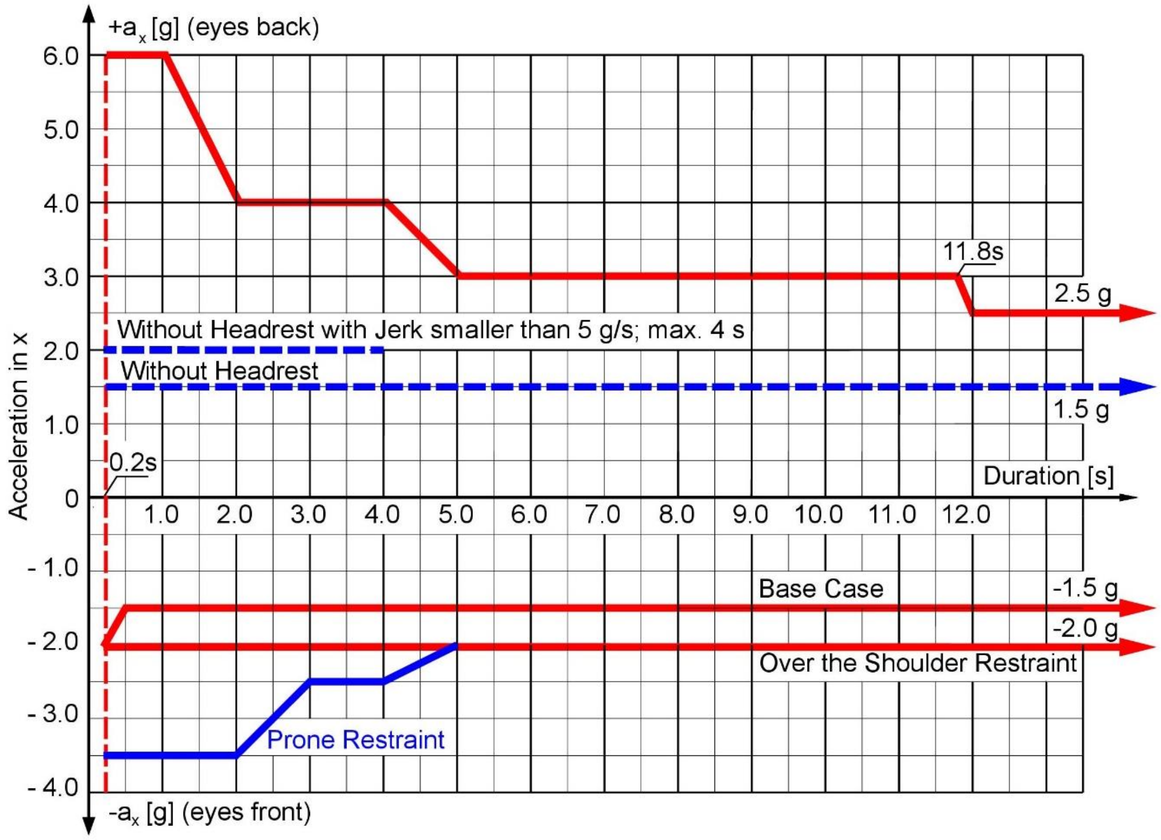


Figure 7.3a Possible revised Acceleration-Duration Limits for the X-Direction

Note: Instead of Figure 7.2 note 1) a possible change of the figure 7.2 including the dashed line is discussed in the G-force Task Group (figure 7.3a). This may simplify the notes under the figure and make the possibilities of allowable accelerations visible when applying the limits of figure 7.3a.

For further information see also chapter 7.3 "Combinations".

7.2.3.3 Prone Restraint and increase of allowable decelerations

For negative longitudinal acceleration ($-a_x$; eyes front) patron neck muscles may be tensed if they are prepared and/or expect braking. Preparatory tensing of neck muscles would be expected in the case of the motorcycle coaster shown in Figure 4.2. The blue colored extended allowance (Figure 4.2 and 7.3a and 7.3b) of higher decelerations of so-called prone restraint is allowable, but the upper torso restraint must minimize the forward motion. Further, in prone restraint scenarios, the containment system must be appropriately padded and the jerk must be less than 15.0 g/s.

Figure 7.3b Example
Prone restraint

Photo: Vekoma

Compared to positive $+a_x$ (eyes back) the negative a_x (eyes front) is reduced because of the neck muscles of the patrons cannot take more than 2.0 g. The author has experience how it feels on the necks muscle on higher speeds on motorcycles. Theoretically it would be possible to allow at least the values of prone restraints or even more if the head is fixed. This possibility must be evaluated including the head-retention device with a biodynamic expert.

Remark: To design an acceptable retention system an adjustable helmet fixed to seat may be one option.

7.2.4 Vertical Accelerations (up/down)

7.2.4.1 Sustained acceleration duration limits in the z-direction

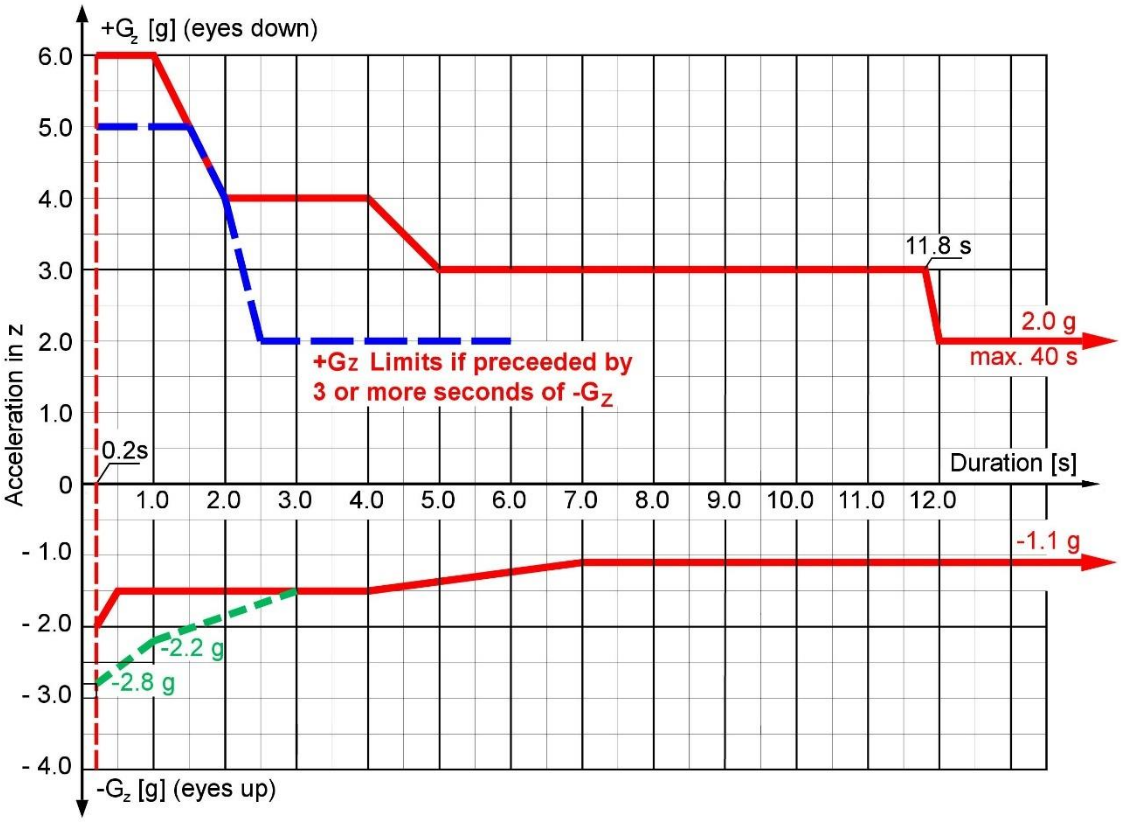


Figure 7.4 Acceleration-Duration Limits for the Acceleration in the Z-Direction (Eyes Down and Eyes Up)

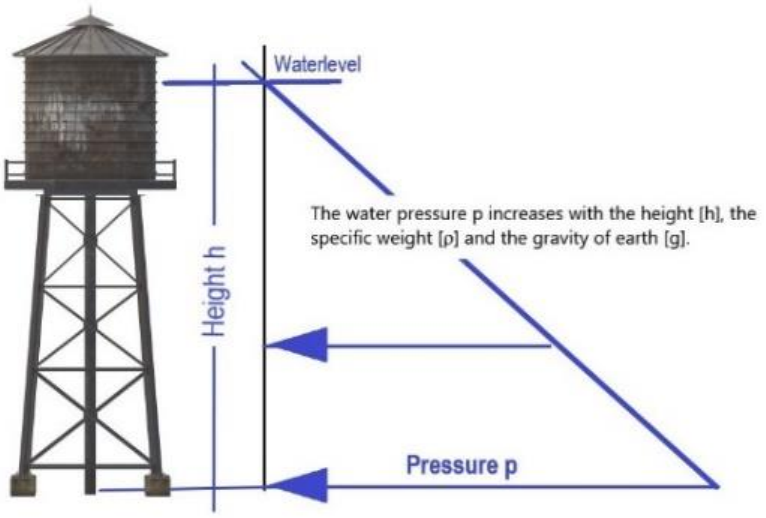
7.2.4.2 Vertical $+G_z$ and Blood-Pressure

To understand the potential adverse health consequences of vertical acceleration, it is necessary to briefly introduce the relationship between blood pressure and acceleration.

The unit of measure for blood pressure is "millimeters of mercury", abbreviated to mmHg, the former unit to measure atmospheric pressure with liquid mercury. In practice, blood pressure is reported via a pair of pressure measurements. The first number, the systolic pressure, represents the pressure in the arteries when the heart beats. The second number, diastolic pressure, represents the pressure in the arteries when the heart rests between beats. The following basic pressure variation example illustrates the reason blood pressure effects should be considered when setting vertical acceleration limits for amusement rides.

In other words, tests on young, trained people like pilots are not applicable.

Foundationally, fluid pressure magnitude is dependent upon the height (or depth) at which that pressure is measured. Consider the case of a water tower.



The water pressure, [p] increases with the height [h]. The formula for pressure is

$p = \rho * g * h$

where
ρ = density,
g = Earth's gravity and
h = 0 at the water level and increases with depth. (see Figure 7.5)

Figure 7.5 Water pressure in a water Tower with the service pipe to the ground

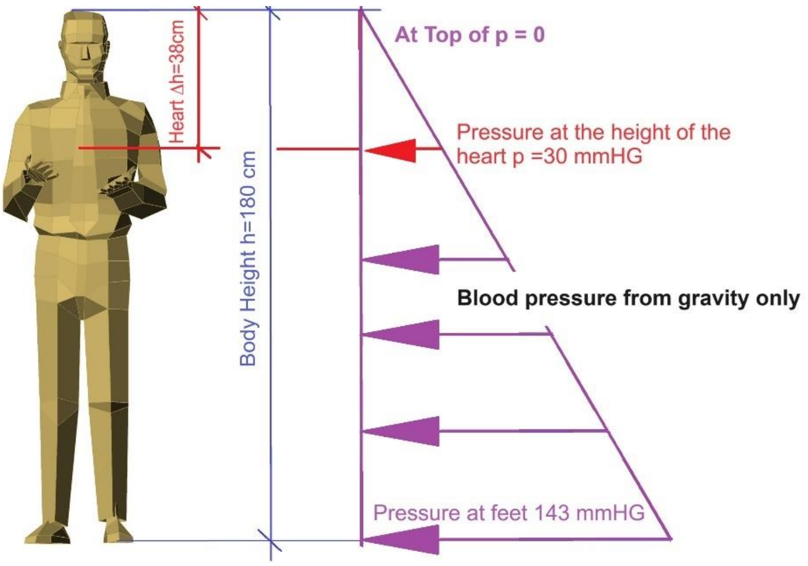
The same concept holds true for the measurement of blood pressure within the human body; blood pressure magnitude will vary at different locations of the body. So as to not the complicate the following calculation, the measurements are rounded and expressed in metric units.

Note: The Blood pressure might be 120/80 mmHg;

Conversion: 100 mmHg ~ 133 mbar ~ 1.93 psi

Or the normal air pressure is 760 mmHG ~ 1013 mbar ~ 14.7 psi .
This is approx. the water pressure in a depth of 10 m or 32.8‘

A typical blood pressure reading will consist of 120 mmHg as the systolic pressure of the heart, but this pressure measurement is only relevant at the same height as the heart. If one would measure blood pressure at the feet or the head, the result would be different.



The same calculation as illustrated with the water tower can be applied to the blood circuit in the human body. The density of bloodis approx. ρ = 1.057 t/m³ (compared with water of 1.000 t/m³).

Figure 7.6 shows the effect of height on blood pressure for a person standing. The pressure is due to gravity only, without the additive pressure from the heart.

Figure 7.6 Blood pressure in a standing human **without** the pressure from the heart

Example calculation of blood pressure from only gravity at height of heart:

$p = \rho*g*\Delta h$ = 1,057 t/m³ *9,81 m/s² * 0,38m
= 4,0 [t*m/s² / m²]
= 4,0 [kN / m²]
→ 4,0 *10 = 40 mBar * 0,75 = 30 mmHg

Assumptions:

- Systolic blood pressure is 120 mmHg.
- Person is seated.
- Anthropometric dimensions as shown.
- Stationary, no movement (e.g., park bench), Gravity is 1 g.
- No physiological response to affect blood pressure.

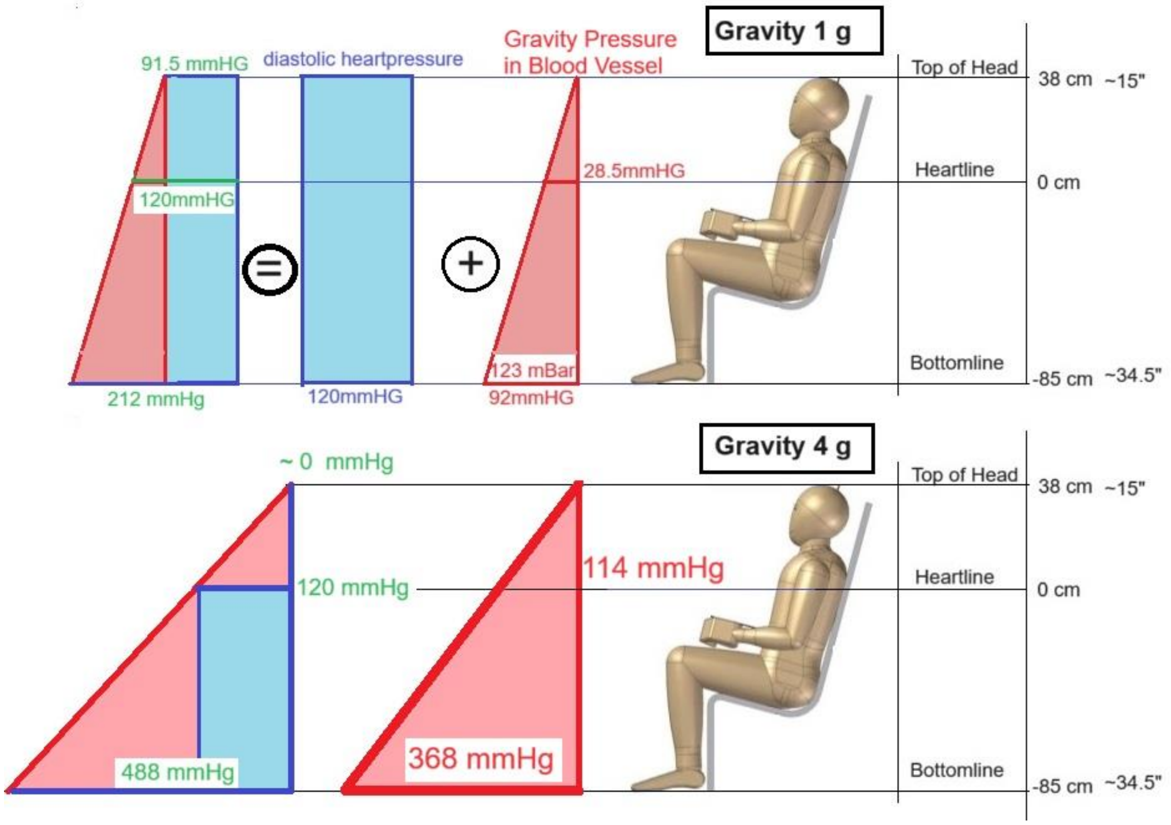


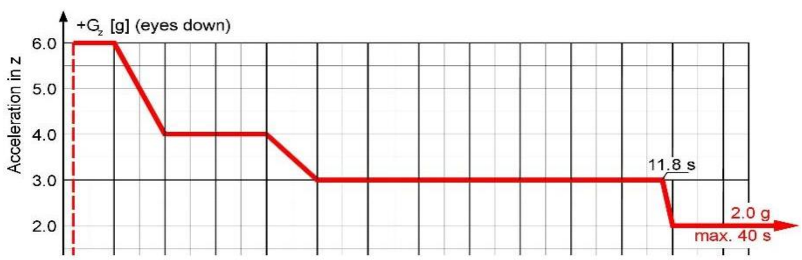
Figure 7.7 Situation Person is sitting with different accelerations +a_z(eyes down)

The red middle image (Gravity 1 g) of Figure 7.7 illustrates blood pressure variation in the body as a result of gravity only; the blue middle image symbolizes the systolic pressure without the gravity. The superposition of these two images is shown on the left represents the pressure at the heart, 120 mmHg. The blood is pumped through the body and because of the gravity the pressure is reduced at the top of head to 91.5 mmHg and at the feet raised to 212 mmHg.

In an amusement ride, assuming a vertical acceleration of a_z = 4 g (second Line of figure 7.7), the pressure in the blood vessel is 4 times higher than at 1 g and has a pressure at the heartline of 120 mmHg. At the top of the head the pressure including the 120 mmHg will result to almost 0 mmHg.

This means that here the acceleration of more than 4 g will cause a blood pressure of 0 at the top of the head. This does not guarantee the oxygen supply to the brain any more.

Note: Into this rough calculation the side effect of BRS or low blood pressure etc. is not included.



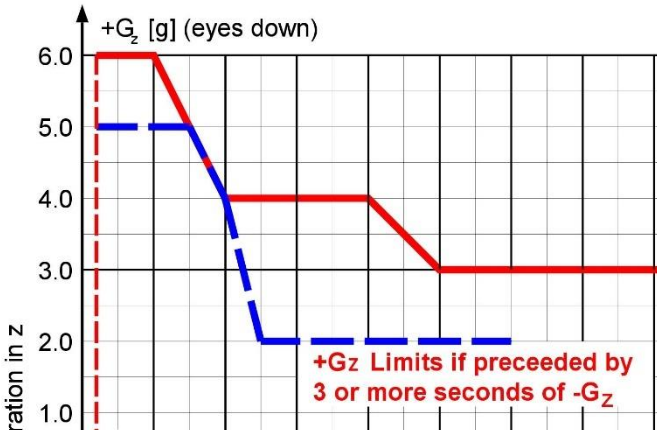
The detail of figure 7.4 shows the result of these discussions. The limits are proven by hundreds of existing rides. These limits also take the fact into account of elderly Patrons and exhausted, tired or drunken patrons using the rides. Reasonable complaints are not reported to the committee.

Summarized: for vertical accelerations +G_Z and if the patrons are properly seated:

- 6 g are acceptable for a period of time of 1 second,
- After a transition the limit is 4 g, followed by 3 g
- After 12 seconds 2 g are acceptable
- After 40 seconds 1 g (standard gravity) must be assured

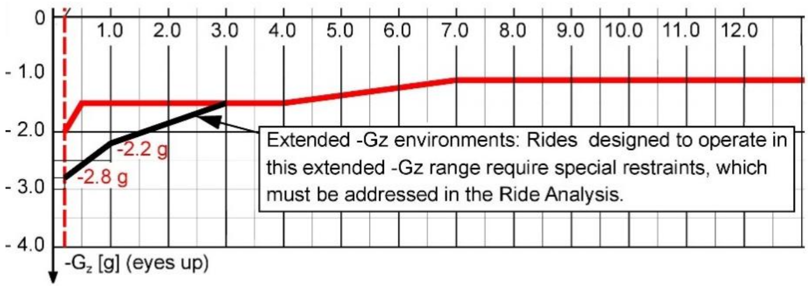
As riders are exposed to accelerations associated with amusement rides, they experience natural physiological responses that include changes in heart rates and/or blood pressure. This effect is referred to as Baroreceptor Reflex Sensitivity (BRS). If blood pressure is elevated, the baroreflex counteracts this by lowering the heart rate and dilating the blood vessels. The opposite happens if the blood pressure is too low. This correction system is not as effective in the older population, and they are less able to compensate for rapidly changing G_Z conditions. This variability in baroreflex effectiveness among the amusement rider population must be considered in the establishment of acceleration limit values, especially for accelerations in the z-direction.
In other words, data only gathered from young, trained people like pilots are not sufficient.

7.2.4.3 Vertical +G_Z and Push-Pull Effect



This reduction (black dashed line) known as "Push-pull effect". It will be explained under "Reversals" in Chapter 7.4.3.1

7.2.4.4 Vertical and extended -G_Z



In ASTM the extended -G_Z environments of figure 7.4 allow higher limits of up to -2.8 g. This extension was added based on empirical data of accelerations experienced during bungee jumping

Bungee jumping has its origin in the South Pacific Islands as a means of initiating young males into the realms of manhood [16]. It gained popularity after a National Geographic film and the US Army documented the Pentecost Islanders practicing it around 1955.

When jumping the Patrons are 100% concentrated and the danger of an accident is small. Accelerations are possible in both vertical directions, depending on the attachment, the guest can jump upside down or feet first.

The case “feet first” means the head is upward and the acceleration is “eyes down” $+G_z$. If the harness is appropriate and the acceleration stays in the limits of figure 7.4, this direction does not cause injuries.

If the cord is attached to the ankles the declaration $-G_z$ may reach -2.5 to -3.0 G or even more. This increased $-G_z$ in the head-down position during the retardation phase of the fall can create high intraocular pressures that in several cases have resulted to eye injuries [15]. These injuries could be more severe with breath holding or even worse with the Valsalva maneuver during the fall. (a forceful attempt of exhalation against a closed airway; Antonio Maria Valsalva (1666 – 1723) Italian anatomist)

Also, the restraints are designed for this type of attraction. EN 13814 does not include bungee jumping and this extension is not applicable.

In the first years of bungee jumping many incidents were reported. One example of many is in [16]. After approx. 20 million jumps in the first 20 years the cords can be designed accordingly to a decent deceleration which just not cause injury.

Nevertheless, for bungee jumping with 100% concentrated and restrained people an extended $-G_z$ for head-down jumps was extended in figure 7.4 to -2.8 g.

Even the $-G_z$ Accelerations (red line) are only acceptable for a time limit of 3 seconds. After this the upside down is limited to -1.1 g.

These extended limits are included in F2291 both because bungee jumping is included in F2291 and because, if the accelerations induced are safe during bungee jumping, they are safe during other activities, such as on roller coasters (if the patron is appropriately restrained).

Note: EN 13814 does not include this extended $-G_z$, because bungee jumping is excluded in EN

7.2.5 Example obtaining admissible Accelerations

The admissible accelerations (adm. a_x, adm. a_y or adm. a_z) can be derived with the examples of Figure 7.8 and 7.8 a. These Figures show examples how to obtain adm. a_x from the filtered measured accelerations in x-direction, the ride is assumed to have an “Over the Shoulder Restraint”.

- Acceleration labels ① and ②: Peaks can be taken for duration of greater or equal 200 ms, see detail for label ①. Accelerations of shorter duration can be neglected. As label ② has a broad peak the maximum acceleration can be taken.
- In this example the check for positive accelerations in x (eyes back) for durations at transitions in the graph over 2 s (adm. a_x = 4 g, label ③), 5 s (adm. a_x = 3 g, label ④) and 12 s (max. 2 g, not shown) may be sufficient.

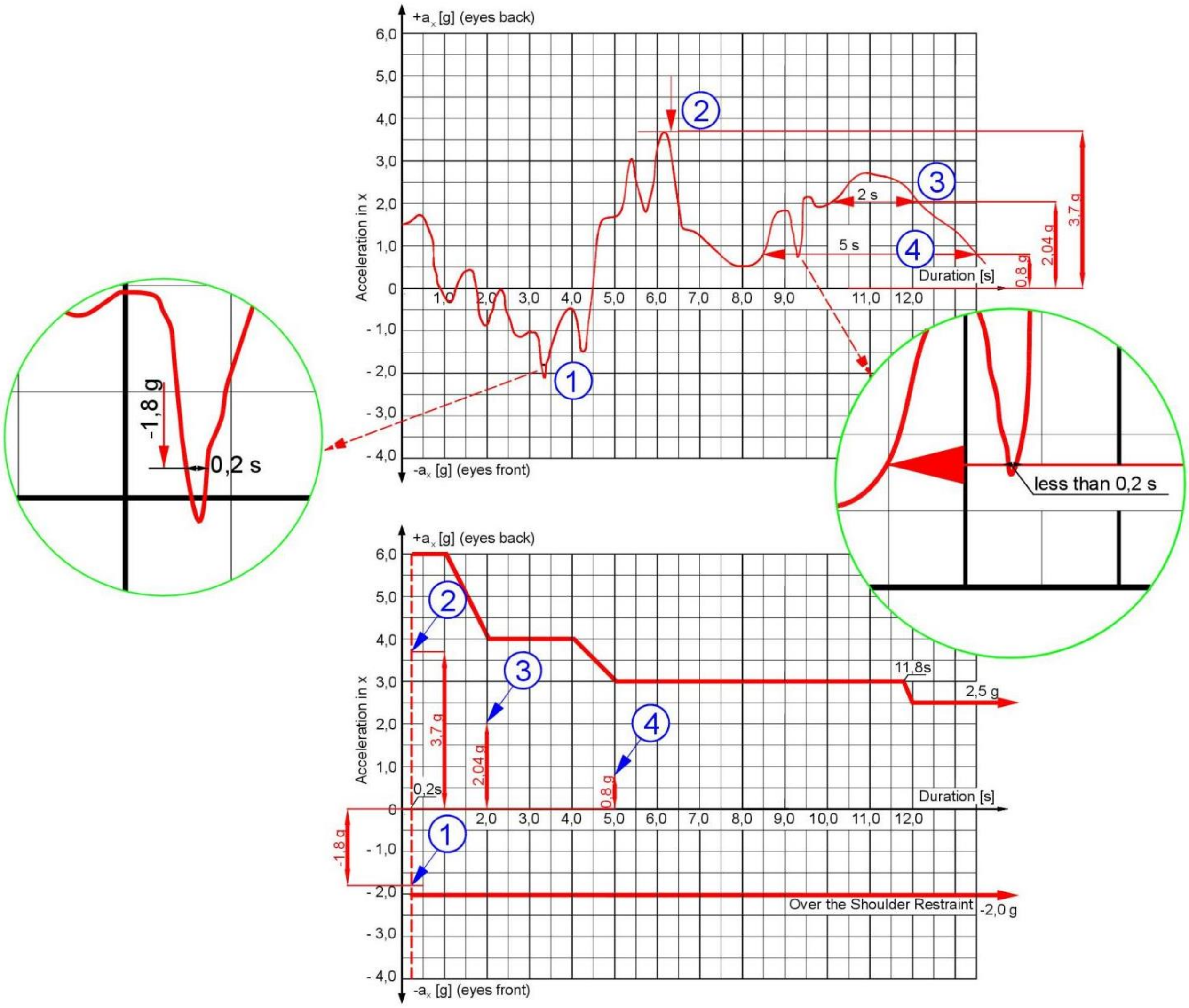


Figure 7.8 Example to develop the admissible accelerations on the time history data

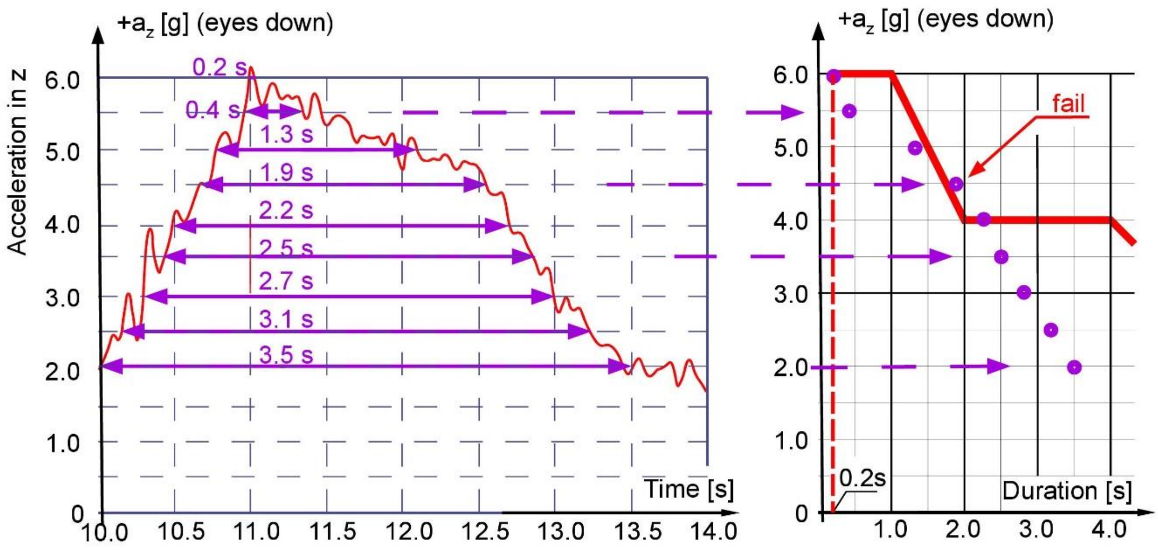


Figure 7.8a Example to check admissible accelerations for one event with slice-method

Note: Normally this procedure is automated in the processing computer program.

7.2.6 Combinations of Acceleration

7.2.6.1 Approach after Incidents on a Portable Roller Coaster

In the 1980s, a race for the ride with the most loops began for portable roller coasters. It ended for the time being with the so-called Thriller with a total of 4 loops in 1986. Details can be found in [12] and figure 7.8b.

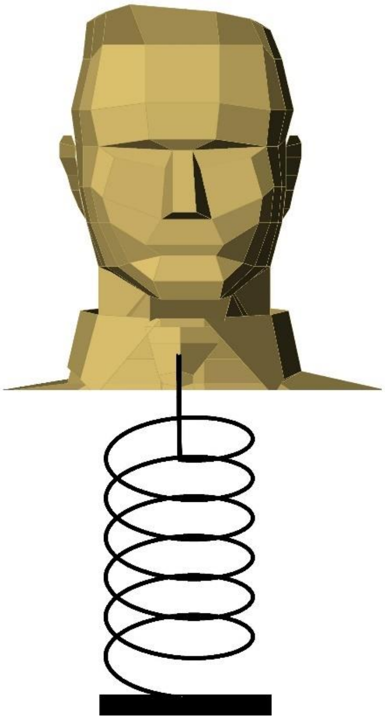
After more than 100,000 Patrons had already ridden the roller coaster, around 35 people were treated for whiplash injuries. This led to the closure of the ride by the health authorities. A large number of unreported injuries are suspected, as whiplash injuries can occur up to 3 days after the event and the investigation started long time after the injuries. Nevertheless, it means that probably far less than 0.2 % of Patrons were injured.

Figure 7.8b Schwarzkopf Thriller build in 1986 (Fotos: www.schwarzkopf-coaster.net)

The search for the cause was difficult. The injuries could also be the result of incorrect posture, age, previous injuries, fatigue and/or alcohol. In the beginning of the investigations, it was also not possible to determine where the probable excessive accelerations occurred.

Although lateral acceleration does not play a significant role in aviation medicine, Aviation physicians were consulted. Possibilities with flight simulators (lateral accelerations too small) or comparisons with crash tests on cars (lateral accelerations too large) were unsuccessful and not applicable.

Comparisons with existing systems were difficult because tests with accelerometers attached directly to the head were not reproducible.



The test on dummies was also found not realistic. Therefore, the accelerometers were attached to the seats at approximately head height.

At this point it should be noted that even today the accelerometers are mounted in an elevated position approximately in the heart line and the EN-SARC test therefore requires a different position than the ASTM ASTM-SARC test according to F2137.

It is also not possible to infer the lateral acceleration at the head, as rotational movements are not normally recorded.

This eventually led to the development of theoretical models and simulations. (Figure 7.9)

The human head has an approximate weight G and the neck has a spring stiffness k. Furthermore, the head can rotate sideways by approx. +/- 60°. Previously, 2.0 g was considered the maximum permissible lateral acceleration (in the y-direction).

Figure 7.9 Mechanical Model of a human head

Assuming a sudden increase (Jerk → ∞) from 0.0 g to 2.0 g lateral acceleration, 27° was measured. This 27° was therefore taken as the limiting angle for the tests.

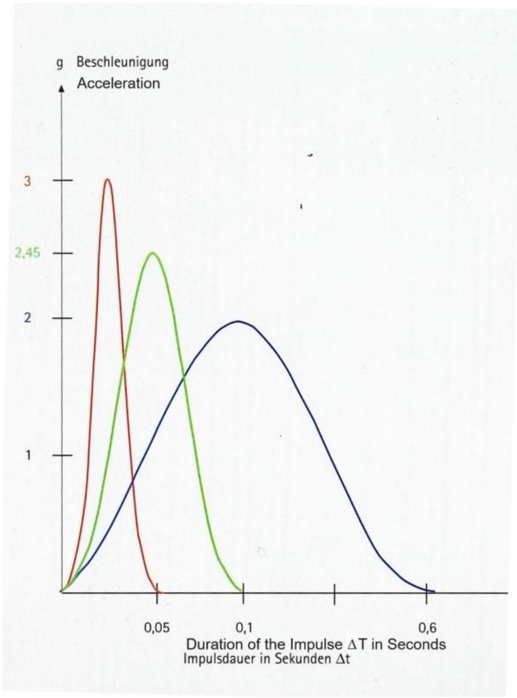


Figure 7.10 Impulses on the human head

The model was tested with different pulses using these input parameters.

The Figure 7.10 on the left is taken from [12]. In the newer standards, all accelerations below 0.2 s are excluded, in this case it is indirectly included. However, today this falls under the heading "Delta-v" Δv. The status of the investigations is described in chapter 8.

Just a brief description: Without spring and damping, the integral of the acceleration over the time Δt is a velocity Δv. This indicates how big the difference in speed between the torso and the head is after the impulse.

In these experiments, the accelerations were varied until the angle of 27° was reached at the head. (Figure 7.11)

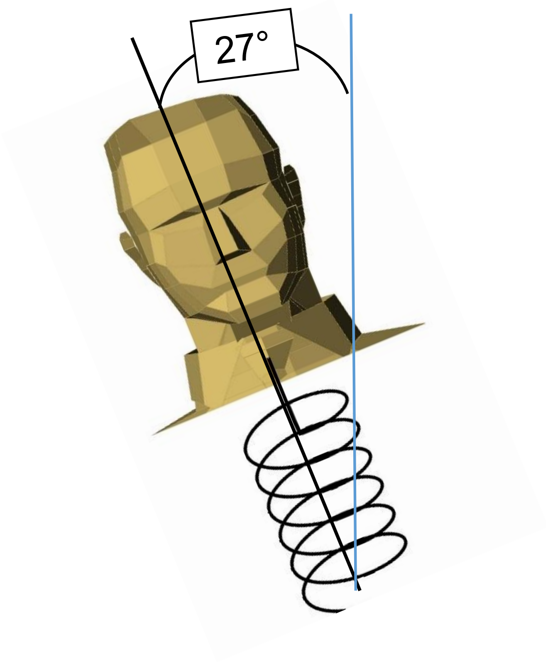
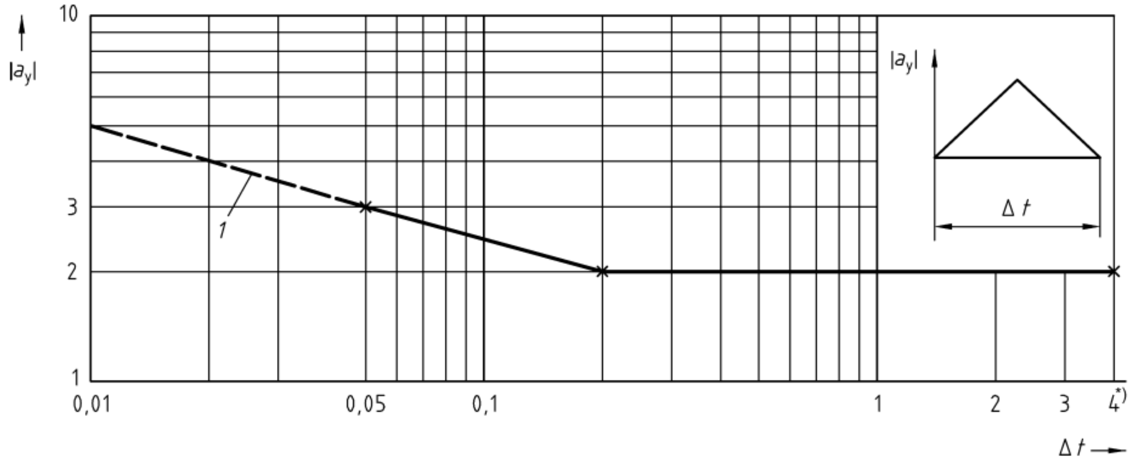


Figure 7.11 27°-Limit of Tilt for the tests

In parallel to the tests, mechanical models with spring rates, geometry and weights were developed which finally led to recommendations to the CEN-standards committee.
In 2004, these results were officially published into EN 13814.

Two pictures from EN 13814-2004 are shown here:



Key

1 Area above frequency limit of 10 Hz

Δt Duration of the impulse in s

*) The area > 4 s is not proven and requires further examinations

Figure G.2 — Permissible acceleration of the seat $|a_y|$ as a function of the pulse duration

Figure 7.12 from EN 13814 - 2004

Note for clarification: The assumption of a triangular graph is simplified and has its origin in the analog measurement technology commonly used at that time. Today, this can be calculated for example using the method according to F2291-Annex X2. This is about the methodology of Δv, which is discussed in chapter 8.
At Δt = 0.2 s, the maximum gradient = Jerk = $\frac{1}{2} * \frac{max.a_y}{\Delta t} = \frac{1}{2} * \frac{2.0\ g}{0.2s/2}$ = 10 g/s. (see chapter 7.4).

The area is $\frac{1}{2} * max.a_y * \Delta t = \frac{1}{2} * 2.0g * 0.2\ s$ = ½ *2.0*10m/s²*0.2 s = 2.0 m/s = Δv; the average acceleration is Δv/Δt = 2.0/0.2 = 10 m/s² = 1.0 g. This limit also almost coincides with the findings of the limits for Δv (Chapter 8).

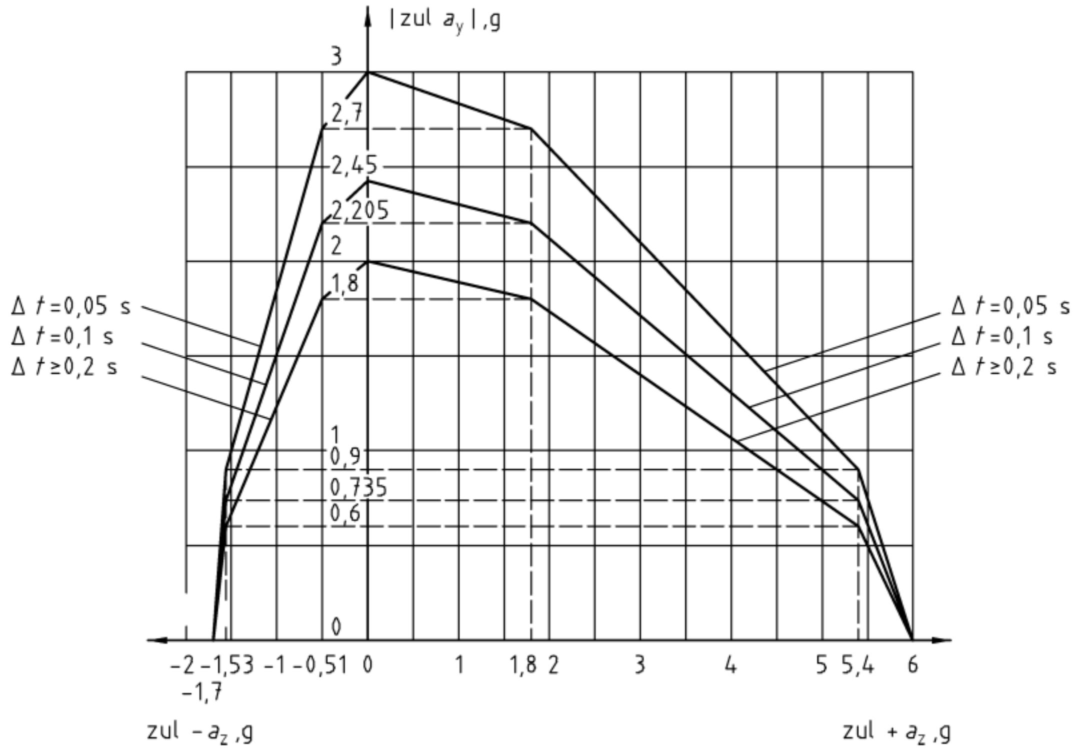


Figure G.5 — Permissible accelerations a_y and a_z when combined

Figure 7.13 from EN 13814 - 2004

Figure 7.13 shows the permissible accelerations subdivided to different pulse durations of 0.05, 0.1 and over 0.2 s.

It should be mentioned that in the design phase these impulses cannot be included. They are often caused by impacts at rail transitions, and they build up during the lifetime of a ride. These can hardly be represented in the design.

Furthermore, the curves were angular due to the small number of test results. The pulse durations were below 0.2 s which are still excluded in all standards.
F2291 had already developed its own limit curves in 2003, parallel to the publication of EN 13814-2004.

It took many approaches before the nowadays x-y combination was found. This is the red curve in Figure 7.14 and the lower curve in figure 7.15.

The differences for two different pulses compared to the F2291 are shown in the top two images in the Figure 7.14 of the history image. The difference is highlighted in yellow and can be understood from the few tests carried out. It is worth noting that especially the impulse of $\Delta t = 0.05$ s is close to the current limit curve. This also means that events under $\Delta t \leq 0.2$ s are already partially included in the limit curves.
The image below shows an example from the first generation of combinations with the current one. Only a few extreme events in combinations cause a ride to fail the check. This was corrected later.

It should also be mentioned that EN 13814-2004 only included the a_z - a_y combination based on verifiable and published studies.

It is important to mention that all figures in the standard need to be as simple as possible without the loss of safety. This helps designers to use and not to mislead them.

It is not known to the author how the limit curves of the other combinations were developed.

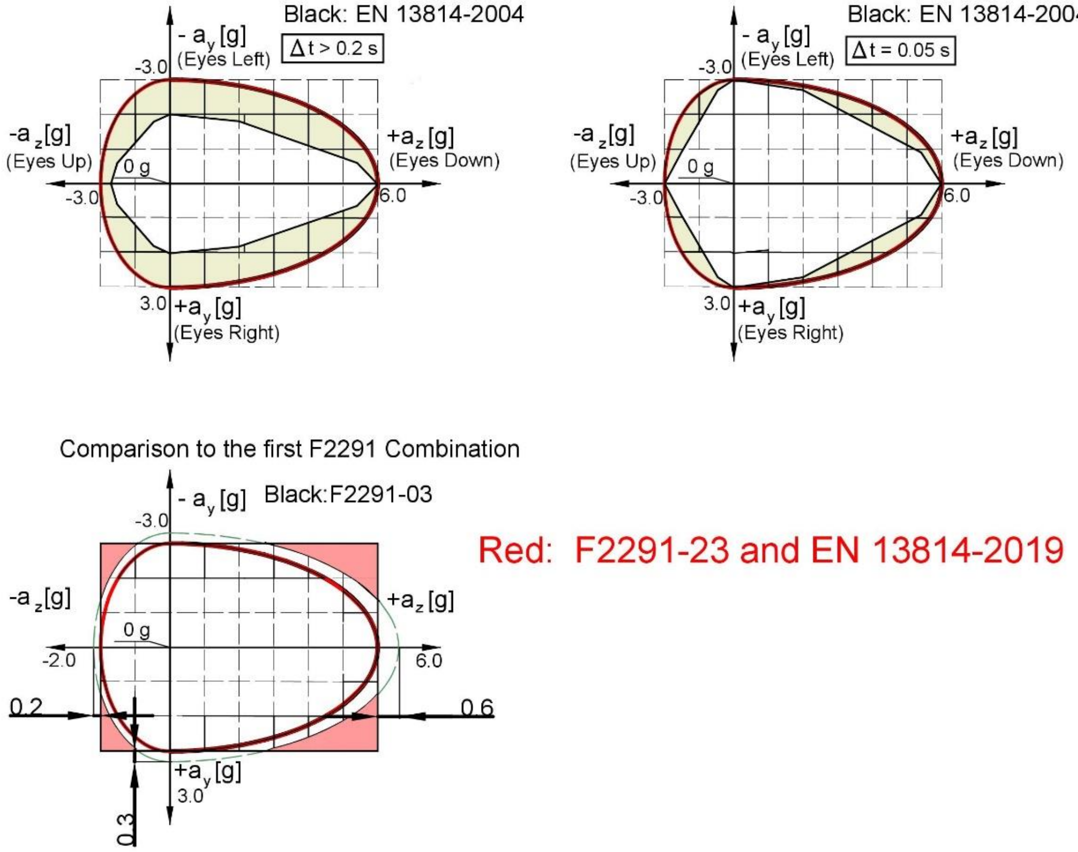


Figure 7.14 Comparison of the different limits for acceleration combinations in the history of the Standards

7.2.6.2 Combinations in x, y and z – the Eggs

Among experts the reduction on simultaneous accelerations is unquestioned.
The 2004 version of the EN suggests the following: a_x, a_y and a_z are the maximum acceleration values seen within a period of 300 ms, i.e. maximum values occurring with a time difference of 0,30 s or less need to be superimposed. In the new revision of EN 13814-2019 this has been dropped and was never in F2291.

The EN has adapted and expanded the acceleration limits of the ASTM F2291. Examples of readings from figures 7.1, 7.2 and 7.4 are shown in table 7.1.

Table 7.1: Examples for the allowable acceleration

Accele-ration	Mininum adm. a	Maximum adm. a	Limit
in x	-2,00 g	6,00 g	Base/Upper Torso
in y	-3,00 g	3,00 g	Base
in z	-2,00 g	6,00 g	Base
in x	-3,50 g	6,00 g	Prone
in z	-2,80 g	6,00 g	Extended

EN 13184-2004 published a standard of combination rules for Amusement Rides; these rules were relatively short and conservative.
The EN committee decided to adapt to the combination rules from the ASTM. Furthermore, the accelerations acting in all 3 directions simultaneously were discussed but not published. [See equation 4].

Figure 9 shows examples for the base limits of allowable combined magnitudes of X, Y and Z accelerations. Most of the engineers titled these limit curves as “Eggs”.

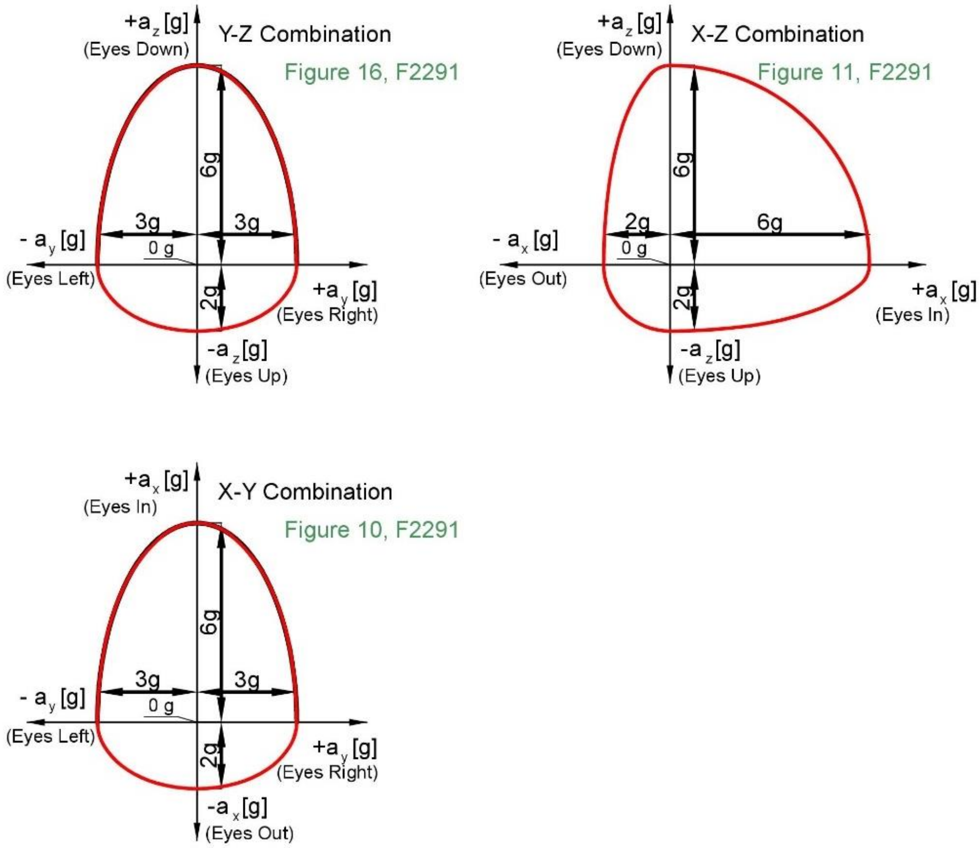


Figure 7.15 Examples of allowable combined magnitudes of X, Y and Z accelerations, related to table 7.1.

Based on the assumption that the “egg” graphs are an assembly of elliptical curves, the combined effect of accelerations can be checked for acceptability by using the formulae below. The combination regulations can be calculated taking the limit acceleration into account, as shown in Figures 7.1, 7.2 and 7.4 and Table 7.1.

$$\left(\frac{a_x}{adm.\ a_x}\right)^2 + \left(\frac{a_y}{adm.\ a_y}\right)^2 \leq 1{,}0 \quad (1)$$

$$\left(\frac{a_x}{adm.\ a_x}\right)^2 + \left(\frac{a_z}{adm.\ a_z}\right)^2 \leq 1{,}0 \quad (2)$$

$$\left(\frac{a_z}{adm.\ a_z}\right)^2 + \left(\frac{a_y}{adm.\ a_y}\right)^2 \leq 1{,}0 \quad (3)$$

$$\left(\frac{a_x}{adm.\ a_x}\right)^2 + \left(\frac{a_y}{adm.\ a_y}\right)^2 + \left(\frac{a_z}{adm.\ a_z}\right)^2 \leq 1{,}0 \quad (4)$$

The figure 7.16 below show the 2-d Plots and for information the 3 d-Plot as well of a typical ride system. It is simple to understand, that all of the green points must stay in the limits.

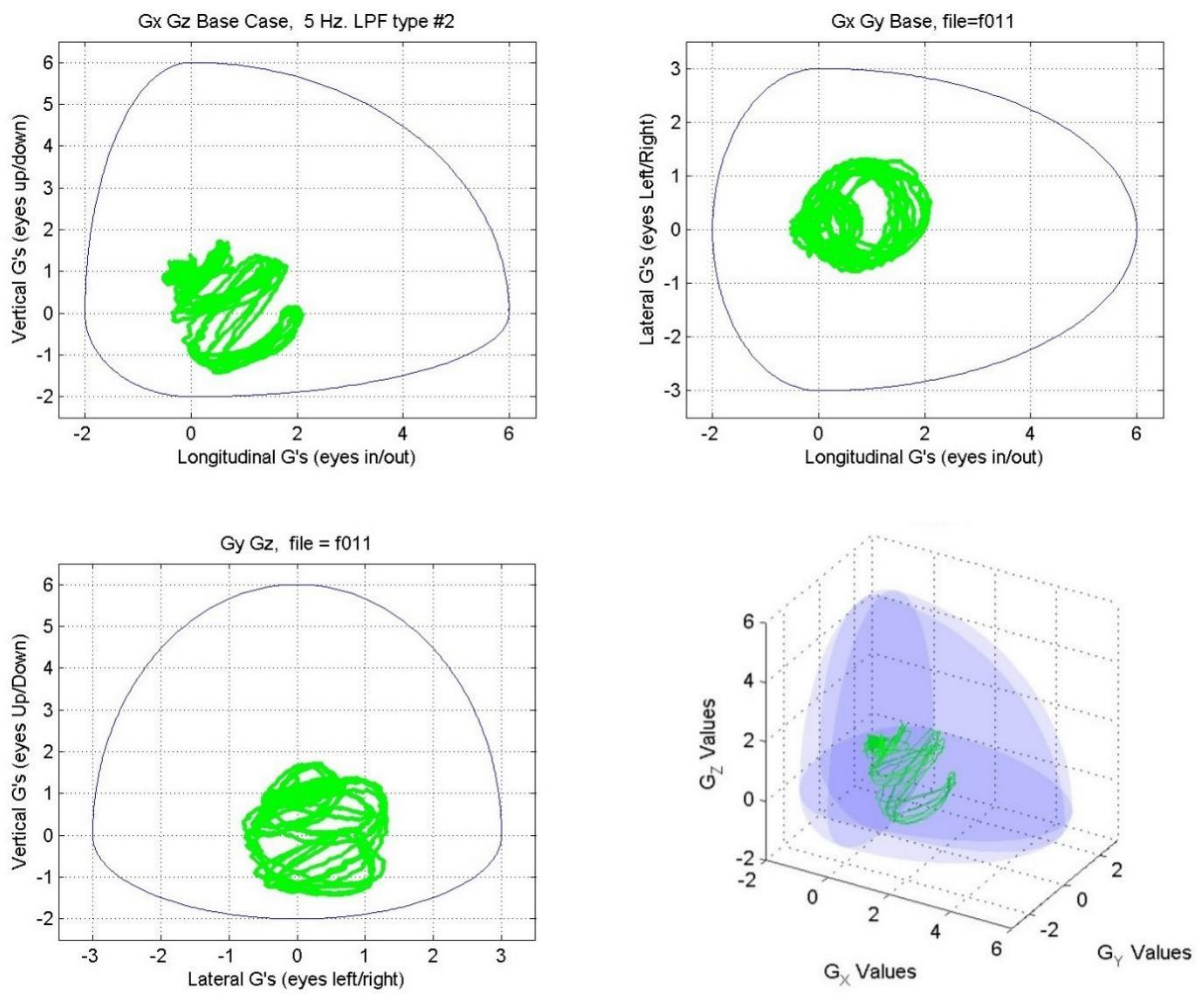


Figure 7.16 Typical 2 and 3 d-Plot if a ride system (Plots from Six Flags)

The 3-dimensional Formula (4) is not mentioned in the standards. The author proposes it as informative, because there are not many amusement rides with high acceleration in x simultaneously with y and z. In other words: In the zones of the start (in x) or at brakes normally there are no curves causing accelerations in a different direction.
The advantage of the formula: One can plot the values over time or distance and there is only one graph to be checked. If there is one location exceeding 1.0 one can identify the location and take a more detailed examination, for example with the 2-d eggs.
Figure 7.17 shows the Ratio – Time Chart.

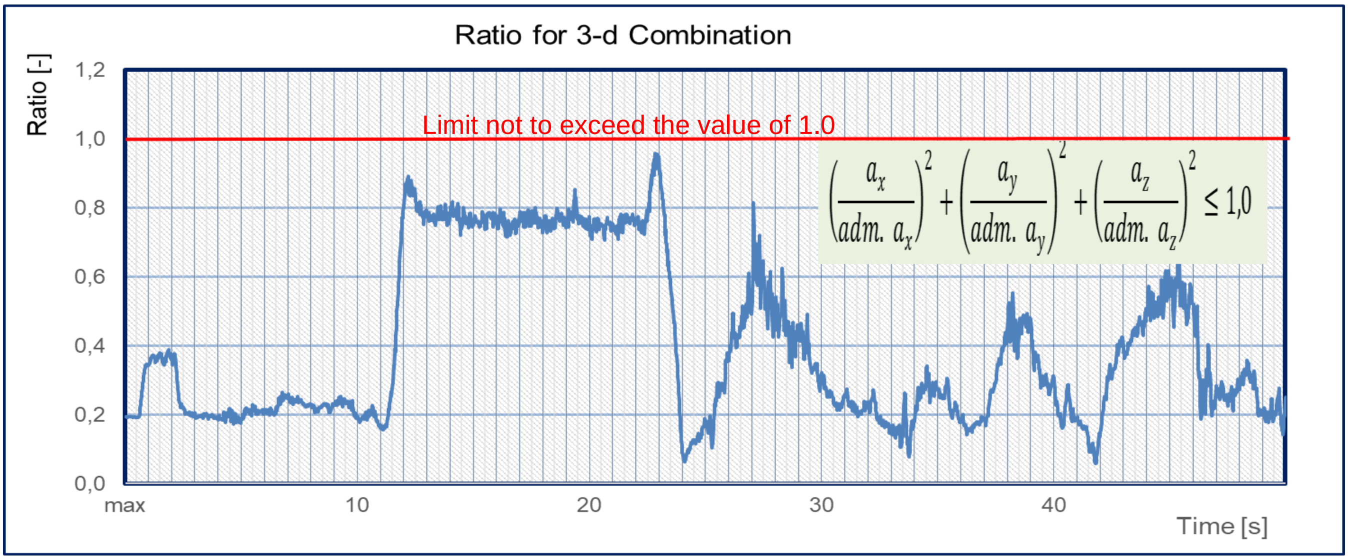


Figure 7.17 Ratio-time chart for the combinations with the3 – formula

The figure 7.18 below explains the discussion:

Left: no Combination Volume = 100%
Right: 2-eggs (Formula 1-4) ~ 70% (called “lantern”)
Middle 3-D approach (Formula 4) ~ 50%

The volume of the sphere is with 50% approx. half of the cube and even significantly smaller than the lantern. But it is obvious that Acceleration in x, y and z simultaneously never happens. To avoid restrictions in new developments and the fact that this method is not scientifically proven, equation (4) is not in the standards.

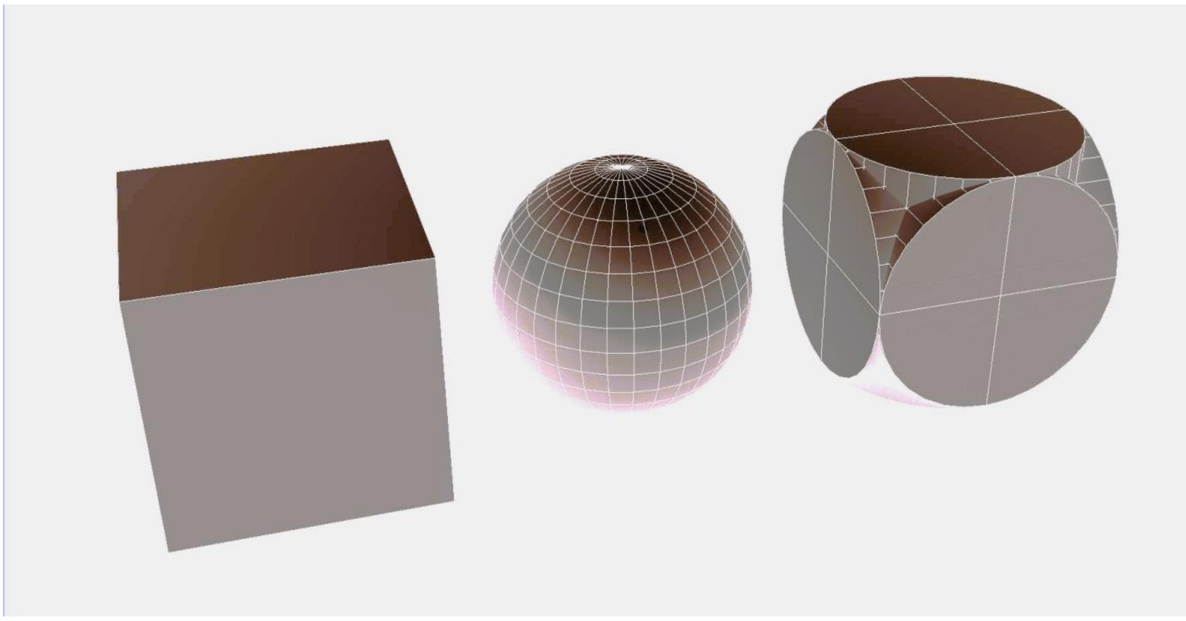


Figure 7.18 Comparison Combinations: Left no Combination, Middle 3-D; Right 2-D

7.3 Jerk/Onset

The danger of a whiplash injury can also be reduced by appropriate head supports but due to all the different possibilities of protection in the head region, a normative approach to limit the jerk problem is complex. The engineer/designer must be aware of his responsibility.
The most critical part of the body is the head, especially in x and y direction when accelerations change. This change is called “jerk”. The dimension is ft/s^3, m/s^3 or even g/s.
In F2291 “Jerk” is named ”Onset”. This Name was probably taken from

> *Terminology of ISO 17929 (2014): 3.12 Rate of onset of Acceleration: Value that characterizes the rate of acceleration growth during the given time interval.*

EN 13814 uses “Jerk”. It is in discussion whether F2291 will change it.

Mathematically this can be expressed:

Distance s		
Speed v	Differentiation: Change of Distance	by time $\dot{s} = \frac{ds}{dt} = v$
Acceleration a	Differentiation: Change of Speed	by time $\dot{v} = \frac{dv}{dt} = a$
Jerk j	Differentiation: Change of acceleration	by time $\dot{a} = \frac{da}{dt} = j$

For clarification about the correlation between s, v, a and j please allow the following graphs (Figure 7.19).

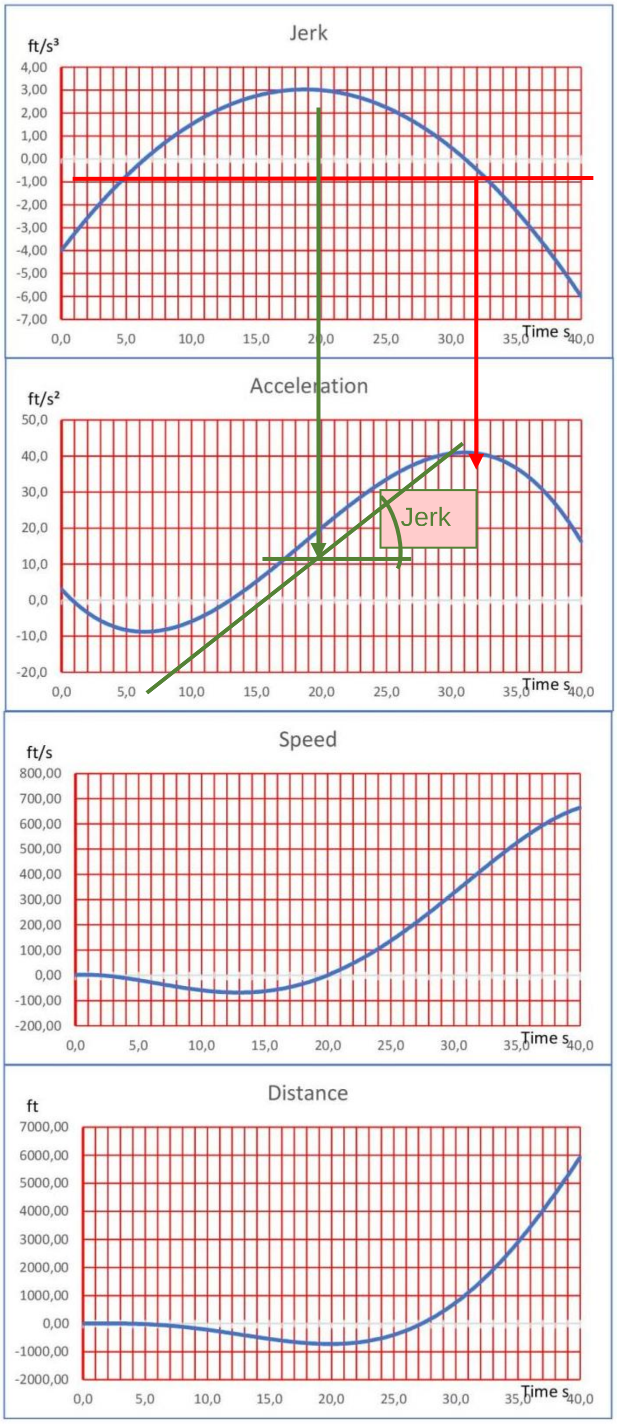


Figure 7.19 correlation between s, v, a and j

The first is the jerk which starts at -4.0 ft/s³ and ends at 6.0 ft/s³.
Red Line: Where the jerk is equal to 0 the acceleration does not change (Maximum or Minimum)
Green Line: Where the Jerk has its Maximum (j=3.00 ft/s³) the slope on the Acceleration Curve has its Maximum → Measured Difference:
Acceleration is 50ft/s² -(-20)ft/s²= 70ft/s²
Time is 29s – 6s = 23 s
Jerk j = 70ft/s³/23ft/s³ ~3,0ft/s³

Here the jerk can be calculated in a simple way with a tangent → slope = jerk.

This is not possible with the collected data. The committee decided to define the slope as shown in the figure 7.20 (figure 9 and 7.1.4.8 in F2291).

Assuming a collection rate of 2000 Data per second the calculation was based on a time frame of 0.1 s or 200 Data points. The jerk is processed step by step with the best fit linear squares Approximation (See figure xyz). The Maximum is the Jerk to be found.

Note: In most cases the jerk is recommended not to exceed 15 g/s. After talking to many designers we recommend 5 g/s or max. 10 g/s in the design phase. The 15 g/s is the max. allowable value when proving the design with the SARC tests.

The Jerk between two events is defined as best fit with a straight line between t_a and t_b. The standards propose at least a regression with at least squares method. The jerk is the slope of the straight line. All other methods may be also applied, if shown that they are appropriate.
In practice a tool must find the maximum slope. A feasible method would be to calculate the jerk a time steps of 5 to 10 ms between the two maximum resp. minimum events.

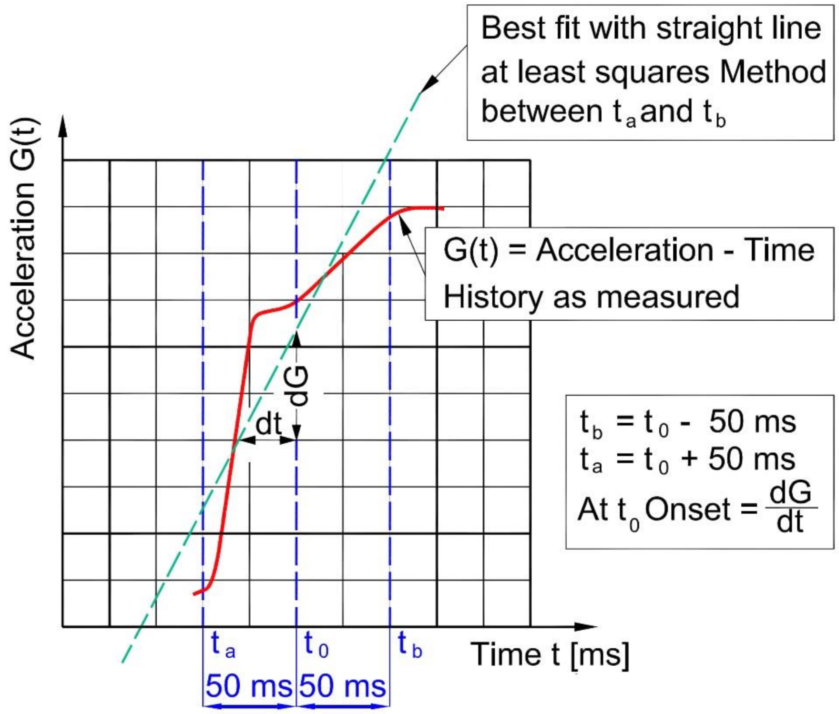


Figure 7.20 *Jerk Calculation*

7.4 Reversals in z, y, and x direction

7.4.1 Time frame

A rider experiencing the dynamics of an amusement ride will naturally brace to counteract the forces acting on them. The body's neuromuscular system has a time delay between sensing a force and then reacting to it, sometimes called reaction time, of approximately 0.20 s. Events lasting 0.20 s or greater are called "Sustained Events".

If the dynamic forces on a ride change faster than a rider's reaction time, the muscular bracing of a rider will be out of synchronization with the forces they are intending to counteract.
In the case of a force reversal that occurs faster than 0.2 s, a rider's delayed bracing may be opposite that needed and amplify containment forces and cause impacts with the containment system or other riders. Injuries resulting from this phenomenon are rare but have included neck strains and clavicle fractures in side-by-side seating arrangements where a small rider is impacted by their larger companion and pushed into the side of the car.

7.4.2 Horizontal Reversals in x- and y-direction

A so-called "neuromuscular force" is necessary for the horizontal position of the head in relation to the torso of the body. This position is controlled by muscles.
(Forces in the z-axis, aligned with the rider's spine, are counteracted by the skeletal system and not subject to this issue.)

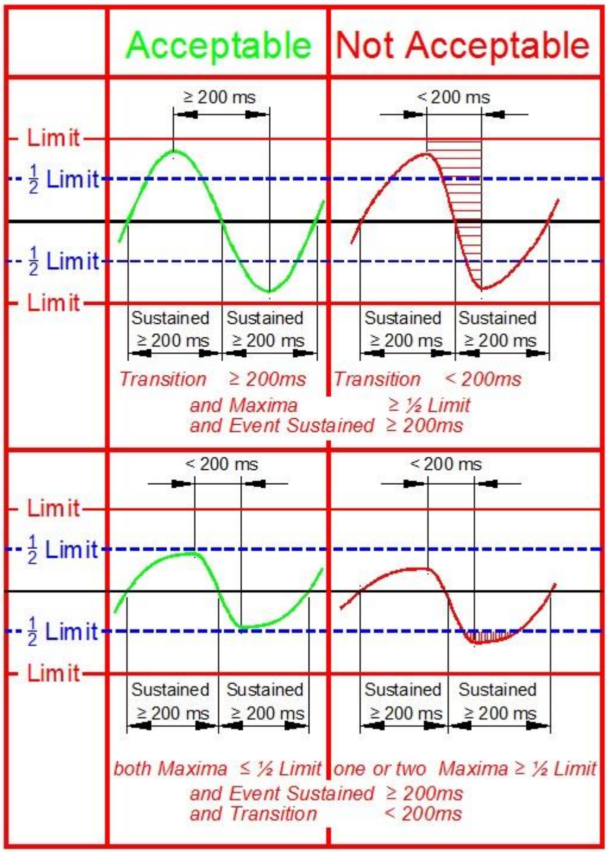
The following conditions combine to create this additive force:

1. The initial force event must last long enough for a rider to react.
2. The reversal of forces must happen faster than the rider's neuromuscular delay.
3. The second force event in the opposite direction must be long enough to be significant.
4. Both the initial and opposite force events must have sufficient magnitudes to create injury.

The criteria ASTM F2291 Chapter 7.1.6, developed empirically, include all of these conditions as follows:

- Conditions 1 & 3 are quantified by "consecutive sustained acceleration events." The reversal events must each be longer than 0,2 s for the limits to apply.
- Condition 2 is quantified by measuring the time between the peak values of the reversal events. This time must be shorter than 0,2 s. for the limits to apply.
- Condition 4 is the limit. The peak acceleration values allowed during the reversal events are 50% of the applicable 0,2 s accelerations from the Acceleration-Duration plots of Fig. 6 & 7.

In general accelerations lasting less than 0,20 s which are followed by accelerations in the opposite direction do not need to be analyzed. Events lasting 0,20 s or greater are called "Sustained Events".



The time to reverse the acceleration from positive to negative in the x or y direction should be relatively long, which is defined as more than 0,20 s. For transition times which are less than 0,20 s, only 50% of the acceleration adm. a from Figures 6-8 is allowable for reversals.

Mathematically the jerk could reach up to $\frac{6g-(-2g)}{0,20s} = 40g/s$ (In case of an inverse acceleration in the longitudinal direction (x) from maximum +6g to minimum 2g).
It is always assumed that the body and head is sufficiently supported. For the lateral direction (a_y) with adm. a_y +/- 3g the jerk can be to 30 g/s.

Since the verbal description is hard to conceive, an illustration can be found in the EN (Figure 7.21).

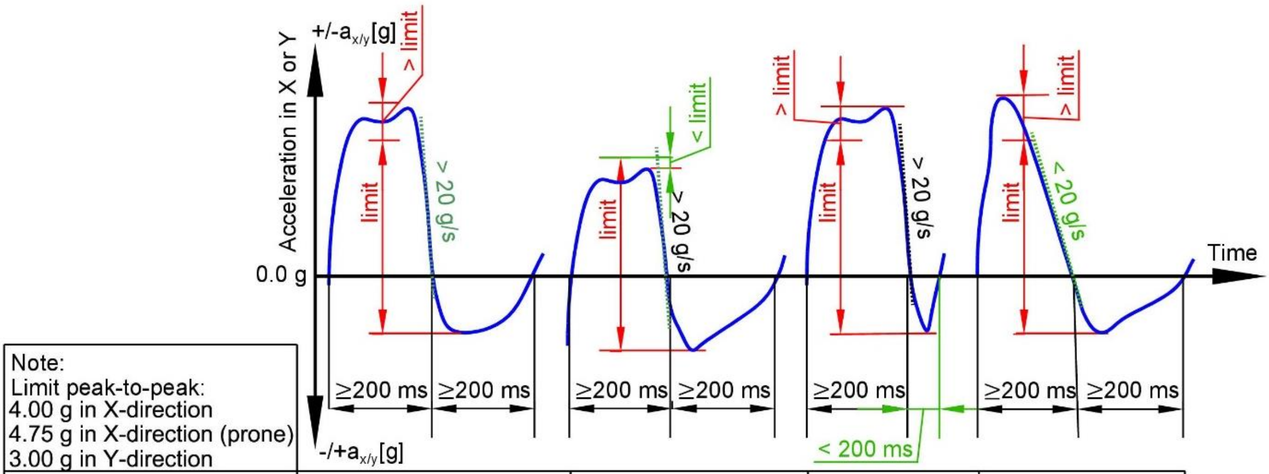
Figure 7.21 Comparison of acceptable and unacceptable reversals in X and Y

Summarized: If the neuromuscular system cannot react (elapsed time between two sustained events smaller than 0,2s) then the peak values of these events shall be reduced by 50%. (F2291 7.1.6.1)

Future Development: On at least two injurious rides the criteria passed. To prove the revised limits, the task group investigates hundreds of amusement rides. It is very difficult to find problematic rides. With to old limits some passed and were injurious, other were not injurious and failed. This is the reason why the Task Group discussed the criteria strictly, as follows:
When a reversal between two consecutive sustained acceleration events has an onset/jerk greater than 20 g/s as determined by the onset/jerk Calculation of Fig. 9, the peak-to-peak acceleration of the two events shall be less than

- 4.00 g for reversals in X
- 4.75 g for prone restraints in X and
- 3.00 g for reversals in Y.

The key of this proposal is the total difference of the actual acceleration in both directions as “limit”. The today’s status is the maximum allowable in one and half of the maximum of the opposite direction. As this is difficult understand and apply the task group proposes the next two figures 7.21a and 7.21b:



Consecutive sustained events	Yes	Yes	No	Yes
Reversal Onset > 20 g/s	Yes	Yes	Yes	No
Peak-to-Peak acceleration exceeds limit	Yes	No	Yes	Yes
	Unacceptable	Acceptable	Acceptable	Acceptable

Figure 7.21a Criteria for Reversals in x or y – direction

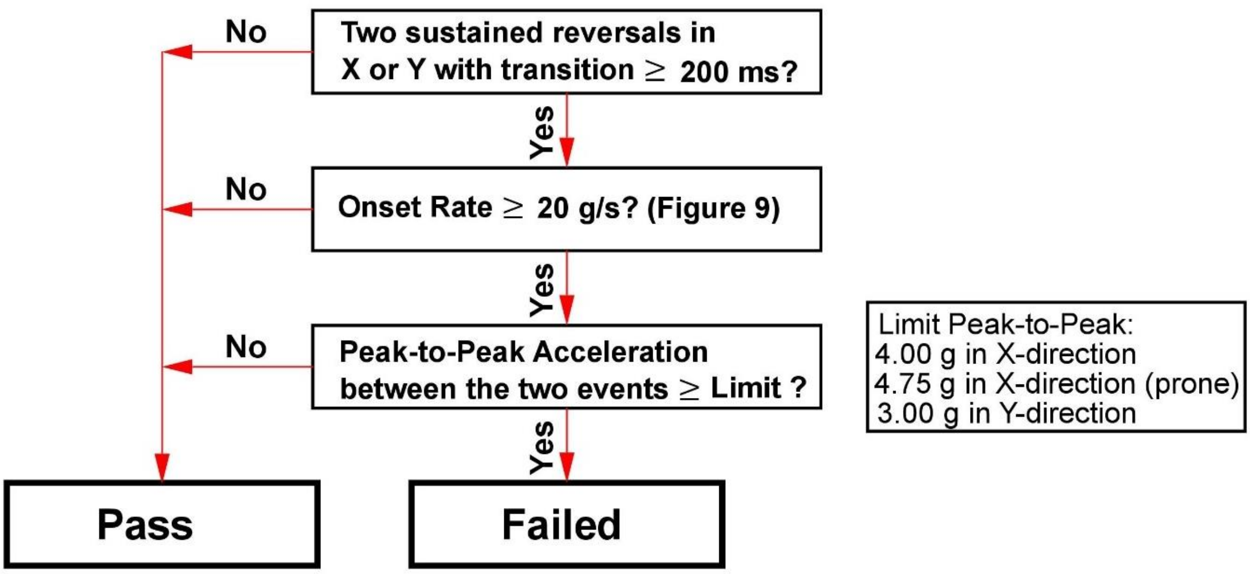


Figure 7.21b Flow Chart for Criteria of Reversals in X or Y – direction

7.4.3 Vertical Reversals Z-direction

7.4.3.1 Push-Pull-Effect

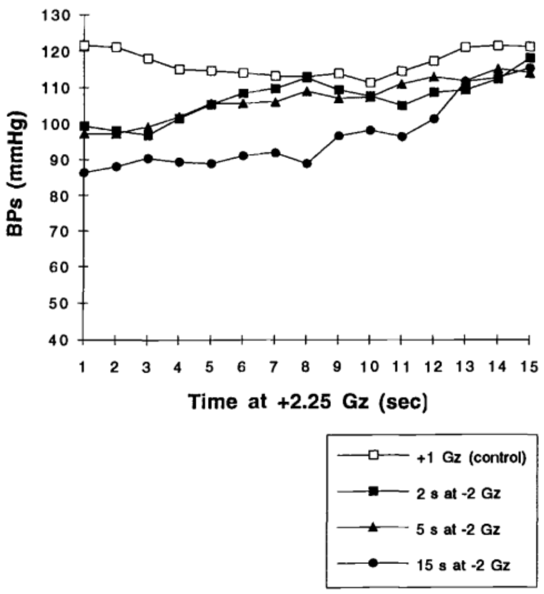
The additional requirement for a reduced +G_z (dashed line) is the result of the so called "Push-Pull Effect". This means, after exposed to negative -G_z (eyes up) for 5 or more seconds following a positive G_z (eyes down) pilots reported about a visual light loss. To clarify tests were made at NASA and US Air Force in 1995 [13], [14] and in 2006 in [24].

One of the tests was that the persons were exposed in three segments to -G_z for 2, 5 and 15 s followed by + 2.25 G_z and return to 1 G_z (Earth Gravity).

Result: Visual light loss from retinal ischemia that results from decreased Blood pressure in the head. The report [13] recommends:

> These findings together with simultaneous and consistent reports of light loss, support the conclusion that +G_z tolerance is reduced by preexposure to -G_z, where the degree of +G_z tolerance reduction depends on the magnitude and time of the preceding -G_z exposure. With further investigations Banks [15] and [24] gave more detailed information which finally resulted to the dashed line.

But the report also published the warning: Since normal cardiovascular tolerance does not return for at least 5 s following -G_z stress, ... , it is possible that residual impairment of +G_z tolerance from previous imposition of -G_z might persist long enough to increase the risk of G-LOC (g-force induced loss of consciousness).

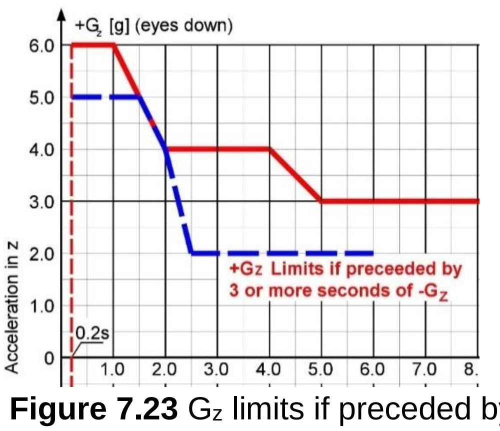


Note: Please consider that the dashed line stops not at 6 s and afterwards the standard (red) line can be considered as limit.

The drop of the blood pressure corresponds to the -Gz exposure, i.e. so longer the exposure so higher the drop of the systolic Blood pressure (BPS). The tests can be found in [13]. In F2291 this was simplified to "3 or more seconds".

Figure 7.22 shows one of the test results (120 mmHg as normal BPS for the test persons).

Figure 7.22 Mean values of systolic blood pressure (BPS) vs time at 2.25 Gz.



In a standard this effect must be addressed in a short and applicable way. Figure 7.23 shows the ASTM solution (copy from figure 8, F2291-23b)

Note: This is a simplified recommendation on the safe side. In doubt please ask a biodynamic expert.

Figure 7.23 G_z limits if preceded by uplift

7.4.3.2 Transitions from Sustained $-G_z$ to $+G_z$

The reversal in z-direction from negative ("Eyes up") to the positive ("Eyes down") requires a reduced acceleration, because in the case of a longer uplift ("Eyes up") the patrons may lose their hold in the seat. If the acceleration then reverses back, the Patron may have problems finding their original and safe position.

One additional effect in the z-direction is important, i.e. the transition must be fast. As the calculation of the jerk with the values measured is very sensitive, it has been agreed to use an average period of time of 0.133s (or 15 g/s). Looking at medical analysis for this time period, the human body has the sufficient capacity to handle this.

Looking at medical analysis for this time-period, the human body has the sufficient capacity to handle possible peaks, if the criteria in figure 7.24 are kept.

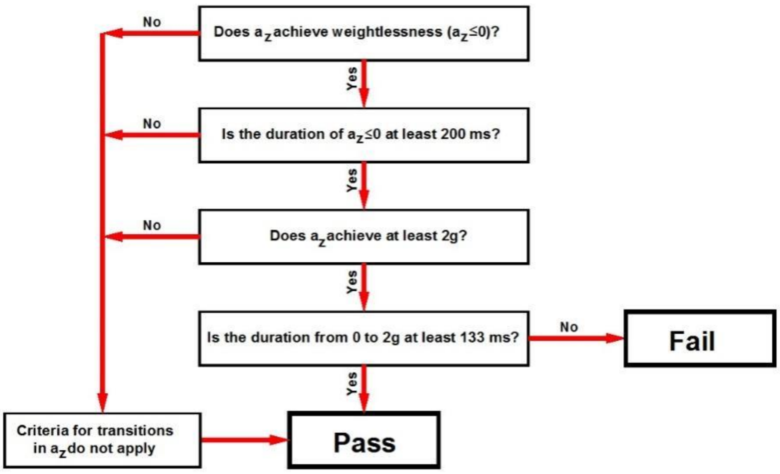


Figure 7.24 Transfer from permanent weightlessness to negative acceleration

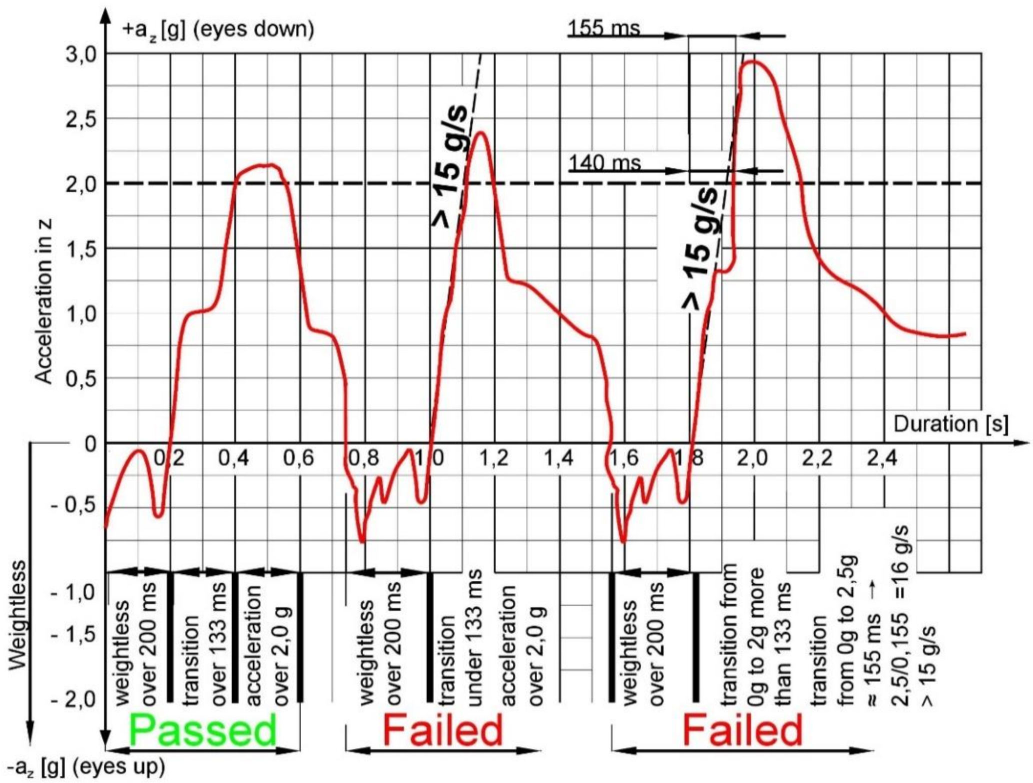


Figure 7.25 Transitions from sustained weightless to positive accelerations

7.5 Riders under 48 inches (Appendix X8 of F2291)

In 2010 through 2013 the G-Force Task group started a study whether the accelerations for children in Amusement rides can be applied or must be reduced. The working title was “Kiddie-Rides”. As commonly known the head of children is in relation to body and muscles bigger. So, it can be assumed that lateral accelerations may be reduced.

Thanks to the Parks of Six Flags, Disney and Universal including Measurements by Recreation Engineering in total 236 so called Kiddie amusement rides and over 3000 data sets were examined. Complaints respectively incidents were not reported on all these rides.
The first was to find the appropriate filter. As result the 5 Hz filter is the best for the study as this is also the filter used for the admissible accelerations (see chapter 5.1).

The first statistical summary was the lateral acceleration in y-direction in table 7.1. The most important results are on the height with many data sets as 32, 40 and 44 inches. Please consider that children of a height of 32 inches or smaller normally are not capable to react on accelerations.

Tables 7.1: Data Sets for Kiddie Rides and the Lateral acceleration y-direction [in g]

Height Restriction	Data Sets
32	1536
35	189
36	27
38	28
39	35
40	804
42	89
44	255
46	85
Total	3077

Height		Age	Absolut Lateral [g]		Fractile		
[in]	[cm]	[years]	Mean μ	Std Dev σ	5%	95%	max.
32	81	3/4 to 1	0,31	0,18	0,26	0,62	1,43
35	89	1 to 1,5	0,75	0,34	0,56	1,3	1,88
36	91	1 to 2	0,66	0,38	0,43	1,28	1,39
38	97	2 to 3	0,68	0,29	0,54	1,17	1,85
39	99	2 to 3	1,11	0,17	1,06	1,39	1,6
40	102	3 to 4	0,59	0,38	0,35	1,21	1,89
42	107	4 to 5	1,1	0,51	0,66	1,94	2,24
44	112	5 to 6	1,52	0,22	1,44	1,89	2,25
46	117	5 to 6	1,09	0,21	1,02	1,43	1,77

The results are summarized in figure 7.26 where the ASTM F2291 “Base case” with 3.0 g for sustained events under 2.0 s was taken for comparison.

With this investigation the dashed brown straight is the recommendation for lateral acceleration of kiddie rides.

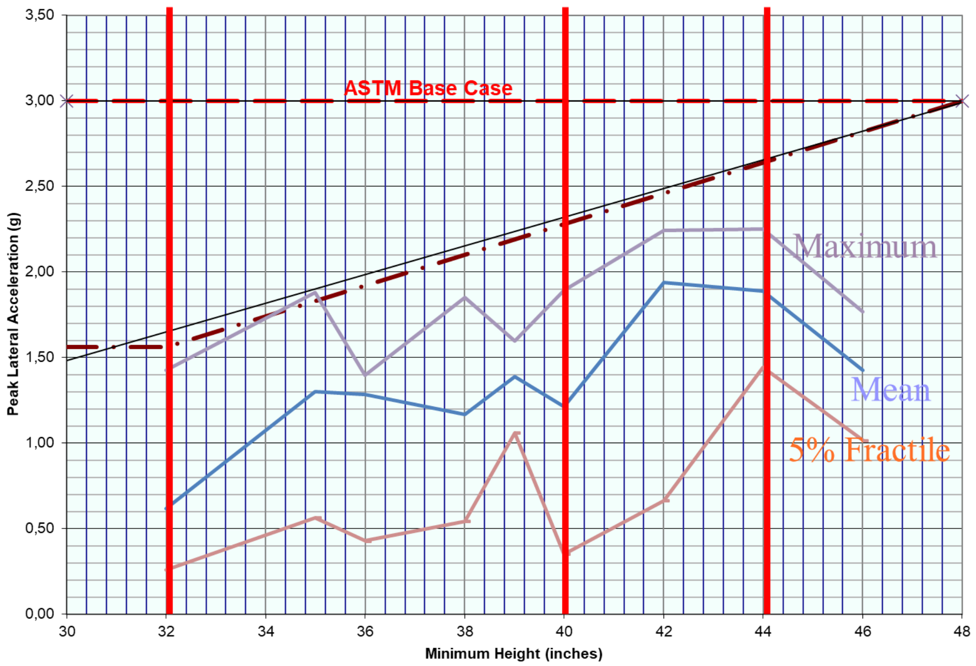


Figure 7.26 Result of the Investigation on Kiddie Rides for Lateral Accelerations in y

Accelerations in x-direction are as critical as in y-direction, especially if there is no headrest (see the investigations explained in chapter 7.2.3.1). Looking through the values for eyes front and rear the values are all smaller than in y -direction.
The decision was to recommend the same reduction.

Table 7.2: Kiddie Rides and the Longitudinal acceleration in x direction [g]

Height		Age	Eyes Front [g]		Eyes Back [g]	
[in]	[cm]	[years]	Mean μ	Std Dev σ	Mean μ	Std Dev σ
32	81	3/4 to 1	-0,26	0,17	0,29	0,20
35	89	1 to 1,5	-0,62	0,22	0,63	0,19
36	91	1 to 2	-0,51	0,24	0,70	0,48
38	97	2 to 3	-0,46	0,14	0,44	0,18
39	99	2 to 3	-0,95	0,11	0,87	0,11
40	102	3 to 4	-0,57	0,28	0,58	0,28
42	107	4 to 5	-0,71	0,32	0,84	0,27
44	112	5 to 6	-0,83	0,18	0,86	0,19
46	117	5 to 6	-0,91	0,12	0,86	0,16

In the vertical direction please see Table 7.3. In figure 7.27 please find the values for different heights. Here the scale is dark blue vertical lines show the mean value μ. The Maximum/Minimum is always μ +/- 3*σ. Assuming a normal distribution this is the 99,9% resp. 0,1% Fractile. (This graph is only shown for vertical accelerations, the other direction shows similar graphs.) The G-Force TG proposed also for this direction the same reduction, but these multipliers are to be applied to the difference between gravity and the Acceleration-Duration Limits.

Table 7.3: Kiddie Rides and the Vertical acceleration in x direction

Height		Age	Eyes Up [g]		Eyes down [g]	
[in]	[cm]	[years]	Mean μ	Std Dev σ	Mean μ	Std Dev σ
32	81	3/4 to 1	0,51	0,18	1,91	0,21
35	89	1 to 1,5	0,34	0,15	1,91	0,29
36	91	1 to 2	0,36	0,30	1,59	0,50
38	97	2 to 3	-0,10	0,12	2,21	0,11
39	99	2 to 3	0,19	0,16	2,99	0,15
40	102	3 to 4	0,15	0,39	2,17	0,47
42	107	4 to 5	0,27	0,54	3,69	0,61
44	112	5 to 6	0,03	0,47	1,90	0,97
46	117	5 to 6	0,00	0,13	0,00	0,46

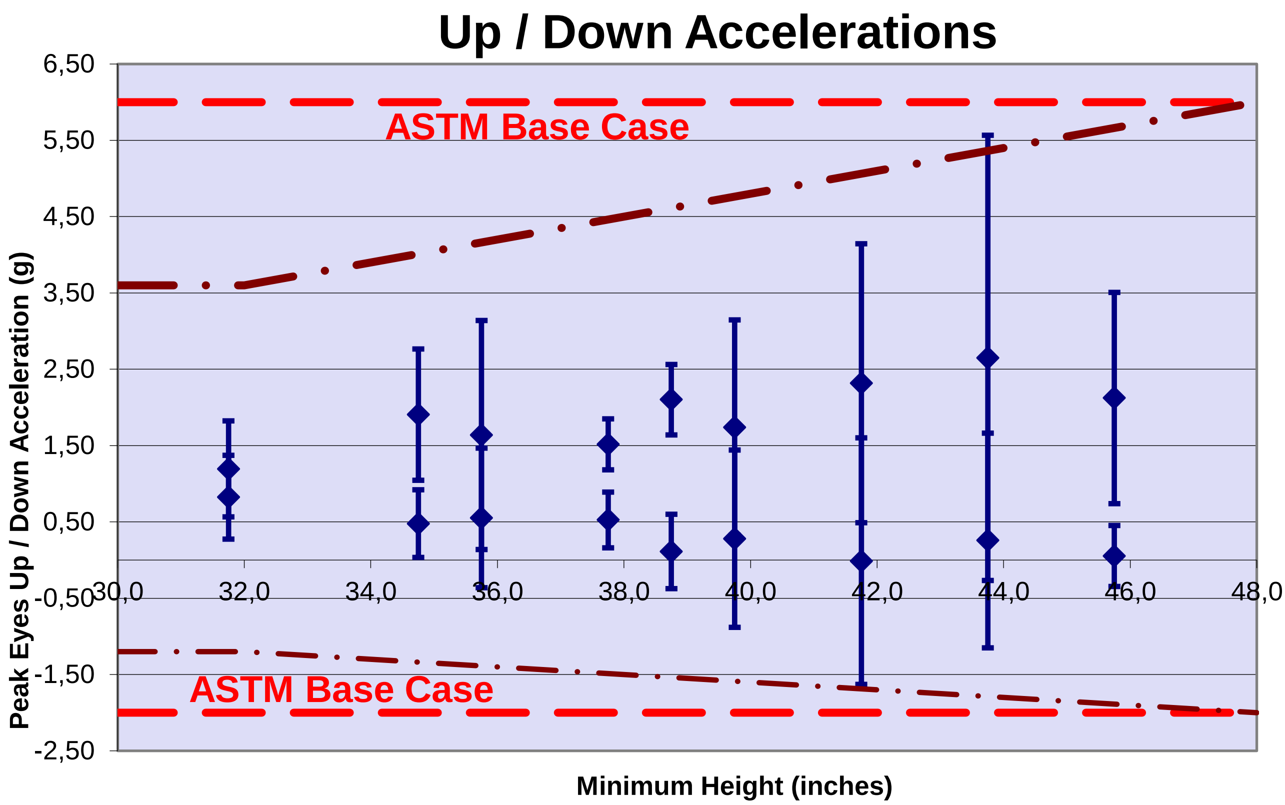


Figure 7.27 Vertical accelerations with the 5 Hz filtered results

Starting 2017 appendix X8 of F2291 recommends a reduction for kiddie Rides. As the values are not based on tests or biomechanical research, the Appendix X8 is informative.

In 2023 the proposals were also presented to the EN committee. As there is not an officially published document available, the EN-committee decided to postpone the decision and wait for the next revision of EN. This will be approx. in 2025 and the method can then be considered as service proven.
The multiplier is in figure 7.28 including the proposal for the new European Revision of EN 13814.
Today the inspectors in Europe have partially different reductions. Prior to the start of the design it is recommended to contact the inspection authorities.

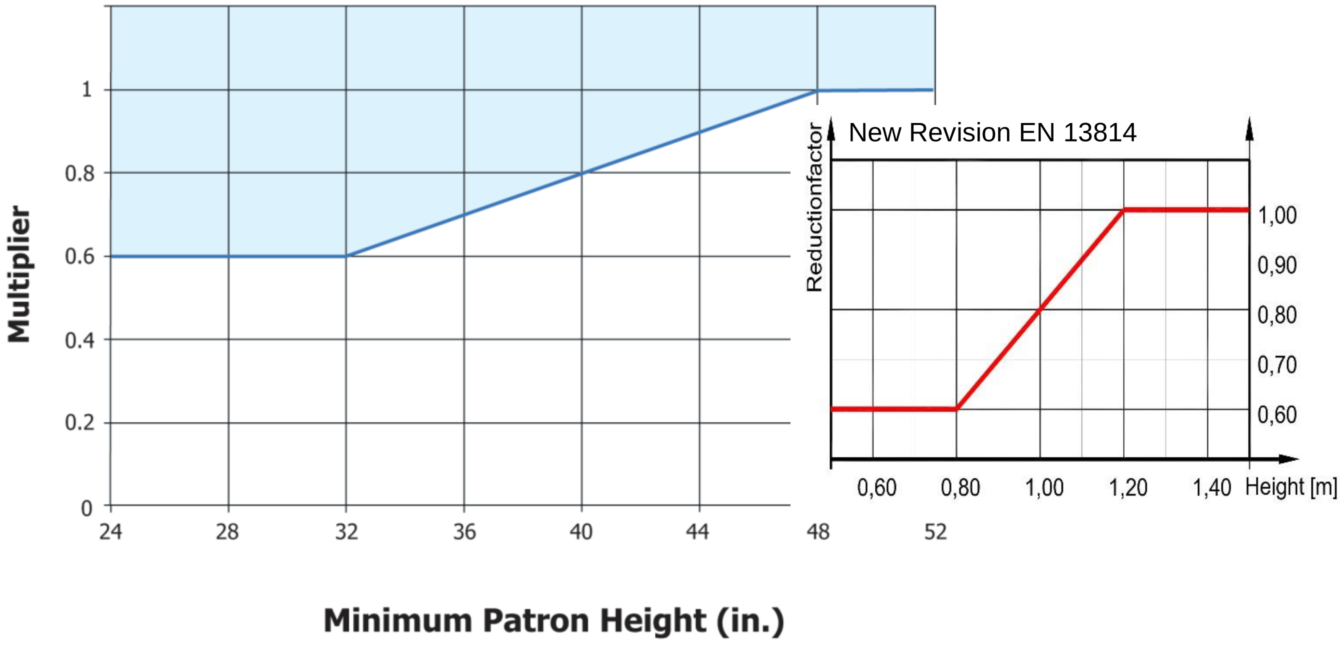


FIG. X8.1 Multiplier for Patrons

Figure 7.28 Multiplier for Patrons in F2291 and Proposal for the new revision in EN

Note from Banks [23]:

> “Having reviewed several videos of children riding the ride and witnessing G-LOC (see Chapter 7.4.3.1) while adults sitting next to them did not experience G-LOC changed his mind as to the G tolerance of children vs adults.
> The inherent danger of experiencing a G-LOC event while the coaster remains in motion is that patron in an unconscious or semi-conscious recovery state has no or minimal muscle tone present. “

This G-Loc effect does not reduce the requirements for riders under 48 inches in appendix X8.

7.6 Vibrations and Rotational Limits

7.6.1 Vibrations

Not only the accelerations in x, y and z trigger the limits of tolerated forces. Rather, vibrations can also place considerable stress on the internal organs. Especially the longer oscillations are to be considered here, which can lead to organ damage in case of resonance. In music, this effect can be partially intentional and can lead to new experiences.

One negative example is the vibration in motorcyclists, where the tendency of the internal organs to vibrate is supposed to be reduced by wearing a tight kidney belt.
It is extremely difficult to quantify, since natural frequencies and damping vary greatly. Some indications of natural frequencies are given in ISO 2631 or [8]. Table 7.3 shows some resonance/natural frequencies.

Table 7.3: Resonance frequencies of the human body

Resonance frequencies of human body [62]

№	Human body and position	Resonance frequency, Hz
1	Upright, stressed (z axis)	6 and 11…12
2	Upright, weak (z axis)	4…5
3	Upright (x axis)	2
4	Sitting (z axis)	5…6
5	Head/shoulders; upright	5…12
6	Head/shoulders; sitting	4…5
7	Tympanum	1000
8	Hand	1…3
9	Thorax	3,5
10	Spinal column (z axis)	8
11	Abdominal cavity organs	3…3,5
12	Thigh, upright (z axis)	4
13	Thigh, sitting (z axis)	2…8
14	Foot, sitting	< 10

Here are some values, where it is unclear which time span may affect the health:
Spine: 3-4.5 Hz; Stomach: 4-9 Hz; Chest 6-12 Hz
Vibrations from 2 to about 40 Hz also may reduce vision, increasing the risk of misbehavior and accidents. There are three important factors, excitation in resonance frequencies, dampening of the organs and length of the frequency shake up the organ.

Injuries of patron due to the excitation of parts of the body in amusement rides are not known. There were some incidents in discotheques with loud music where low frequencies may have exited some organs.

7.6.2 Rotations

In the standards of amusement rides, rotational accelerations are not mentioned and not measured. If it is generally assumed that the design calculation is based on the heart line. The designer can determine the rotational speed and accelerations at any point of the installation. The Rotation were discussed in many papers, for example in [8] or [10].

The figures 7.29-7.31 as below show the definitions and the possible accelerations at the head.

It depends on the seats and what restraints are chosen. With the so called "Upper Torso Restraints", it can be assumed that only the head will have an effect during rotations. With the distance to the heart line "D" the accelerations can be derived as an example for the head.

Especially for the accelerations in the direction of the z axis, the amount of blood that shoots into the head is a fundamental factor. An addition with the vertical accelerations including the possible earth acceleration is to be considered.

Again, in case of doubt, consult a biomechanical expert.

Another problem can be the dizziness. As an example, imagine a roller coaster with a corkscrew. The rotation takes place over the longitudinal axis (x-axis) and rotates around the accelerometer. If the ride figure is designed to simulate an additional free fall then all three directions of acceleration would show zero, but a dizziness is not excluded.

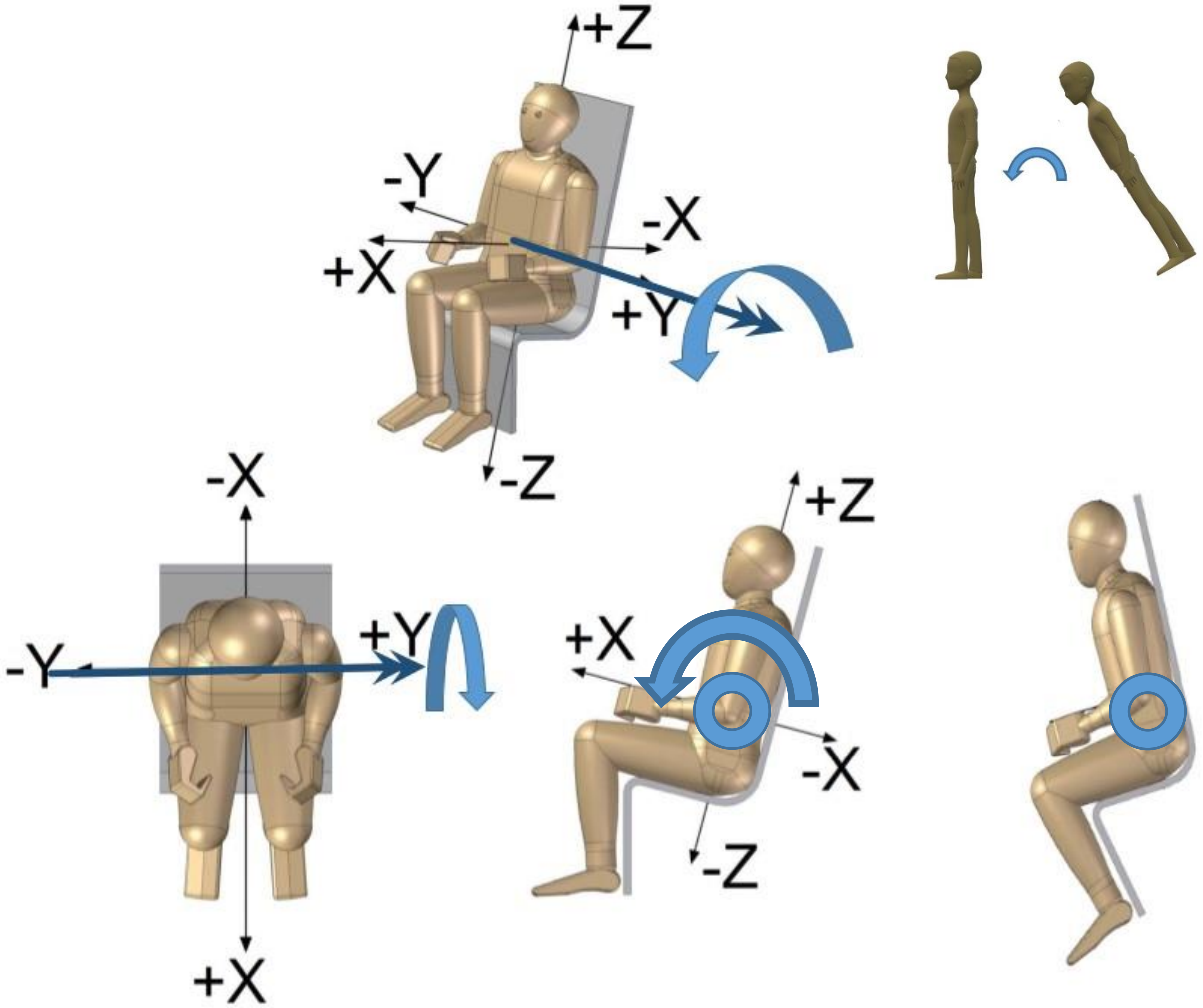


Figure 7.29: Positive Rotation $\dot{\varphi}_y = \frac{d\varphi_y}{dt}$ [Rad/s] around y-axis (Roll)

A positive rotation cause centrifugal accelerations, in the location of the head forces “eyes up”. With Distance R is the Acceleration a = $\dot{\varphi}_x^2$ * R

A positive change of Rotation (rotational acceleration $\ddot{\varphi}_y = \frac{d^2\varphi_y}{dt^2}$ [Rad/s²) causes forces “eyes left” in the location of the head. With Distance R is Acceleration a = $\ddot{\varphi}_y$ * R

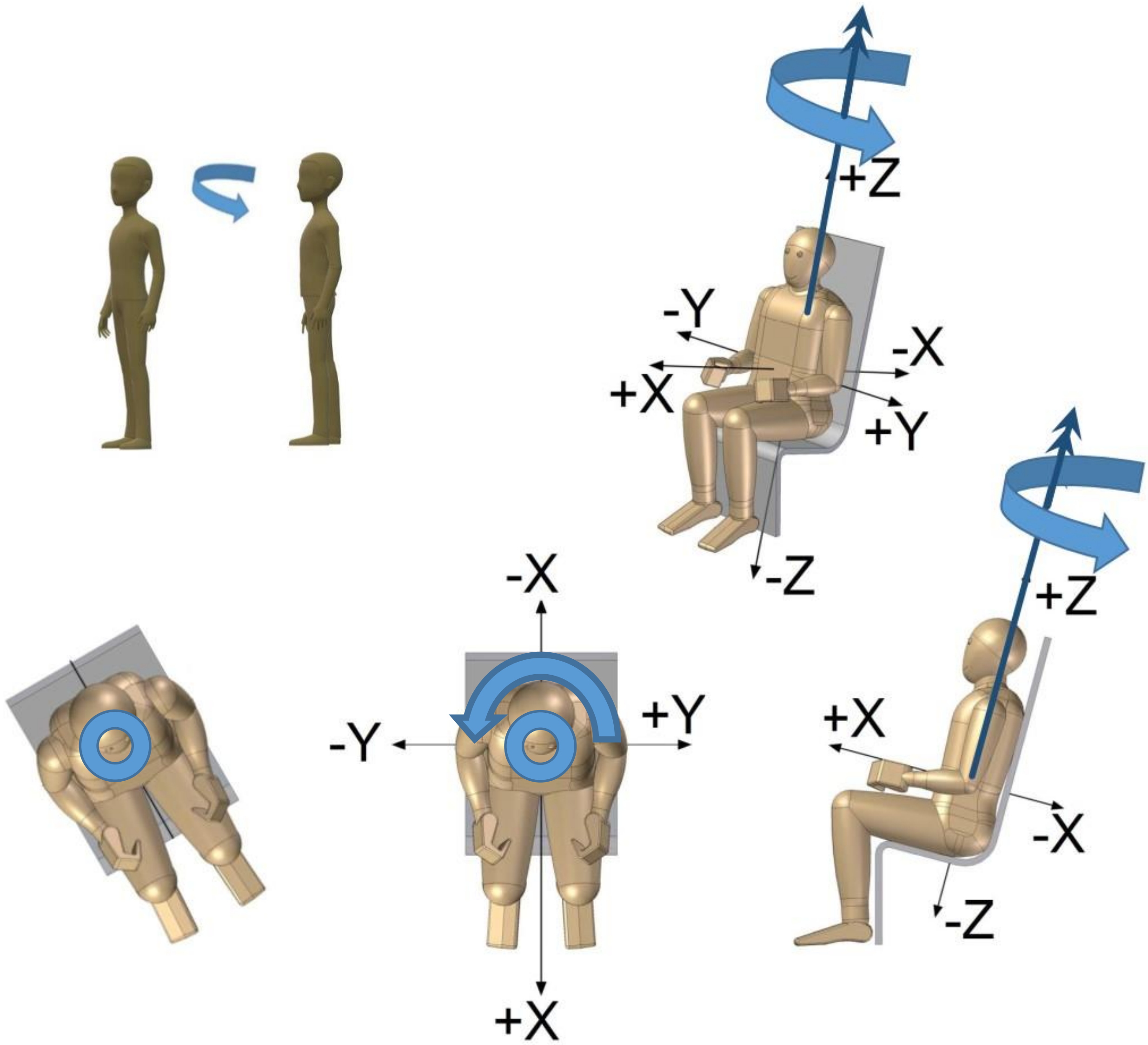


Figure 7.30 Positive Rotation $\dot{\varphi}_z = \frac{d\varphi_z}{dt}$ [Rad/s] around z-axis (Yaw)

Remark: A positive rotation rotational acceleration $\dot{\varphi}_z = \frac{d\varphi_z}{dt}$) causes centrifugal accelerations, in the location of the head negligible forces.

A positive change of Rotation (rotational acceleration $\ddot{\varphi}_z = \frac{d^2\varphi_z}{dt^2}$ [Rad/s²) which are negligible.

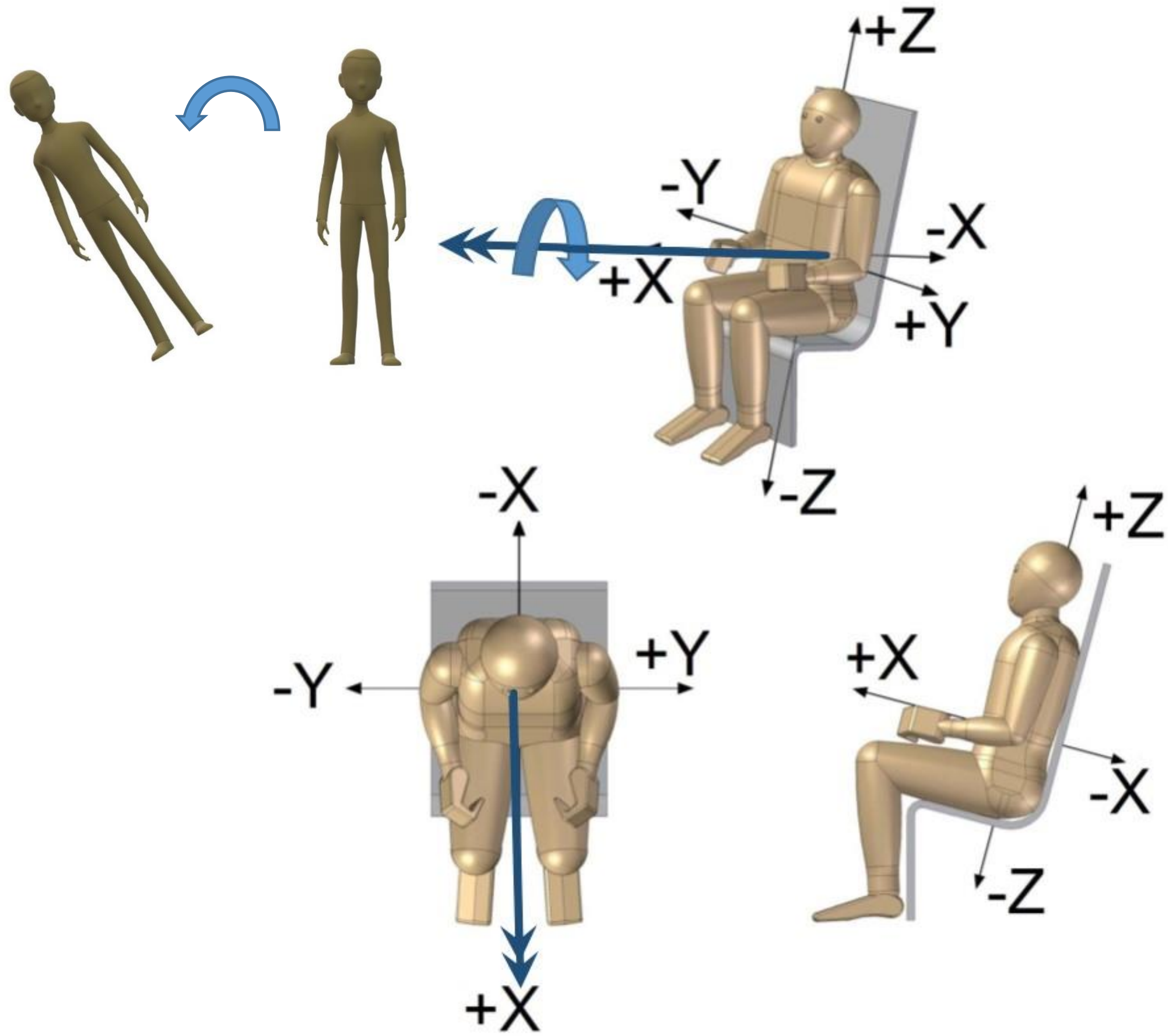


Figure 7.31 Positive Rotation $\dot{\varphi}_x = \frac{d\varphi_x}{dt}$ [Rad/s] around x-axis (Roll)
Remark: A positive rotation cause centrifugal accelerations, in the location of the head forces "eyes up". With Distance R is Acceleration a = $\dot{\varphi}_x^2$ * R
A positive change of Rotation (rotational acceleration $\ddot{\varphi}_x = \frac{d^2\varphi_x}{dt^2}$ [Rad/s²) causes forces "eyes left" in the location of the head. With Distance R is Acceleration a = $\ddot{\varphi}_x$ * R

Summary: The rotations are not necessarily measured. The accelerometer for the SARC – test according to F2137 are relatively far away for the head. Especially this head is the most critical part of the human body and the accelerations as measured can differ from the ones at the head. The designers must include the rotations into their calculations.

The rides are tested, and the proof (inspector and designer) must consider this when comparing the results with the design.

8 Events with a duration under 200 ms

Limits currently contained in Section 7 of ASTM F2291 do not address accelerations with a duration of less than 200 msec as explicitly stated in 7.1.4.2. These events are commonly referred to as “impact events.”

While sustained accelerations (> =200 msec) limits are generally driven by cardiovascular response, impact event limits are driven by neuro-muscular responses. Biodynamic considerations for impact events are typically associated with the interaction of the patron and the patron containment system. A primary metric of this interaction involves the velocity of any potential contact between the patron and the patron containment system, which in turn is a function of the change in velocity undergone by the ride vehicle over short periods of time (i.e. less than 200 msec). Change in velocity is established in the aeronautical, automotive and biodynamic literature as an important metric for impact events.

A method of consideration of the biodynamic effect of impact events is contained within Appendix X.11 including a calculation method for Delta-V (change in velocity undergone by the ride vehicle over durations of 200 msec or less) and Average Acceleration (Delta-V divided by the duration of the event and is thus a single metric which incorporates both Delta-V and duration for impact events).

To establish informed safe limits of Average Acceleration, data was collected, per F2137, and analyzed, per method in Appendix X.11, from rides across the industry for rides with and without known injurious related to Impact Events. In total, 142 rides were reviewed including 91 Wood Coasters, 19 Steel Coasters, 13 Family Rides, and 4 Flat Rides. Upon compilation and review, no clear pattern in which data from injurious rides stood out in Delta-V vs. duration or Average Acceleration vs. duration (see Figure 7.31). However, injuries have been known to occur due to this phenomenon. Because biodynamic considerations for impact events are typically associated with the interaction of the patron and the patron containment system, and the data analysis method does not represent this factor, it is concluded that rides above a certain Average Acceleration threshold that are not injurious must have a patron containment system that properly accounts for and mitigates this potential injurious state. It can therefore be deduced that an explicit requirement to consider the patron containment system in this context above a certain potentially injurious value of Average Acceleration will yield a higher threshold of safety within the industry.

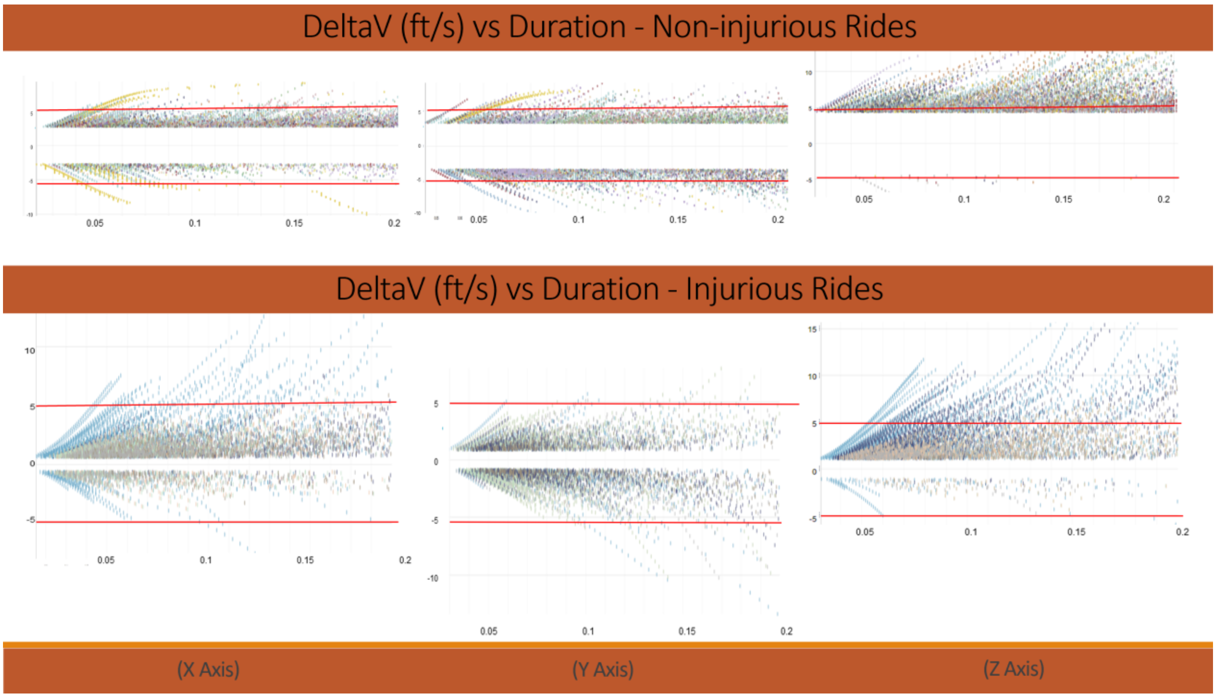


Figure 7.31 Delta-V values plotted for 142 rides (Note: gaps in data points around 0-axis are omitted due to graphing capabilities with millions of data points; all limits shown)

To determine a known safe limit of Average Acceleration/Delta-v, one may consider walking into a wall at an average human walking speed (~5ft/s). Above this speed, the patron containment system, specifically what may be impacted, shall be considered. The designer/engineer shall determine the appropriate design of the patron containment system including whether it is an addition of padding (reducing the potential travel distance of the patron during an impact event) or removal (removing the object that the patron may impact during an impact event) that is most appropriate for the given device.

Note: Average Acceleration/Delta-v Limits is actively under review by the ASTM F2291 Acceleration Task Group

9 Example Looping

The first known looping roller coaster was the "Chemin du Centrifuge" built by Clavières in Paris in 1846. Almost at the same time, several coasters with loops and patents were built in the USA. All coasters had the characteristic of going from a straight line directly into a curve. In physical terms, the transition to the loop was built from a curve with an infinite radius directly into a curve with a finite radius.

Unfortunately, all the installations disappeared quite quickly. This was due to many personal injuries, ranging from spinal compression and whiplash injuries to serious, incurable damage to Patrons.
It was not until shortly after 1950 that another attempt was made with the same personal injuries, so that these rides disappeared just three years later.

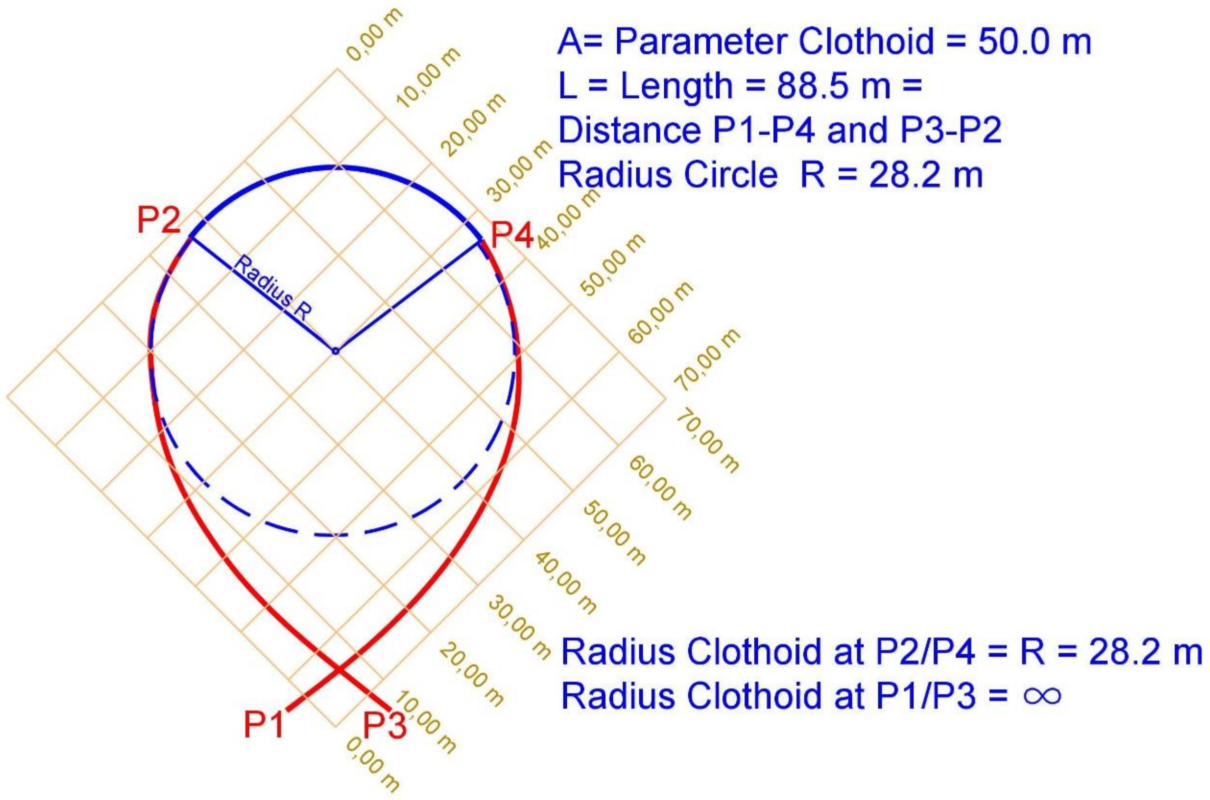


Figure 9.1 Exemplary clothoid

It was not until 1974 that Six Flags planned a new attempt at its park in Valencia, California. The ride builder Schwarzkopf, together with civil engineer Werner Stengel, had found the solution through the curve characteristics in the planning of curves in road construction.

Every car enters a curve and the driver has to turn the steering wheel, so the transition from an infinite Radius to a finite radius is no longer abrupt. The same is done in railroad construction. There, this transition for the radius is chosen including a superelevation (Normally the roller coasters build superelevations and transitions in curves as well). This also eliminates lateral acceleration at a certain speed. (Figure 9.1)

The problem is described with the following considerations, whereby the focus should be on the G-force. Further details, including the history of the looping, are described in detail in [12].

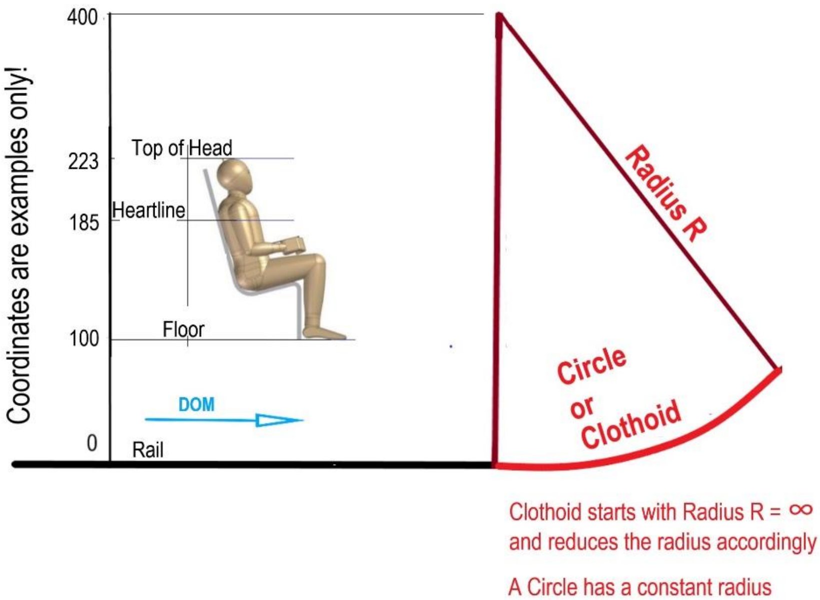


Figure 9.2 Exemplary entry into a loop with circle and clothoid

The entry into a looping is shown in Figure 9.2. The results are shown in Figure 9.3.

The first two diagrams above show the speed over the length. The transition begins at x = 1.0 m. The train enters at the selected speed, whereby the speed at the rail remains the same. The head, however, has a different speed. This is due to the distance to the center of the circle. Theoretically, the speed at the head would even be 0 if it were directly in the center of the circle. In this case, the entire longitudinal speed would have been converted into rotational speed when entering the circle. This difference means that the head is accelerated immediately. This also explains the problems with the first loops. The situation is different with the clothoid, which linearly reduces the speed at the head.
The question now arises as to which limit values are permissible. The manufacturing process must also be taken into account, as 3D rail bending machines have only recently been used. This also meant that it was only possible to bend transition pieces with a constant radius and reduce the radius piece by piece.
The second line shows vertical accelerations. A jump in the acceleration can also be seen here. In the straight line with 1g, it then increases by leaps and bounds, while the course of the clothoid is only uniform to a limited extent. The non-linearity is due to the reduced height in the loop and the associated reduction in speed. However, the course of the vertical acceleration hardly caused any problems.

The longitudinal acceleration in the x-direction at the head in the third line shows an infinity point for the circle and a jump for the clothoid.
In the case of the circle, the jump in velocity at the top is the reason, which is only partially visible in the graph, but leads to the known problems.
In the case of the clothoid, the focus is on the uniform linear increase in lateral acceleration due to the definition of the clothoid. It would also be possible to develop a new form of transition in which not only the first but also the second derivative is zero. However, this does not make sense because of the manufacturing accuracy.

This can also be seen in the 4th line. The jerk therefore also has an infinity point at the transition. It should be borne in mind that the jerk must act over a certain period of time (chapter 7.4). In this case, at 20 m/s and 0.2 s, this would be a traveled distance of 4 m. The jerk over this distance is not shown. This is then calculated using the squared error method via the accelerations.
After discussion with some designers, it can be assumed that a jerk of approx. 5 g/s is usually taken into account. (You could also calculate with a maximum of 5 g/s here, but this should be done carefully).

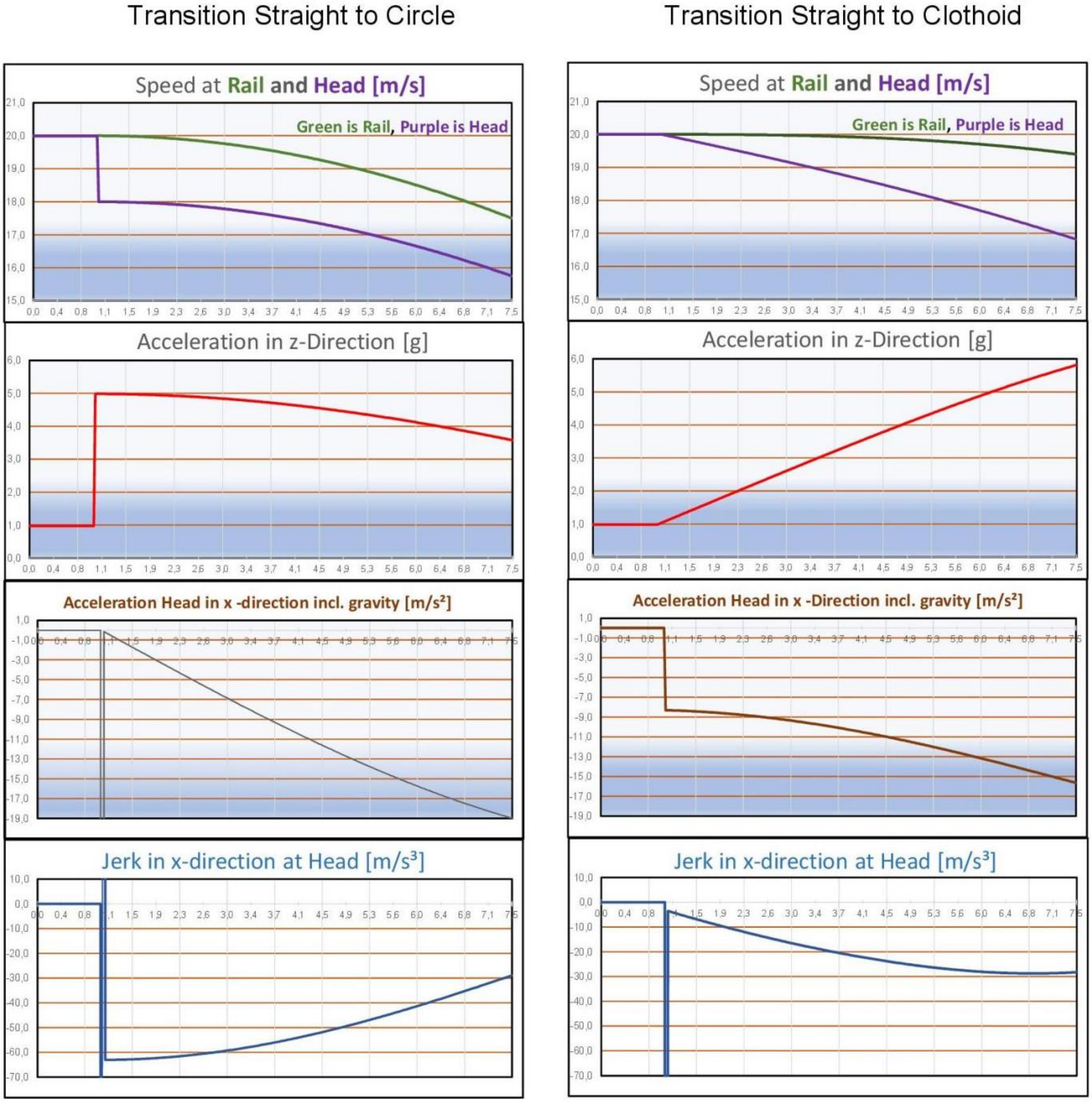


Figure 9.3 Graphical comparison of the entry circle into a loop

All calculations are theoretical and must be confirmed by testing according to ASTM F2137. Here it is not enough to simply plot the results, but also to understand them accordingly.

1) For example, when roller coasters are commissioned, the temperatures are usually low and the train has not yet been properly run in. This usually means that the trains run much faster in summer than when they are commissioned. This means that all accelerations are lower.

2) Especially in loops, the first cars have a much higher speed than the last ones. This results in two effects, namely different accelerations of the front and rear carriages.
In addition, superelevations are designed for a certain design speed. But in addition, high lateral accelerations can occur with the individual wagons, which can exceed the limits in borderline cases.
3. as described above, the position of the head is important. It was a compromise to allow the accelerometers for the ASTM and the EN at different positions.

The following is an excerpt from ASTM F2137:
12.1.5.2 Location-Children: (SARC)
For a ride or device in which patrons ride while seated, the center of seismic mass of the accelerometer (or point center of seismic masses in the case of multiple accelerometers) shall be mounted at a location between 11 and 14 in. **(28 and 36 cm)** above the seat level .... (Adult: 12 and 16 in.)
13.5.2 Location-Children: (SARC - EN)
For a ride or device in which patrons ride while seated, the center of seismic mass of the accelerometer (or point center of seismic masses in the case of multiple accelerometers) shall be mounted at a location between **50 ± 5 cm** (20 ± 1 in.) above the seat level ..... (Adult: 22 and 26 in.)

In Europe, it was thought that measurements should be taken exactly in the heart line, as this is decisive for the design. A measurement here would therefore be directly aligned with the design and comparable. Normally, the difference is not significant. Especially in loops like this one, the head can experience higher accelerations than measured due to the distance to the rail. In addition, there is the rotational speed in the loop. This also leads to accelerations in the extremities such as the head. If in doubt, the designer should check and assess the measurements.
It would be desirable to have only one (harmonized) position for the accelerometers. This is currently being discussed in the relevant committees.

10 Perspectives and Summary

The EN Committee for revising EN 13814 has updated the limits for the acceleration, harmonizing them with the American Standard ASTM F2291. With the experiences of already existing informative and normative rules as well as the experiences of amusement parks and manufacturers, a lot more details have been included.
Not all possible health influences could have been sufficiently researched and included in the new draft of the EN therefore medical testimonies are needed in certain cases.

New findings are frequently added and the still undefined limits may be described. The approach of the ASTM to include their new and approved findings on an annual basis seems promising.

It is difficult to standardize the issues with handicapped patron as well as motion sickness. Other issues come from speed as high speed may hurt the eyes from collisions with flies or sand in desert areas.

Also some people have claustrophobia or acrophobia. Many other influences only can be treated with warning signs, so people do know whether they can access the amusement ride.

A project to characterize an amusement ride like the way the skiing resorts do would be desirable.

11 Acknowledgements

The G-Force Task Group give a special thanks to the American and European Amusement Parks, who have provided plenty of data to work with. On behalf of this are Walt Disney Parks and Resorts, Euro Disney Associés S.C.A., Six Flags as well as Universal Parks and Resorts may be named. Furthermore, the author thanks all the experts of the ASTM and Euronorm committee for the creative cooperation to create this standard.

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13 Participants

The G-Force Task meets annually at the two ASTM conferences in February and October. In addition, the Task Group meets in one amusement park every year for a 3 day summer meeting. We thank all parks for hosting, in the last 10 years at Six Flags, Universal Studios, Disney, WDI, Rockefeller Center, Lagoon Park and Dollywood.

Participants Summer Meeting 2011 at Disney World, Orlando:
From left to right: Bruce Butler, Brian King, Chuck Monson, Larry Chickola, Tim Stone, Justin Schwartz, Tom Szabo †, Har Kupers, Emmet Peter †, Bill Bussone, Mike Kiddoo, Matthias Rohde

TG during the Summer Meeting June 2022 at Epcot.
From left to right: Larry Chickola, Amanda Zielkowski, Mike Kiddoo, Francis Tam, Justin Schwartz, Peggy Shibata, Bill Bussone, Tyler Jaegers, Matthias Rohde, Liz Dias, Lars Reinhard, Chuck Monson, Chris Noveral

TG during the Summer Meeting in June 2023 at Dollywood.

From left to right: Eric Etherton, Jason Parrish, Kevin Russel, Gina Claassen, Justin Schwartz, Robert (Bob) Cargill, Mike Kiddoo, Bill Bussone, Larry Chickola, Matthias Rohde, Chuck Monson, Amanda Zielkowski

Active Members of the G-Force Task Group:

Name	Company	Notes
Amanda Zielkowski	Universal	Co-Chair
Matthias Rohde	VdV Germany	Co-Chair
Brian King	Recreation Engineering	Ex-Chair
Justin Schwartz	Universal	Ex-Chair
Chuck Monson	GMH Engineering	
Larry Chickola	Engineering	
Lars Reinhart	BRC	
Mike Kiddoo	Universal	
Peggy Shibata	ESI Engineering	
Robert Cargill	Cargill Bio Engineering	
William Bussone	CBE Consultants	
Aaron Foster	Disney	
Gabi Queiroz-Miranda	Universal	
Jason Parrish	RMC	

Thank you to all members of the Task Group. The experts helped to improve the Acceleration limits and nit to forget all work during their free time.

Fun?? Not for everybody

Special thanks to Amanda Zielkowski and Peggy Shibata for reviewing the draft and helping to convert it in a readable summary.

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The Autor does not forget that the CEN and ISO committee who also added many details to the exiting limits. It is always a pleasure to work with all of them and feeling “work hard, play hard”.

Walt Disney Imagineering (WDI) 2013 in Burbank / California

2019 New York Rockefeller Center

Bike Tour 2014 after the summer meeting in Wintergarden, Fl

February 2024

Matthias Rohde

Some Details about the Development of Acceleration Limits for Amusement Rides

Foto:
Thanks to EuroProfessional,
Phantasialand, “Klugheim-Taron”

Right:
Thanks to EuroProfessional
“Flucht von Novgorod”
Hansapark, Germany