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Design of Roller Coasters

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Abstract of master's thesis

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Abstract
This thesis combines several years of work experience in amusement industry and a literature review to present general guidelines and principles of what is included in the design and engineering of roller coasters and other guest functions attached to them.

Roller coasters are iconic structures that provide safe thrills for riders. Safety is achieved using multiple safety mechanisms: for example, bogies have multiple wheels that hold trains on track, a block system prevents trains from colliding and riders are held in place with safety restraints. Regular maintenance checks are also performed to prevent accidents caused by failed parts.

Roller coasters are designed using a heartline spline and calculating accelerations in all possible scenarios to prevent rollbacks and too high values of accelerations, which could cause damage to riders' bodies. A reach envelope is applied to the spline to prevent riders from hitting nearby objects. The speed and curvature of the track combined create accelerations that need to be countered with adequate track and support structures. A track cross-section usually consists of rails, cross-ties and a spine, while support structures can vary depending on height and loads. Most coasters use circular hollow sections as supports, which are spliced using flanged connections at straight sections. Concrete footers or steel lattices are usually used as foundations for supports.

To maximize the hourly ride capacity, the station area can be enhanced with individual queue gates, effective placement of employee as well as entry and exit points for riders. Queue experience can be improved with design choices, thematic elements and various queue methods that don't necessarily involve guests standing in line. The ride experience can also be improved with thematic elements and virtual reality.

Keywords Roller coaster, amusement ride, amusement park, queue, theming, ride experience

Tiivistelmä
Tässä diplomityössä yhdistyvät usean vuoden työkokemus huvipuistoalalta sekä kirjallisuustutkimus, joiden avulla muodostetaan yleisiä ohjeita ja perusteita vuoristoratojen ja niihin liitettyjen oheistoimintojen suunnitteluun.

Vuoristoradat ovat tunnettuja rakenteita, jotka antavat matkustajilleen turvallisen mahdollisuuden huvitteluun. Turvallisuus muodostuu useiden varajärjestelmien yhteiskäytöstä: esimerkiksi telit on varustettu useilla pyörillä, jotka pitävät vaunun kiinni radassa, lohkojärjestelmä estää junien törmäämisen ja turvapuomit pitävät matkustajat junan kyydissä. Säännölliset tarkastukset ja huoltotoimenpiteet estävät viallisten osien aiheuttamat onnettomuudet.

Vuoristoradat suunnitellaan käyttämällä keskilinjaviivaa ja laskemalla kiihtyvyydet kaikissa tilanteissa estäen täten junan taaksepäin valumiset ja liian suurten kiihtyvyyksien aiheuttamat henkilövahingot. Rataprofiilin ympärille asetetaan suunnitteluvaiheessa ulottumavaippa, jonka avulla tarkistetaan, etteivät lähellä olevat rakenteet osu matkustajiin. Radan käännökset yhdessä vaunun nopeuden kanssa aiheuttavat dynaamisia kuormia, jotka tuetaan riittävällä rata- ja tukirakenneratkaisuilla. Radan poikkileikkaus koostuu useimmiten raiteista, poikkisiteistä ja rangasta, kun taas tukirakenteet vaihtelevat riippuen kuormista ja radan korkeudesta. Useimmat vuoristoradat käyttävät tukipilareina pyöreitä putkia, jotka liitetään toisiinsa laippaliitoksilla. Betonianturoita tai teräsristikoita käytetään tavallisesti tukirakenteiden perustuksina.

Vuoristoradan tuntikapasiteetin maksimoimiseksi asema-aluetta voidaan tehostaa penkkirivikohtaisilla jonotusporteilla, työntekijöiden tehokkaalla sijoittelulla sekä sisään- ja ulostulojen sommittelulla. Jonotuselämystä voidaan parantaa oikeanlaisilla suunnittelupäätöksillä, lisäämällä temaattisia elementtejä ja erilaisilla vaihtoehtoisilla jonotusmenetelmillä, jotka mahdollistavat muunlaisen jonotuksen kuin paikallaan seisomisen. Vuoristoradan ajoelämystä voidaan myös tehostaa esimerkiksi temaattisilla elementeillä ja virtuaalitodellisuudella.

Avainsanat Vuoristorata, huvilaite, huvipuisto, jonotus, teemoitus, ajoelämys

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Terms and Abbreviations

Derailment	A train leaving its tracks
OTSR	Over-the-shoulder-restraint
MCBR	Mid-course brake run
Catwalk	A narrow walking ledge alongside coaster track with handrails
DOT	Direction of travel
Ride operator / Ride attendant	Trained staff that operate a ride and provide customer service
Element	A specific segment of coaster track curves that combine into a recognizable shape that has a signature name (e.g. loop, corkscrew, Immelmann)
Banking / Roll	Rotation about x-axis relative to DOT (Figure 2)
Pitch	Inclination about y-axis relative to DOT (Figure 2)
Yaw	Rotation about z-axis relative to DOT (Figure 2)
Valley	A convex element on a coaster track
Hill	A concave element on a coaster track
Inversion	A coaster element where the riders are rotated upside-down in relation to Earths' surface i.e. banked more than 135 degrees. This value can be debatable, but 135 is closer to being upside-down than to vertical [1], and is thus used in this thesis
Gravity run	A portion of a coaster track that has no external machinery to affect the train and its speed
Dark ride	A ride type featured in multiple amusement parks: a slowly moving car on a fixed path that goes through various themed scenes in an otherwise dark or dim building
Stacking	A situation where more than one coaster trains are stopped on consecutive blocks, excluding the station. Usually happens due to slow dispatch time or technical problems
Valleying	A coaster train is unable to complete a gravity run portion and starts rocking back and forth in a valley until it stops. The train then needs to be evacuated and manually towed through the remaining course

G-load ("g-force", g) refers to acceleration normalized by Earth's gravitational pull (9,81 m/s^2): a resting object has 1g towards Earth's surface. In this thesis, vertical g refers to acceleration in z-direction, lateral g to acceleration in y-direction and longitudinal g to acceleration in x-direction. These directions are contextual to the rider orientation, as shown in Figure 1. Gs are often misinterpreted as centrifugal forces due to their subjective nature and are thus incorrectly called g-"forces" – even though they are a type of acceleration.

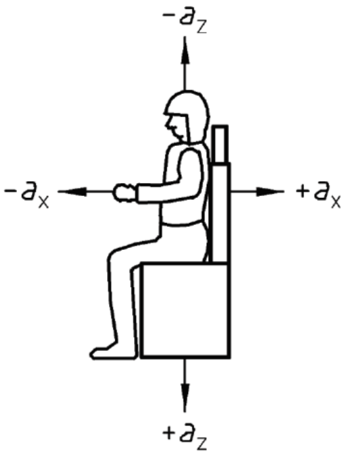


Figure 1: Acceleration directions (lateral acceleration ±a_y into and out of plane) [Fig. 1]

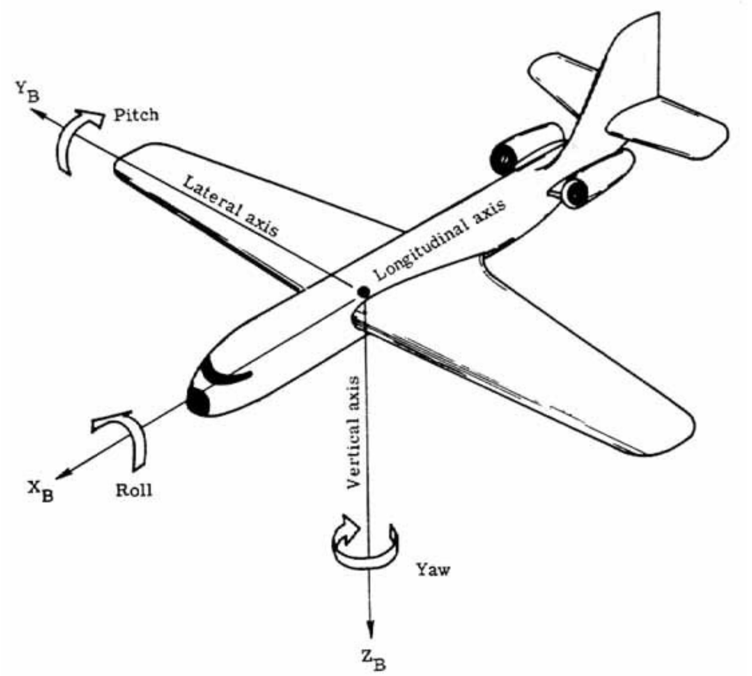


Figure 2: Yaw, pitch and roll demonstrated on axes of an airplane [Fig. 2]

1 Introduction

Ever since early days, man has dreamt of flight and sought adrenaline rush. Amusement industry has evolved and thrived to cater both needs, and to sustain this positive development amusement parks need to constantly expand and make investments to draw more crowds and create continuous revenue. Roller coasters are iconic structures in amusement parks that create exciting sensations of motion in a safe way for all riders, which makes guests re-visit parks and rides again and again. This thesis explores how these structures are designed and engineered, and how the guest experiences are created and enhanced.

The aim of this thesis is to provide a general overview on the design and engineering of roller coaster layouts, structures and attached functions. This thesis is a collaboration with Linnanmäki [3] and was initiated when a large-scale roller coaster project entered planning phase, and various design methods and criteria needed to be studied. Very little academic research has been made about this subject, so this thesis is an explorative research to find and discuss features especially linked to layout design. Several years of working in the industry both in an amusement park [3] and a coaster manufacturer [4] provided a lot of hands-on experience, and in addition a literature review was performed to provide further theoretical knowledge and academic references. These are combined in this thesis to present and analyze multiple real-life examples of existing coasters and their design. Throughout the thesis roller coasters are referenced with both the name of the ride and the park written in superscript.

Roller coaster structures combine civil and mechanical engineering, with static structures (track, supports and adjacent buildings) being a part of civil engineering and moving components (trains and mechanisms) being a part of mechanical engineering. Both fields utilize similar principles but have their own focus points. This thesis emphasizes civil more than mechanical engineering but retains a broad view to include other aspects as well. As complex pieces of engineering, the use of computers in calculation and modeling is present and vital in roller coaster designing, similarly to all engineering.

This thesis focuses on modern steel sit-down roller coasters with closed cycle gravity run layouts, mainly built in Europe and Northern America. Various principles, legislations and perspectives that should be considered while designing roller coaster layouts, track cross-sections and support structures are presented. Basic principles of coaster trains are explained, but not detailed. This thesis is not a research about shuttle or powered coasters, brakes or other mechanisms included in a coaster layout, nor foundations. Neither any details about structural design are examined, as they share the same basic principles with all structures and thus are trivial, but they also vary per manufacturer and designer and thus can be trade secrets. Because designing layouts can be approached as an artistic medium, choosing elements for a layout is not discussed here, although some recommendations for adding intensity are briefly presented.

Chapter 2 explores the multiple safety features found in most coasters, concerning both design and engineering as well as operations. The following Chapter 3 explains common methods and tools used in designing a roller coaster layout. In the next Chapter 4, the special engineering aspects of static roller coaster structures are discussed with emphasis on track and support structures. In Chapter 5, some additional features, buildings and design possibilities are presented that are often connected to a roller coaster in an amusement park (e.g.

queue and station) to improve both operations and guest experience. Chapter 6 presents a discussion about the development possibilities of each concept presented in previous chapters, as well as their effects on coaster layout design. Lastly in Chapter 7, brief conclusions are made.

2 Safety Features

The most important aspect and source of engineering on roller coasters is their safety. The amusement industry is extremely susceptible to the bad press coverage caused by even the smallest occurrences (emphasized by current use of social media), which is also why the number of these cases needs to be minimized. In order to remain allowed to operate, coasters have multiple safety features – both passive and active – to prevent accidents happening to riders, spectators and operators. Passive features are mostly choices made or regulations followed during design phases, while active features are performed continuously while the ride is in operation. This chapter explores common safety features found on all coasters: wheel bogies, safety restraints, reach envelope, block system and brakes, evacuating a coaster and daily operations.

2.1 Wheel bogies

Roller coasters have trains rolling on a track using wheels. Wheels are coupled in bogies that are attached to axles. One or two floating axles are suitably constrained to a car that holds riders. In order to have the train stay on the track during the whole course, bogies at the end of each axle have multiple wheels to prevent derailing: load wheels, side wheels and upstop wheels [5], as shown in Figure 3. These main wheel types can have many different names, but their functions remain the same. Load wheels run on top of the rail and, compared to side and upstop wheels, are subjected to biggest loads. This is due to the maximum allowed g-figures [6]: allowed lateral and uplifting gs are smaller than allowed vertical gs downwards. Usually load wheels are also bigger in size to prevent unwanted vibrations and excess wear as well as to help sustain momentum and speed. If load wheels are not designed to absorb lateral forces, side wheels are required to prevent derailing during lateral movement i.e. curves [2 §5.4.3.3]. Each axle has a bogie at each end resulting in side wheels on both sides of the track to counter accelerations in both directions (left and right). Side wheels run either inside or outside the two rails, though outside wheels are preferred due to their easier maintenance access and simpler track profile manufacturing (see Chapter 4.2 for details). Upstop wheels run under the rail and prevent derailing when the train is suspect to accelerations that would cause it to jump or fall off the track. Even if there are no accelerations that could cause lift-off, a safety device capable of withholding 50% of the fully loaded vehicle weight is required [2 §5.4.3.3]. The upstop wheel may also be replaced with a small steel plate.

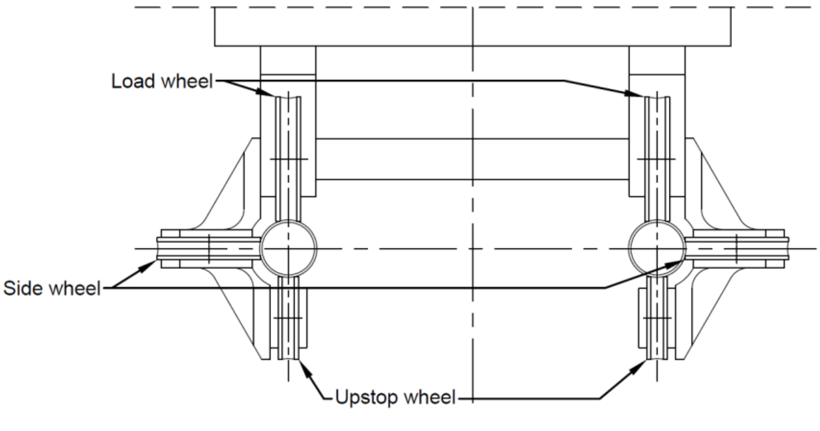


Figure 3: Wheel and bogie system with side wheels outside rails

Using wheel bogies is a passive safety method used in design stage. While losing one wheel during the ride is already improbable, losing two wheels simultaneously is practically near impossible, and a coaster should be able to make it safely back to station even after losing one wheel. Most manufacturers have set on the same type of bogie style with the previously mentioned three-wheel type assembly regardless of the size and layout of the ride – from smallest kiddie coasters (Dvergbanen - Tusenfryd) to record breakers (Kingda Ka – Six Flags Great Adventure).

A coaster train consists of single or multiple connected cars. Single cars have wheel axles both in the front and back of the car. Multiple single cars can form a train with coupling rods and uniball joints holding them together (in this thesis referred as classic train, see Figure 4). Instead of connected single cars, most modern steel coasters have trailered cars to reduce weight, length and friction while also "accommodating more passengers on a given length of track" [7] as the cars can be made shorter. A trailered car has only one axle in either the front or back of each car and to remain in balance it relies on the car either in front or behind it. The first or last car of the train then has two axles connected with restricted movement and ability to absorb the load thus providing stability to the whole train [7]. Instead of including this connection in the first or last car, a zero-car can also be used as a stabilizing connection as shown in Figure 4. Unlike other cars, a zero-car doesn't have seats for riders but only provides the stabilizing connection to the adjacent axle. Zero-cars often have some decorations, and/or the ride logo painted on as presented in Figure 42.

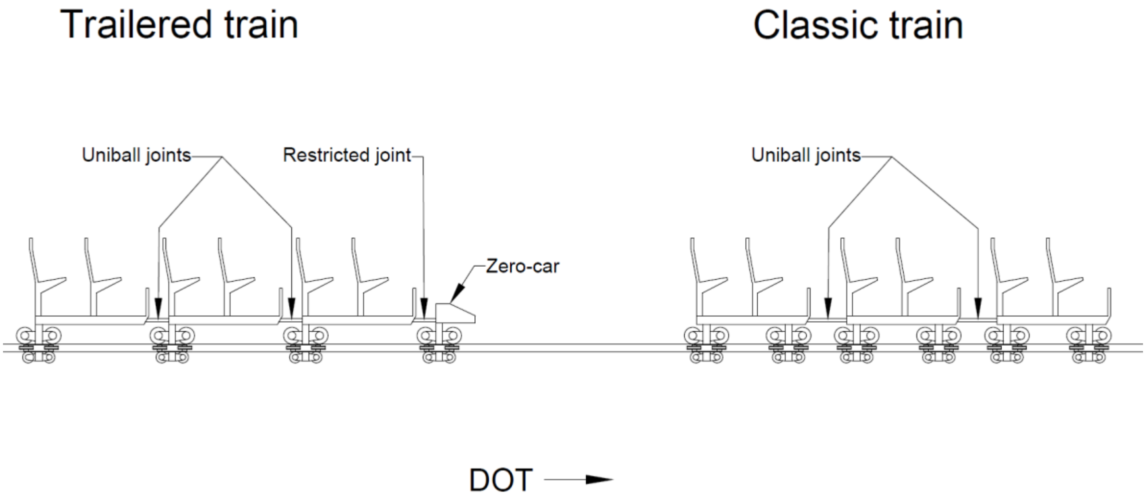


Figure 4: Trailered and classic train axle joint systems

2.2 Rider safety restraints

Rider safety restraints are used to keep people on-board during the ride and propped up in a specific way to prevent injuries caused by gs. The design of a restraint "shall also minimize risks of hitting parts in relative motion or being trapped in between them, being injured by sudden movements, being struck by parts of the structure in which they are carried and being hit by other passengers resulting from the type of motion induced by the ride" [2 §6.1.6.2.2]. The most common restraint design is an individual lapbar, which is a horizontal, often padded metal bar that is designed to keep the rider's lap connected to the seat, thus preventing moving around in the seat, standing up and jumping out of the train. The lapbar is pivoted allowing easier access while boarding and locked before dispatching. If the resultant vertical acceleration of the passenger goes below 0,2gs the riders need to be secured more specifically according to [2 §6.2.3.3]. The minimum requirements for passenger restraints are divided into classes listed in [2 §6.1.6.2.1] and the required class for restraint depends on the accelerations during the ride, which are listed in [2 §6.1.6.2.4.1].

Coasters that feature one or more inversions can have over-the-shoulder-restraints (OTSR) [8] that have more contact to the rider's body than a simple lapbar. They also keep the upper part of the body straight and spine supported by the seat which helps the gs to be absorbed as designed. However, a recent trend in roller coaster industry is to increase rider comfort, mostly via eliminating upper-body restrictions as those can induce head-banging into the restraints and reduce riders' visual field. The new trend is to have a more cup-shaped seat and lapbar, which together have enough capability of securing the rider while still allowing upper body freedom. This trend started when Maurer Söhne [9] first debuted their X-Car design in EAS 2004 [10]. Since then, most major manufacturers have debuted similar designs which not only allow freedom of upper body and feet, but also can ease loading and unloading due to the openness of the trains. The newest Intamin [4] and MACK [11] trains have the lapbar lowering from overhead the rider (shown in Figure 5) leaving the front of each seat unobstructed for loading and unloading. Rocky Mountain Construction (RMC) [12] and Premier Rides [13] trains use shin bars with more classic lapbars to prevent free movement of feet and provide two points of movement restriction (see Figure 6) instead of a pivoting point on lap area which results from only one support point. Using only lapbars adds thrill factor especially in rides that feature inversions due to their sense of freedom. Though the locking mechanism is similar in both, a lapbar offers less feeling of safety to the riders leaving the upper part of the body completely free unlike OTSR.

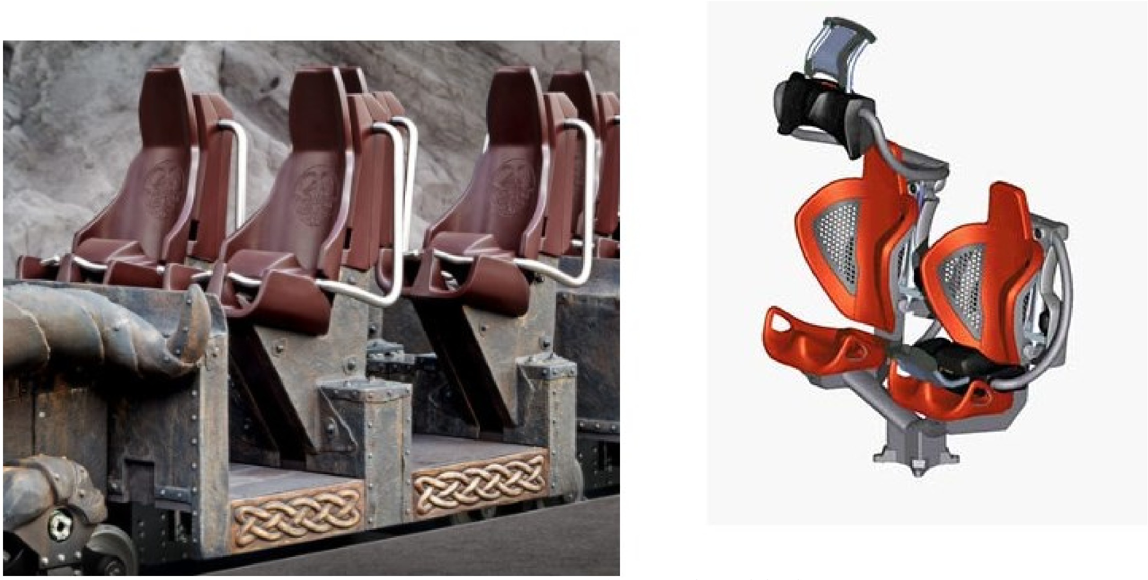


Figure 5: Intamin Elevated seat (left) [Fig. 3] (Taron – Phantasialand) and MACK Rides Hyper Coaster seat (right) [Fig. 4] (blue fire Megacoaster – Europa Park)

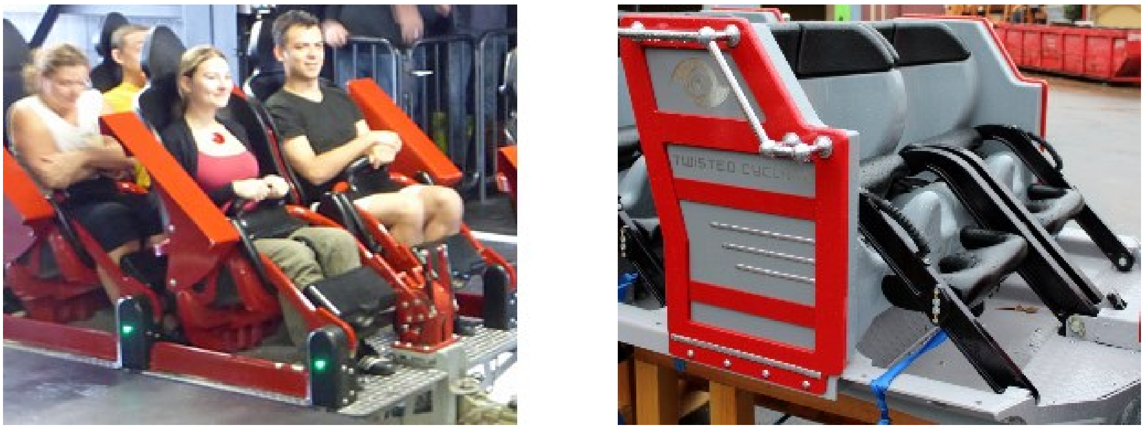


Figure 6: Premier Rides Sky Rocket train (left) [Fig. 5] (Sky Scream – Holiday Park) and RMC train (right) [Fig. 6] (Twisted Cyclone – Six Flags Over Georgia)

Locking the restraints can happen either mechanically, hydraulically, pneumatically or magnetically. Each passenger is always secured with more than just one mechanism to prevent accidents in case of failure. Each system works individually and is able to hold the rider safely on board. Having multiple redundant systems greatly reduces the risk of accidents, since the probability of multiple mechanisms breaking down between regular inspections is miniscule. These extra mechanisms vary between manufacturers and train models, but most often they are extra cylinders, ratchets, seatbelts or straps connected to the restraint. The detailed design of restraint machinery is not explored in this thesis.

In older coasters, opening the restraints is often done with a mechanical switch on the car itself (Vuoristorata – Linnanmäki, Lisebergbanan - Liseberg). A similar mechanical switch can be included in all mechanically locked restraints to allow emergency release, but in most modern coasters opening the restraints is done electrically and thus is possible only with an external power source (excluding dismantling the restraint system) [2 §6.1.6.2.1]. Electricity is fed into the locking mechanism via conductors usually near wheel bogies during normal operations (ride station areas) or via special outlets designed for evacuation purposes. In station areas the conductors also transmit information to the ride's main computer if the restraint is closed below minimum limit to allow dispatching. The restraint systems are passive systems; without external power the restraint remains in place or can only be tightened. Being able to tighten during the ride may increase safety as a loose restraint can tighten during the ride, but it may also cause discomfort if the restraint is pressed down too much by either the rider or the gs.

2.3 Reach envelope

While riding a coaster, riders are seated and held in place with restraints, but their limbs are free to move – often even outside the train. In order to prevent limbs from hitting anything during the ride, a reach envelope (shown in Figure 7) is applied to the track layout during design. This envelope must remain free of all obstacles, including the track and its supports, walls, ceilings and any themed external elements as well as the envelope itself. The dimensions of a reach envelope depend on the seating configuration and rider restraints of the train. [2 §6.1.6.1.2]

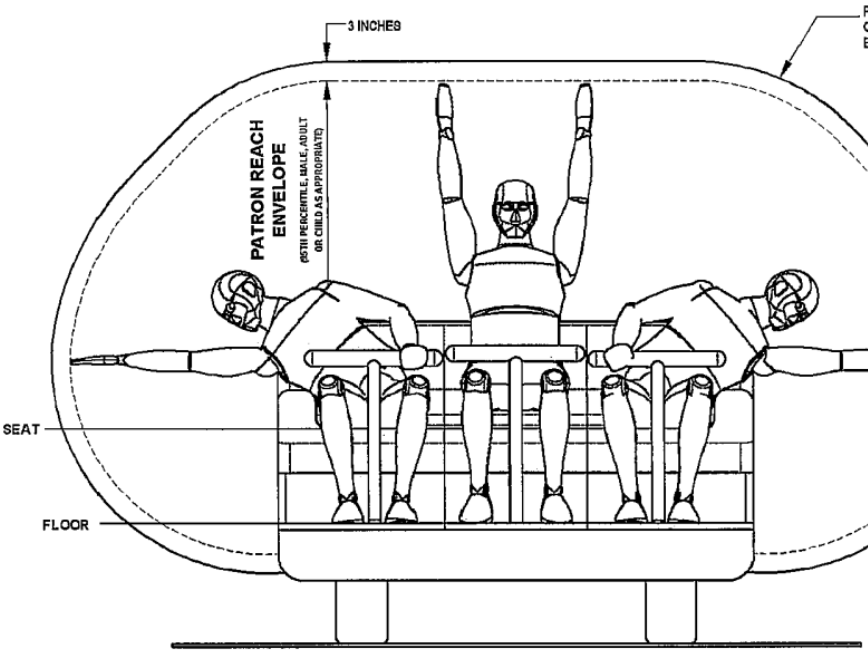


Figure 7: Reach envelope [Fig. 7]

Besides ensuring passengers onboard from hitting anything, customers walking nearby the coaster need to be protected as well. Coasters can have low to the ground sections and access to these hazardous areas must be limited with railings, walls, trenches etc. There have been numerous cases where a guest or wildlife has trespassed to this area with fatal results [14] [15] [16].

2.4 Block system and brakes

Most roller coasters operate more than one train at a time. To prevent trains from colliding, the layout is divided into blocks with each block having a fail-safe method to stop the train even in the most unfavorable conditions [2 §6.2.3.5.2]. Usually the stopping method is a mechanical brake or a transport device. Block system states that if the next block is occupied, the train is stopped and held in position until the next block is clear [17] [2 §6.2.3.5.1]. A block needs to be at least as long as a train and a coaster needs to have at least one block more than it has trains to allow smooth operations. Examples of blocks are stations, lift hills and brakes either in mid-course (MCBR) or at the end of the layout.

The only case when a train collision is feasible is in sections where trains are propelled forwards with transport devices (see Chapter 2.4.1) at low speeds (around 10 km/h or 3 m/s) with only small distances between them. The trains also don’t have extra blocks between them unlike in higher speed parts i.e. gravity run portions of the layout. In these sections, it is possible for the transport devices to slip due to wet conditions or high wear, causing trains to bump into each other at said low speeds. For these circumstances, a buffer and its counterpart plate are added to opposite end of the train (see Figure 8). The buffer is made of soft material which collapses on impact, lessening the impact on riders.

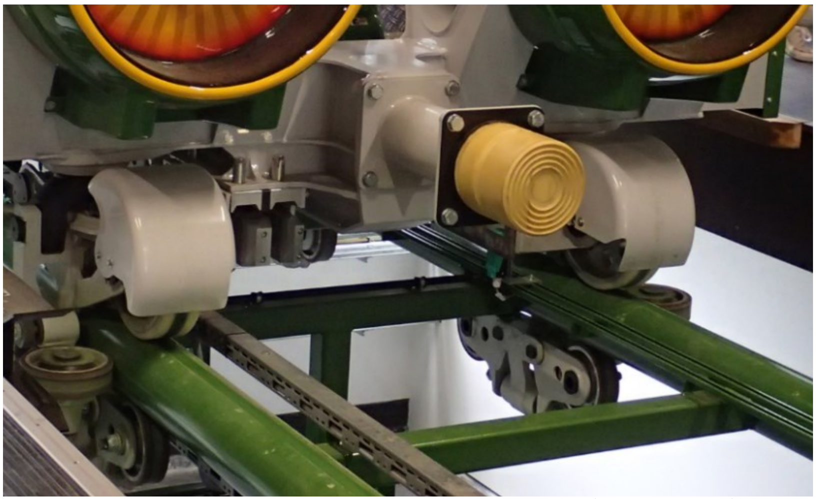


Figure 8: Buffer at the back of a train (Junker – Power Park)

Brake devices utilize either magnetism or friction. Magnetic brakes induce eddy currents to create magnetic fields between the brake units on the track (“stators”, shown in Figure 17) and brake fins on the train which cause the train to lose speed [18]. The magnitude of braking force is dependent of the speed of the train and the overlapping area between stators and brake fins, which can be adjusted by moving the stators to either increase or decrease the overlapping area. Electromagnetic stators with controlled electricity and magnetic field can also be used to launch the train. Friction brakes can be skid-type or clamp/double-jaw -type (shown in Figure 9) [19]; a traction surface mounted on the train – in most cases either horizontal or vertical – touches the brake unit on the track creating friction that slows down or stops the train. The magnitude of this braking force is dependent of two factors (by kinetic friction force definition): applied normal force and friction coefficient. Since the coefficient is constant because both surfaces remain unchanged during braking, the braking force can be controlled with the applied force i.e. moving the brake units. These braking devices are operated by the ride’s main computer with pneumatic or electric methods. When the brake is closed by default, the machinery works against springs etc. to hold the brake open. Having all brakes closed as default greatly decreases the risk of trains colliding during trouble situations and power outages.

Figure 9: Double-jaw friction brake, operated by pneumatic pistons
(Salama - Linnanmäki)

Permanent and stationary mounted magnetic brakes have multiple benefits compared to moving magnetic brakes and friction brakes: they are very reliable as they don't require any external power to operate, their braking force is related to the speed and unrelated to the weight of the train always providing the same exiting speed (as long as the brake section is long enough to counter the weight variation of the train), they are not affected by humidity or moisture and they don't have any wear or tear in normal operation. Magnetic brakes are also silent and provide a very smooth decrease of speed. However, magnetic brakes can never fully stop the train and thus a friction-based mechanism may be needed in form of friction brake or transport device. [18]

A brake section that is not a block brake is called a trim brake. Trim brakes are only used to reduce the speed of the train (if necessary) and cannot stop or hold a train in position. The ride computer monitors the speed of the train with sensors before the trim and engages or disengages the trim brake devices to reach the required exiting speed at the end of the trim brake.

2.4.1 Transport devices

Transport devices propel the train onwards at a constant low speed. These devices include mostly tire drives and chains. Tire drives can be either a single or a pair of rubber tires powered by individual electric motors. The tires touch a friction surface on the train (often utilizing the same surface as friction brakes) and either push forward or slow down the train. Tire drives are mostly used in flat sections of the track like stations and brake sections, but they can also be used as lift hills instead of a chain as shown in Figure 10.

Figure 10: Tire drive lift hill [Fig. 8] (Rabalder – Liseberg)

Chains travel in a trough between rails wrapping around cog wheels to form a closed loop which is moved by an electric motor. The chain engages a chain dog at the bottom of the car(s) (shown in Figure 11) pushing the train forward. Due to this engaging method the chain is (in most cases) only able to move the train in one direction, not even holding it in place unless the track is inclined. However, this feature is utilized in lift hills as the train can automatically roll off the chain when it crests the lift hill. In case of stops, power outages and chain failures, additional anti-rollback measures (ARB) are added for safety (see Chapter 2.4.2).

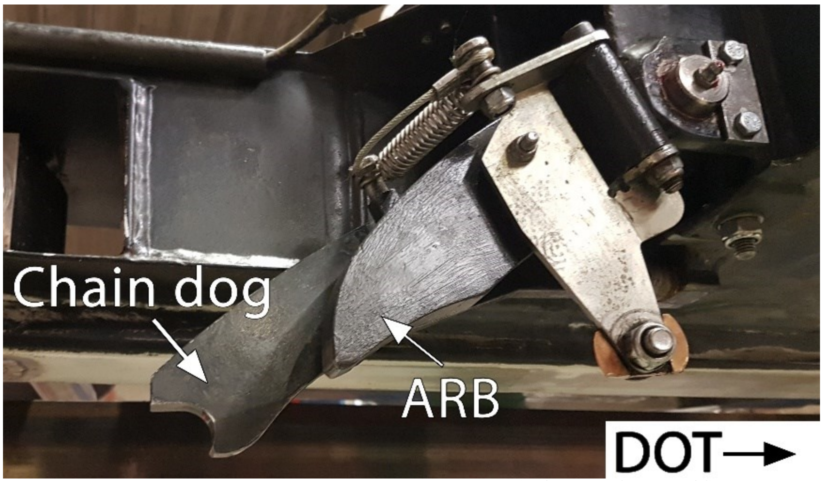


Figure 11: Chain dog and ARB (Salama – Linnanmäki)

Transport devices can be made redundant by making the track slightly declined allowing gravity to propel the train onward. This method is commonly used in brake sections as well as gravity run sections nearby the station where the train is designed to move at a slow speed. Wooden coasters especially often use this method in stations to induce nostalgia that is often connected with wooden coasters in general. Utilizing slopes instead of mechanical devices reduces need for maintenance and electricity but needs to be taken into account while designing evacuation/maintenance accesses and especially the station area floor. The minimum required slope of the track is calculated using resting friction coefficient between wheels and track.

2.4.2 Evacuation

Wherever a train can be stopped on purpose, a safe method of evacuation should be provided. Usually this means having catwalks beside the track like in Figure 10. The minimum catwalk width for evacuation is 0,60m [2 §6.1.3.3] and railing height is 1,0m with an intermediate rail at half height [2 §6.1.4.1.2] to allow walking on it without safety harnesses. The catwalk and railings need to be placed outside the reach envelope (Figure 7) but still close enough to prevent falling between the catwalk and train. Catwalks are also used for maintenance purposes because wherever a train can be stopped on purpose, there are mechanisms that require regular inspection and maintenance. With this in mind, the catwalk structure should also be designed applicable for harness attachment [3].

Whenever a train is propelled by external devices, there should either be safety devices or automatically acting brakes to prevent running backwards [2 §5.4.3.5]. If a train is stopped on a lift hill, the train needs to be secured to place with an anti-rollback mechanism or brought controlled backwards to allow evacuation. The anti-rollback mechanism is usually a set of ratcheting teeth (shown in Figure 12), which the train catches on to when falling backwards (see Figure 11). Non-vertical lifts normally use ratcheting teeth because a sloped or staggered catwalk (or a special moving lift platform) can be built beside it. Vertical and beyond vertical lifts need to utilize either a special mechanism to evacuate riders from all points or have a method to bring the train safely to a more accessible location. For example, Intamin uses two adjacent chains (Kirnu – Linnanmäki, Fahrenheit – Hersheypark) that can individually hold the train in place (as anti-rollback) or move the train upwards or downwards. Gerstlauer [20] and Zamperla [21] use permanent magnet stators that allow the train to slowly return to the beginning of the lift hill (Smiler – Alton Towers, Thunderbolt – Luna Park) where it can be evacuated using catwalks.

Figure 12: Anti-rollback teeth [Fig. 9] (Griffon – Busch Gardens Williamsburg)

To enhance smooth operations, most coasters have enough block brakes at the end of the ride to hold all the trains near the station. Because evacuation and approaching the riders is much easier near ground level, the trains may – in case of minor faults – be allowed to travel all the way until the end brakes. The trains can then be evacuated using catwalks. These blocks may also be used to store the trains at the end of daily operation.

2.5 Daily operations

Daily operations can be divided into two categories: inspections and maintenance made by mechanics, and operations performed by guest service staff. In order to keep a ride operating, the manufacturer assigns inspections and tasks that have to be done with regular intervals (daily, weekly, monthly, yearly etc.). Daily inspections on a roller coaster include at least visual inspections of the train and track and mechanic testing of safety restraints [2 §7.7.1.3] and tasks can include daily adjustments of wheels and machinery etc. Access to all parts of the train during daily inspections is vital and some tests may require transferring the train to a maintenance bay (see Figure 18) or other specific location on the layout. [3]

After technical inspections, the most important safety feature performed by human action is the closing and checking of safety restraints before dispatching. Modern coasters have sensors built in the restraints to check the clearance and the ride computer allows dispatching only when all the restraints are properly closed. The minimum restraint clearance designed by manufacturer is also stated in the ride operation manual but having the bar only at minimum clearance doesn't always mean that the rider is seated correctly or that the bar is touching the rider like it's designed to. The ride attendants' responsibility is to double-check (physical and visual check) all restraints before dispatching and ensure correct sitting positions.

The attendants also need to do several other safety precautions before checking the restraints: prior to boarding the ride they check all guests for minimum height and other requirements set by manufacturers and ensure that loose items are secured. To prevent falling loose items during the ride, some parks even have metal detectors installed not only at the park gates [22] but at ride entrances as well [23]. Even with all these precautions, there have been cases where a loose item has fallen from a ride harming another customer [24]. Methods to secure loose items are discussed in Chapter 5.1.1.

3 Designing a Roller Coaster Layout

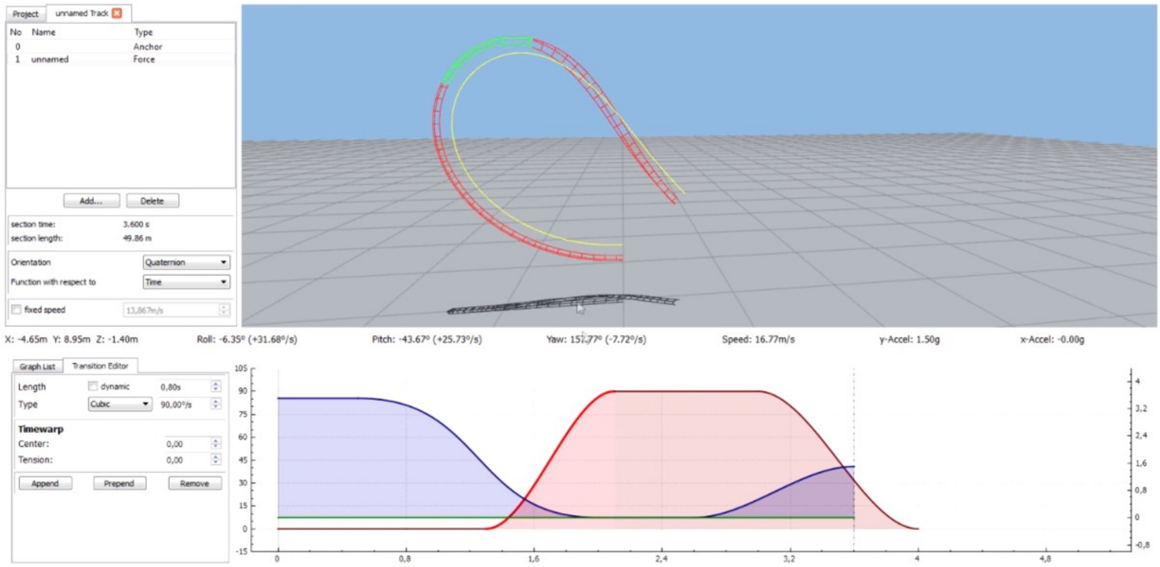
The design of a roller coaster layout starts from an idea that is conveyed into reality using different visualization and calculation tools. These tools can vary from simple pen and paper to bent wire coat hangers [25], miniature models and modern CAD 3D-simulations. The goal in layout design is to make a track layout that is fun and exciting while filling the customer's requests, is safe for riders and also realizable regarding certain limits in engineering and manufacturing. This chapter explores some methods and tools that can be used for layout design, some basic features, needs and requirements in layouts and some real life starting points to creating a layout.

3.1 Design softwares

The use of CAD has made designing roller coasters easier and even approachable to non-professionals. Not only simulations but even popular games like RollerCoaster Tycoon and Planet Coaster have been made with roller coaster or theme park designing and managing motives. The leading commercial software at the moment is NoLimits 2 when it comes to designing professional-level coaster layouts. It is also used by many manufacturers for marketing purposes to create visually appealing pictures (see Figure 13) and animations of coasters [26] [27] [28].

Figure 13: A NoLimits 2 coaster model with additional scenery [Fig. 10] (Taiga – Linnanmäki)

NoLimits 2 utilizes a spline method to create and save a track layout. Nodes of the spline can be moved and adjusted individually, and the software calculates a smooth Bézier curve using these nodes to create the final track shape. As an upgrade from the original NoLimits, the sequel manages roll separately from track nodes that control pitch and yaw. The location and roll of the spline at given intervals can be imported and exported as a list, allowing further use in other softwares as well. One of these softwares is FVD++ [29] ("Force Vector Design") which allows the user to create the coaster layout using mathematical formulas with a function of time as shown in Figure 14. This is similar to the professional method used by coaster manufacturers; the shaping of the layout and elements is created using accelerations on the rider rather than track radii. Because the accelerations are dependent of the traveling speed of the train which changes not only when elevation changes due to potential energy, but to the travelled track length as well due to friction losses (discussed in Chapter 3.3), the shape of each valley and hill has a constantly changing radius in force design method. Shaping of individual elements is discussed further in Chapter 3.4.1.



No	Name	Type
0		Anchor
1	unnamed	Force

section time: 3.600 s
section length: 49.86 m
Orientation: Quaternion
Function with respect to: Time
☐ fixed speed 13,867m/s

X: -4.65m Y: 8.95m Z: -1.40m
Roll: -6.35° (+31.68°/s)
Pitch: -43.67° (+25.73°/s)
Yaw: 152.77° (-7.72°/s)
Speed: 16.77m/s
y-Accel: 1.50g
x-Accel: -0.00g

Length ☐ dynamic 0,80s
Type: Cubic 90,00°/s
Timewarp
Center: 0,00
Tension: 0,00

Figure 14: FVD++ user interface and resulting acceleration graphs [Fig. 11]

The software to create and calculate a layout is a key competition tool between manufacturers. Track cross-sections and support methods can be easily reverse-engineered and analyzed because they are visible, but the software behind the layout is a differentiating factor and thus considered a trade secret. Ultimately it is that software that generates the feel and experience of each ride. Though coaster elements are not patented or protected, and most are used widely among all manufacturers, some repeating and manufacturer-preferred and -specific patterns can be recognized when analyzing the curves and shapes of coaster elements. [4]

One limitation in layout design are the radii of track that the trains are able to navigate through [2 §6.2.3.2c]. The cars cannot overlap and there are often mechanical parts also below the floor between the rails – mainly braking fins, chain dogs and anti-rollback devices – that need to be prevented from hitting the track. With CAD these track radii can be easily checked, which together with computer calculations has allowed the creation of more complex and three-dimensionally simultaneously rotating elements, as presented in Figure 15.

Figure 15: Example of track simultaneously rotating around all axes [Fig. 12]
(Lech Coaster – Legendia)

3.1.1 Heartline

Using CAD, the track can be designed not around the center of rails, but around heartline of the riders (see Figure 16). This is done by shifting the roll axis towards the center of rider's chest (hence the name "heartline") upwards while remaining laterally in the middle of the rails. Even though most coaster trains have more than one passenger sitting next to each other and thus the heartline is not located in the actual center of a single rider, moving the roll axis from center of rails minimizes a lot of unwanted and uncomfortable lateral movement (especially to the rider's heads) creating a more comfortable ride experience. The heartline height varies with different seating arrangements, but on regular sit-down coasters it is approximately one meter upwards from the center of rails [30]. Though utilizing heartline eliminates most unwanted gs, some additional gs are caused by the seating arrangement's width during rolls. The wider the train, the further away from the rotation axis the riders sit and the bigger the additional gs can become. However, this can also be used for extra effect and surprising sensations for the riders by designing the elements with this in mind (B&M Wing coasters, S&S Sansei 4th Dimension coasters).

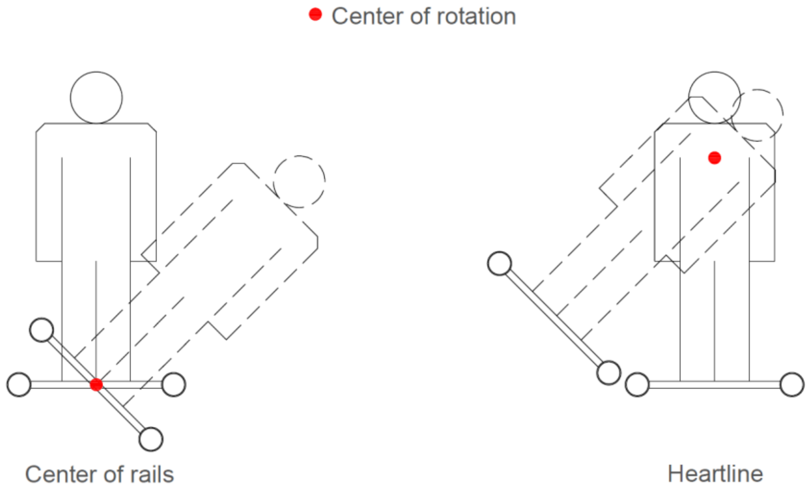


Figure 16: Heartline visualization

3.2 Basics of layout design

“Roller coasters normally have an endless track loop. Riders load and unload at a platform or station, typically at a low elevation. At the beginning of each ride cycle, a roller coaster car or a train of cars is generally towed or moved up a relatively steep incline of an initial track section to the highest point on the entire track. The car is then released from the high point and gains kinetic energy, which allows the car to travel entirely around the track circuit or loop and return back to the loading/unloading station. The roller coaster track typically includes various loops, turns, inversions, corkscrews and other configurations intended to thrill the riders.” [31]

As stated, every coaster has a station, a means to provide mechanical energy for the train, a gravity-run portion (the main part of a coaster) and a method to stop the ride. Powered coasters have electric drive motors in the trains themselves that propel the train forward and control the speed of the train constantly [32], but these coasters are not covered in this thesis. Mechanical energy is usually given as potential energy when the train is pushed on top of the lift hill, or as kinetic energy when the train is launched forward at high speeds with electromagnets or other devices. Lift hills are the highest points of rides giving the trains enough potential energy to navigate through the layout. Potential energy is converted into kinetic energy as the train passes through valleys, and into potential energy again when cresting hills. A launch is typically followed with a tall element to ensure two things: if the launch fails, the train rolls back to the launch track where it can be stopped and re-launched, and to ensure the train has enough potential energy to make it through the rest of the layout after it crests the element even if it momentarily stalls on top of it [33]. Most coasters are located on a flat area where the ride has to start with a lift hill or a launch, but there are also cases of “terrain coasters” that begin with a gravity run (Helix – Liseberg, Time Traveler and Thunderation – Silver Dollar City).

While the train is propelled onwards using transport devices, its speed is controlled and invariable. In the gravity run portion however, a plethora of variables comes into action (see Chapter 3.3) and the speed at the end of the gravity run can vary a lot. The train is usually slowed down with brakes at the end of gravity runs before entering any transport devices (see Chapters 2.4 and 2.4.1) to prevent excess wear and tear. If the speed variance is small, the transport devices themselves may be used to slow down the train. Regardless of the braking equipment, all block brake sections are designed long enough to be able to stop the train if necessary, without exceeding a max deceleration value of 7,0 m/s^2 (0,7g) in emergency, and 4,9 m/s^2 (0,5g) in normal operation [2 §5.4.3.4]. Most brake sections are straight pieces of track, either level or slightly declined (as mentioned in Chapter 2.4.1) considering “The maximum transverse inclination of the rail at the spots at which the car is likely to come to a full stop for operational reasons (e.g. at brakes) shall be limited to a max. value of 25°.” [2 §5.4.3.1]

Most current track-mounted devices require a straight piece of track to align the equipment properly with their counterparts on the train. In case of vertical mounted brake fins the track may have a change in pitch, but yaw and roll need to be restrained for proper alignment e.g. in Figure 17. Same restrictions may apply for transport devices as well. Most lift hills allow only pitch change, but rare cases of yaw changes exist as well (Jetline – Gröna Lund et. al. Schwarzkopf).

Figure 17: Pitch change with magnetic stators [Fig. 13] (Zaturn – Space World)

The capacity of a coaster can be upgraded by having more MCBR’s or end brake blocks to allow multiple trains on the track simultaneously. The block system (explained in Chapter 2.4) is taken into account by making each block shorter in duration than the previous one to prevent stacking of the trains. From each block brake, a train must be able to complete the layout from a standstill (lowest speed, discussed in Chapter 3.3.1). While calculating the theoretical capacity of a coaster, the time required to move the train from one block to another with the means of transport devices becomes important. It takes time to accelerate a train, move it at least a train length to the next block and then brake again. While this is happening, the block system prevents the following train from moving and there is lost time when simply one train is moving at a time. Intamin has developed a special dual-loading station system where a block violation is happening under control and two trains are moved simultaneously with only a relatively small gap between them (Maverick and Millennium Force – Cedar Point). [4]

If a coaster is designed to have more than one station, the load and unload positions of a train need not be the same (see Figure 40). While having the guests only to board or exit the train takes less time than to do both, there is also the time loss in moving the train between these two locations due to block system. Because of this, having separate load and unload positions is reasonable only when there are at least three or more trains running and both the load and unload position can have a train in them at all times. However, having them separate does make the capacity higher and especially Disney parks favor this design choice. Xpress: Platform 13 – Walibi Holland and Rock ‘n’ Roller Coaster – Walt Disney World have identical layouts besides station arrangement: Xpress has a single station for both loading and unloading, while Rock ‘n’ Roller Coaster has separate stations for loading and unloading. As a result, Xpress has a theoretical capacity of 1200 pph while Rock ‘n’ Roller Coaster has 1800 pph [34] [35]. More station types are discussed in Chapter 5.1.

While the main focus is to design for the riders, the maintenance aspect needs to be taken into account as well. Regular checks and off-season maintenance work require access to the train both above and below the rails. If the station area is not suitable for maintenance purposes, a separate maintenance area or bay is required. If the coaster has more than one train operating, a method to add and remove train(s) from the track loop is also required. This method is usually either a track switch that works as a split and guides the train to the maintenance bay, or a transfer track where the train is held in place and the track piece moves horizontally or vertically to the maintenance bay access. Examples of both methods are presented in Figure 18. Coasters that have more than two trains usually have a transfer track and multiple maintenance bays (one for each train). The maintenance bays are also utilized as storage if not all trains are needed in operation (low-attendance days).

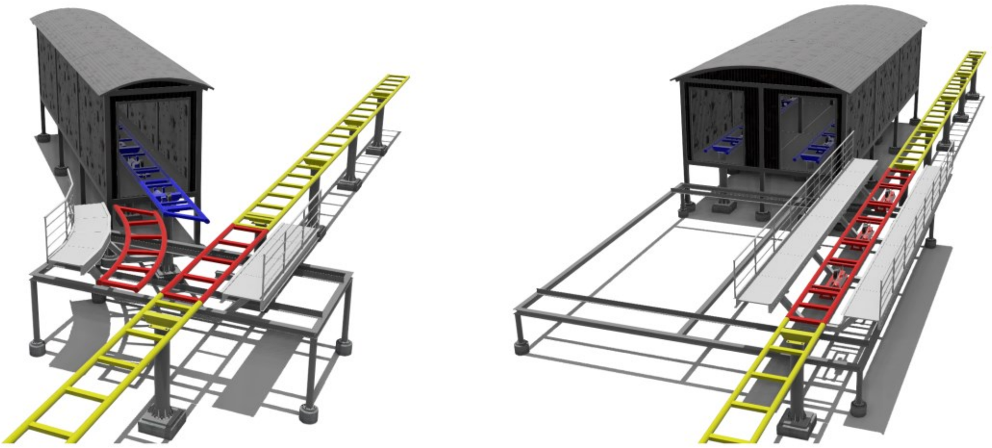


Figure 18: Maintenance bay with switch track (left) and transfer track (right), moving parts of the track are colored red

3.3 Speed and gs

As a train is rolling along a gravity run, it’s constantly losing its kinetic energy due to air resistance (drag) and friction. Their values and proportions are dependent on a plethora of small variables; not only on the used materials and speed of the train, but on operating conditions such as air temperature, wheel and other parts’ temperature and loading of the train as well. The friction losses consist of rolling friction between the wheels and track and more complex rolling resistance inside bearings etc. moving parts in the train. Air resistance or drag is calculated as a function of speed squared, meaning that drag increases exponentially with growing speed, while friction remains more unchanged once the train has started moving (further calculation and modeling is not included in this thesis). At low speeds the drag is minuscule compared to friction loss due to the high number of wheels on a coaster train; the popular bogie system presented in Figure 3 uses 6 wheels per bogie = 12 wheels per axle, which on a four-car articulated train like in Figure 4 results in a total of 60 wheels and depending on design, all wheels may be required to touch the track at all times creating more friction loss.

“A typical wheel used on a roller coaster is constructed by taking an aluminum hub and bonding a polyurethane tire to the hub’s outside diameter. The entire ‘wheel assembly’ is then connected on the axle through a bearing.” [36 p.55]. Instead of polyurethane, nylon can also be used. Polyurethane is softer and more susceptible to changes caused by temperature – thus it works better in warmer temperatures (roughly +10 C° and up) meaning the friction coefficient between wheel and rail is smaller. Not only the environmental temperature affects the material, but it also heats up during use. Because polyurethane is soft, it is able to absorb some imperfections (bumps and vibrations) on the rails, not only providing a smoother ride but also preventing minor fatigue damage to the train. Compared to polyurethane, nylon is harder and has a smaller change in friction coefficient during temperature changes. “Nylon wheels vibrate a little more and put more wear into the track, making it a rougher ride but also results in a little bit faster of a ride.” [36 p.58]. [3]

3.3.1 Lowest speed and fastest speed scenarios

Although the speed of the train in gravity run portions is variable, it stays inside a certain envelope throughout the layout. The two different extreme speed conditions at any point are here referenced as lowest speed and fastest speed scenarios. Lowest speed is the minimum speed at which the train can just make it through the layout with unfavorable conditions such as empty train and low temperatures. Fastest speed is the maximum calculated speed with optimal conditions such as a fully loaded train after hours of continuous operating in optimal temperature and other conditions. In terms of conditions, an empty train means less mass and thus less inertia, while lower temperatures affect the friction coefficient both between the wheels and rails as well as the greases' viscosity in all bearings etc. [4]

Lowest speed can be assessed by setting the starting speed of the train to zero in all transport sections such as the top of the lift hill(s) and MCBRs and simulating the following gravity run with unfavorable conditions. Similarly with launch coasters the speed at the top of the tallest element (usually following the launch) is set to zero and then ensuring that the train is able to make it through the following gravity run. Fastest speed can be assessed with designed speeds on all transport devices (including launches), a full train and lower friction coefficients etc. optimal conditions. These coefficients can be estimated with calculations but are ultimately assessed through experience and are thus manufacturers' trade secrets [4] [37].

The importance of lowest speed calculation is to ensure the train can complete the layout even in the worst case especially with previously mentioned unfavorable conditions, while fastest speed calculation is made to prevent too extreme gs. Because the speed of the train varies but the track curvature remains the same, the gs experienced by riders also vary (gs are discussed further in Chapter 3.3.2). The varying actual speed in each gravity run during the coaster's operation should thus always be covered within these two extreme cases.

At low speed portions of a gravity run, the kinetic energy of the train reduces and thus the train becomes more susceptible to external factors, especially wind. Usually the lowest speeds on a layout are on the tallest elements, which have the least protection from wind. This increases the probability of stalling when the train needs to be pushed forwards manually [33]. The risk of stalling can be reduced by increasing the design speed in tallest and slowest elements and reducing the number of low speed elements.

If the fastest speed calculations indicate exceeding gs but track layout is to remain unchanged, trim brakes may be added to the layout. Trim brakes can also be used to homogenize every ride by reducing the speed variance; i.e. every ride feels the same regardless of operating conditions. Reducing speed can also prevent excess wear and tear, and thus trims can also be retroactively added. Trim brakes are explained in more detail in Chapter 2.4.

3.3.2 Gs

“Being exposed to changes in motion and movement can have significant biomechanical effects on the human body and, in general we try to minimize our exposure to movement. Most transportation devices are designed to reduce acceleration as much as is reasonably practicable. Amusement rides on the other hand, are unique in that they are deliberately designed to expose us to large and changing types of motion. … Our body does not feel velocity, but only the change of velocity i.e. acceleration, brought about by the force exerted by an object on our body.” [38]. These accelerations are called gs.

Gs are one of the key aspects in roller coasters to cause excitement, but excessive gs start to induce unwanted symptoms and even damage to the human body such as greyouts and unconsciousness [38] [39]. To prevent injuries, gs have standardized tables of maximum values depending on the seating and restrains arrangements [6], where the limit value decreases while its duration increases as shown in Figure 19. With each duration a minimum deceleration is presented as a trapezoid [38]. However, the stated absolute maximum values are more than most manufacturers use in extreme rides and more common and comfortable maximum values are presented in Table 1. In addition to one-axial gs and their duration, their combination as multiaxial gs are important as well. When there are simultaneous lateral and vertical accelerations, their rations also have maximum values and durations according to [2 §G.2.4].

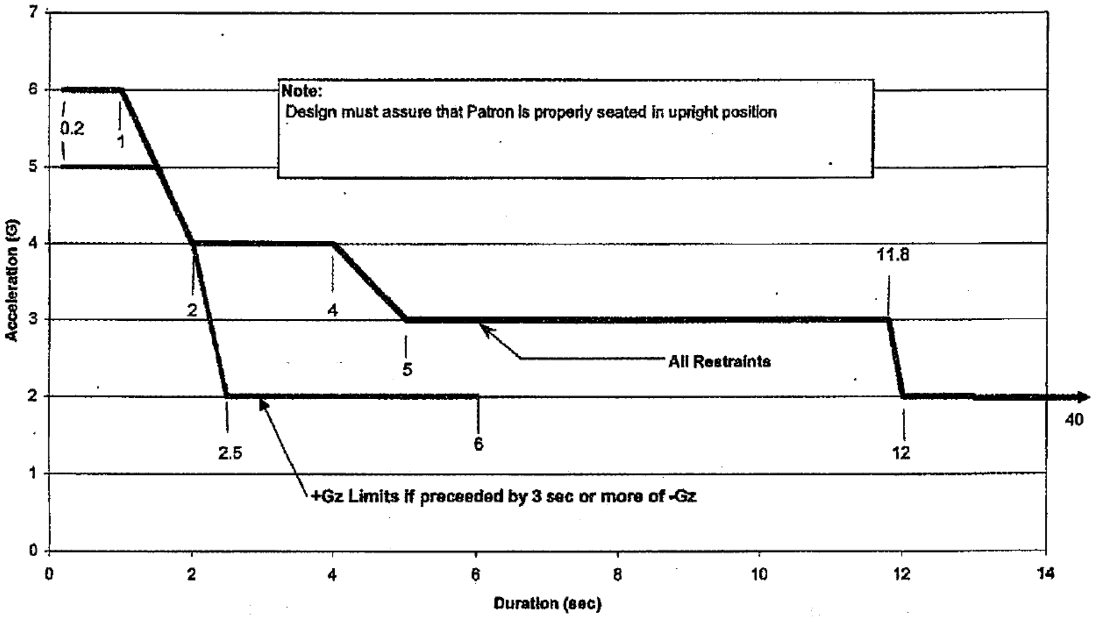


Figure 19: Time duration limits for positive vertical gs [Fig. 14]

Table 1: Max g values

	Max short term value [6]	Common max value [2] [64] [65]
vertical +	6	5
vertical -	-2,8	-1
lateral ±	3	1
longitudinal +	6	2
longitudinal -	-3,5	-0,5

While avoiding too high gs is important, it’s also important to calculate how these accelerations are applied by taking another dime derivative (jerk). These are important especially while transitioning between elements, as it greatly affects the shaping in the beginning and end of each element. A gradual jerk gives a smooth increase in radial acceleration, and constant jerk gives a linear increase. In practice, reducing jerks is done by utilizing clothoid shapes. Accelerations during the ride are considered impacts if they last less than 200 ms and gs if they last equal or more than 200 ms [6 §3.1.1].

The length of the train does not only contribute to the mass and energy losses, but also affects the distance between center of gravity and furthest seats on the train. The gs between each seat and car always have some variance, and the more cars there are in a train, the bigger the variance. This variance needs to be considered while designing the layout because extreme gs stated by standards cannot be exceeded in any seats in any conditions. This is also why most manufacturers attach accelerometers on the train during commissioning before allowing anyone onride. The resultant acceleration acting on riders is a combination of designed loads on the track spline and additional loads caused by seating arrangement, track deflection and vibrations on the train etc. minor real-life causes. When designing coasters that have wider cars i.e. riders sitting further from the roll axis, the roll rate becomes more important since rolling creates additional accelerations that increase at furthermost seats, as mentioned in Chapter 3.1.1.

3.4 Pacing and thrill

Though making a coaster layout can be referred as an artistic medium and people have different opinions, the primary function of a coaster is to thrill. Listed in this chapter are some topics to consider while making a thrilling layout.

Perhaps the most commonly loved feeling during a coaster ride is the feeling of weightlessness, called ‘airtime’. Airtime can be experienced when a train is cresting a hill with speed, making the riders feel like they are flying upwards away from the train while the train keeps going downwards. Airtime can be categorized further into ‘floater’ and ‘ejector’ airtime. They don’t have standardized categorization or values, but in this thesis, floater refers to +0,5g…-0,5g vertical and ejector to -0,5g vertical and lower. While negative vertical loads add a sensation of fun, positive vertical loads add intensity and are often compared to astronaut training. Lateral gs are often considered uncomfortable since the seat rarely has adequate or comfortable support for the rider. Banking the track converts laterals into positive vertical loads, which the seat can support more comfortably. Laterals are generally avoided, except in wooden coasters where they add to the feeling of being out-of-control, but in these cases the seats often have extra cushions and proper supporting abilities.

To keep adrenaline flowing during the ride experience, a constant non-stop action pace should be sustained during the course. Every time nothing interesting is happening, the possibility of riders getting bored increases. Transferring between gravity run and transport sections always slows the pacing, since enough safe margin needs to be taken in slowing down the train to a controlled speed. Brake runs and other straight or uneventful track sections can give a breather in both good and bad regarding thrill. While it can be profitable to have a short pause to highlight the following track section, it may also be boring for some riders.

Even though speed is always controlled at the end of the ride, the aim should be to not waste too much energy. The designed layout should aim for a decent speed entering the end brakes. If the train crawls during the last elements, it may lessen the thrill and even increase risk of valleying but entering the ending brake run too fast can be a waste of energy and increase the risk of trains colliding. Of course, there are some exceptions where specific client requests were made for certain height, speed or budget (Kingda Ka – Six Flags Great Adventure, Red Force – Ferrari Land, Leviathan – Canada's Wonderland).

Utilization of terrain plays a huge role in pacing, as it opens more possibilities to shape the layout with something different and unexpected. Coasters that remain close to natural landscape are often referred as terrain coasters (Helix – Liseberg, Nemesis – Alton Towers) [40] to highlight their dissimilarity, since most coasters are built on a flat area.

Crowd interaction with coaster layout is often found interesting, since it creates a possibility for non-riders to share and connect with the riders. Crowd interaction elements include parts of layout that are travelling over, under or nearby park paths, viewing platforms or ride queues. Visually impressive elements and water splashdowns often have specific viewing platforms built next to them to provide photogenic views and, in case of water elements, a splash zone (SuperSplash – TusenFryd, Pulsar – Walibi Belgium).

3.4.1 Order and shaping of elements

In general, variance in layout is good and surprising riders is even better. Repetition in elements and predictability can be boring as they often reduce intensity – thus dynamic rides are generally considered more exciting. A shift in recent design can be seen which emphasizes constant and even progressive thrill throughout the whole ride, not just during the first big hills/elements (Lightning Run – Kentucky Kingdom, Taron – Phantasialand, Lech Coaster – Legendia, Taiga – Linnanmäki).

Coasters often have a big start to make riders' adrenaline flow and utilize speed and height, and a strong finish to make the ride memorable and give re-rideability [41]. If all 'fun' elements are used in the beginning and the end is just a slow crawl back to station, it may bring re-rideability and riders' adrenaline levels down. A slow lift hill can be a great build-up followed by a big drop, and a fast launch can kick-start the ride and surprise riders. Some elements require or have advantages if taken with more speed, so they are often in the beginning of the layout (e.g. loops and other tall elements) while some can be done with lower speeds and thus are often placed near the end (e.g. barrel roll, corkscrew).

Most coasters start with a lift hill followed by the biggest drop and hills then get smaller towards the end of the layout naturally due to lost mechanical energy. While this is often unavoidable due to multiple reasons, it's still not impossible to induce intensity with smaller elements. The intensity comes from gs, which are caused by the curvature of the track and the proportional traveling speed. High speeds require big track radii, providing the intensity with sustained gs. A high speed and/or height can be exciting as it is and the layout may not need to have a lot of changes in acceleration to thrill the riders. By tightening the track radii, the same gs can be achieved throughout the whole layout even with varying speeds, just with smaller durations. Towards the end frequent and sudden changes in acceleration can create a feeling of being out-of-control, substituting absolute speed with fast direction changes.

When designing the exact shaping of an element, using global orientation (see Chapter 4.3) "Curves of various shapes can be described through a set of differential equations, prescribing the derivatives of the position with respect to distance, s, along the curve." [42]:

$$\frac{dx}{ds} = cos\ \theta; \ \ \frac{dy}{ds} = sin\ \theta; \ \ \frac{d\theta}{ds} = \frac{1}{r}$$

In the case of a vertical loop, the train travels a full 360 with centripetal acceleration either amplified or reduced by Earth's gravitation. Calculating the pitch radius with a frictionless train and constant centripetal acceleration [42]:

$$a_c = \frac{2gh}{r}$$

is a linear function of loop height [42]:

$$\frac{d\theta}{ds} = \frac{1}{r} = \frac{1}{r_0}\frac{h_0}{h}$$

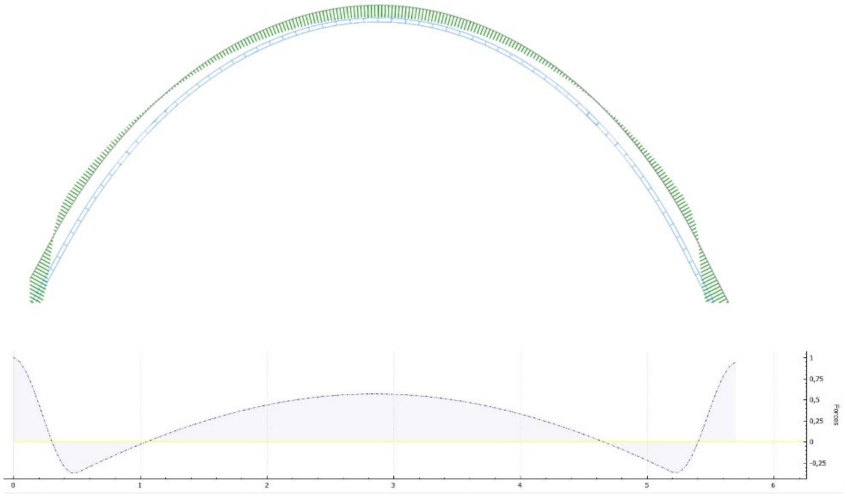
To calculate the actual acceleration on riders, Earth's gravitation is taken into account [43]:

$$\frac{1}{r} = \frac{1}{h}(\frac{h_0}{r_0} + \frac{cos(\theta_0) - \cos(\theta)}{2})$$

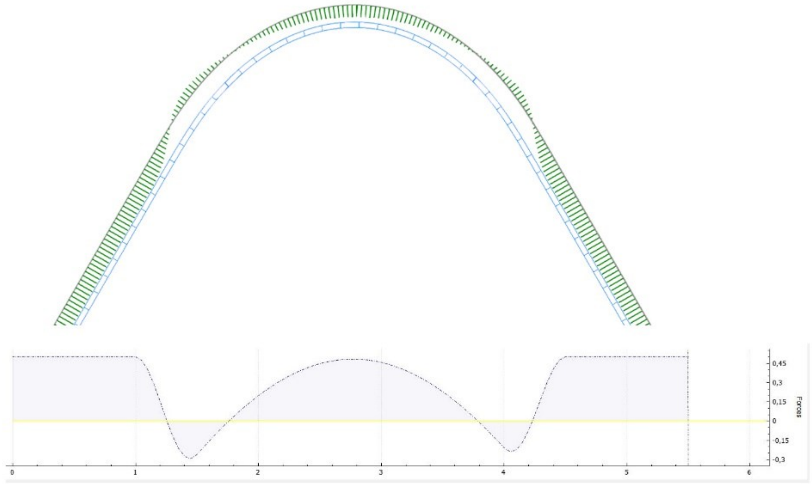
where
θ = track pitch
θ_0 = initial track pitch (start of element)
s = loop track length
r = local radius of pitch
r_0 = initial local radius of pitch
h_0 = loop height
h = vertical distance from the highest point of the coaster where the train starts from rest

With similar calculation methods, the gs can be controlled directly and even elongated throughout elements. For example, to maximize the airtime on a hill, the pitch radius is not constant, but instead the shape follows a parabola. Figure 20 shows three different cases of an airtime hill shape: constant radius, straight inclination followed by constant (small) radius and parabolic shape. On top is the shape of the track with vertical acceleration comb and below is a graph presenting vertical gs with a yellow line at 0g. The graphs, shaping and visualizing were made using FVD++ and NoLimits 2. In this case, the aim was to have 0gs sustained as long as possible. With constant radii, the gs only shortly cross the 0g line and even provide unwanted negative gs. The parabolic curve shape was calculated using force design, and thus the 0g sensation is sustained and controlled throughout the whole element.

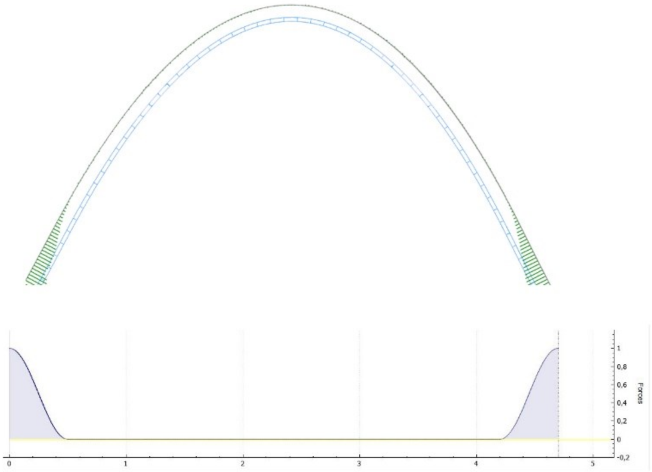
This force design method can be applied to every element and transition on a coaster; having a big drop or hill with constant inclination can be boring if airtime disappears because with it, so does the thrill as well. A drop with constantly changing inclination can induce a longer lasting airtime and thus more thrill. With the control provided by force design the element transitions can also be made more compact which improves pacing. Force design can also reduce jerks since every targeted g can be reached smoothly with a chosen shape function. The parabolic hill shape in Figure 20 was calculated using sinusoidal shape functions to transition to and from 0g.



Constant radius



Straight inclination followed by constant (small) radius



Parabolic shape

Figure 20: Airtime hill shaping and resultant vertical g

3.5 Starting points for layout design

When a park/customer decides to buy a new roller coaster, they assess their needs, resources and limitations before contacting manufacturers and starting the tendering process. These can include target audience, budget, ride area and other specific elements or features. These topics then provide boundary conditions and starting points for layout designers.

Target audience means not only the required minimum height of the riders, but who the new ride is being marketed to (and who the park especially wants to ride it). The ride statistics (speed, height, number of inversions etc.), intensity (mainly gs) and other elements included can dictate the major demographic of actual riders ranging from small children to adrenaline-seekers. A popular way to categorize coasters according to their height is a four-point scale: kiddie, family, thrill and extreme coasters [44] – however this method of categorization is not official or exact but is often used especially in marketing as it gives a general idea of the target audience. Other ways to categorize a coaster include their building material (steel/wood/hybrid), height, train type, seating type, layout, manufacturer etc. One scale commonly used especially when talking about tall coasters is: Hyper coaster (height over 61m or 200ft), Giga coaster (over 91m or 300ft) and Strata coaster (over 120m or 400ft) [41]. In 2017, there were a total of 57 coasters operating that are more than 60m tall [44]. A new type of coaster is also under development called Polercoaster where the coaster travels wrapped around an existing tower structure [45].

Budget is just as important as in every construction project. Manufacturing complex and long coaster tracks is not only expensive because of design and material costs, but because of the required tolerances in manufacturing as well. Bending and welding of the steel pieces (track, supports etc.) need to be done accurately to avoid structural defects. Budget on the park's perspective should also include the cost of foundations and external theming including new buildings. Most ride manufacturers provide until "bottom of steel" [3] [4] meaning the responsibility of designing and contracting (or outsourcing) the foundation work is on the park (foundations are discussed further in Chapter 4.5).

Allocated ride area is the total area where the coaster will be, and requests may include the location for the station building(s), storage/maintenance building(s) or queue. The layout area can include interaction with other rides, and designing a new ride interwoven into existing structures may even require 3D-scanning (Twister – Gröna Lund, Taiga – Linnanmäki). There may also be limitations about foundations or clearance for walkways or even legal restrictions (for example maximum height of the ride). The park can also ask for a specific amount of inversions or a record-breaker feature to attract more thrill-seeking guests.

While most coasters are custom-made, parks/customers may also buy a copy of an already existing coaster from the manufacturer (or in rare cases, request a copy of their competitor's ride (Aplina Blitz – Nigloland)). This naturally saves cost because most calculations and drawings have already been made, but it may not attract as many visitors due to its non-uniqueness, especially if another identical ride is located nearby.

Amusement parks often have requirements regarding the guest throughput i.e. capacity [4]. The theoretical capacity is calculated by how many trains can be dispatched multiplied by the number of riders in a single train (i.e. how many guests can ride the coaster) in an hour, resulting in a unit called pph (people per hour). The minimum dispatch time is the time before the block after station is empty and the next train can be dispatched. The theoretical capacity can be increased by having more block sections or more people per train. However simply having more trains and blocks and then trains stacking on every brake does not make the capacity go higher (Blue Tornado – Gardaland), the whole layout needs to allow smooth operations without stacking. The actual capacity is also dependent of multiple small variations, e.g. the ride attendants' and guests' actions. Moving station floors and conveyor belts have been introduced recently to keep the dispatch time constant (Hollywood Rip, Ride, Rockit – Universal Studios Florida, Cobra's Curse – Busch Gardens Tampa). In these cases, the trains are slowly moving through the station at a constant speed and a conveyor belt as a part of the station floor next to the train is matching the train's speed allowing guests to enter the moving train. An example of a moving station floor (conveyor belt) is presented in Figure 21. More station variations and possible design choices are discussed in Chapter 5.1.

Figure 21: Moving station floor / conveyor belt [Fig. 15]
(Hollywood Rip, Ride, Rockit – Universal Studios Florida)

4 Engineering Designs into Reality

A coaster superstructure is designed to support trains traveling on a continuous track. The superstructure on a steel coaster discussed in this thesis can be divided into track substructure, support structure and foundations. The track substructure can be further divided into rails, cross-ties and spine, as shown in Figure 22. Coasters discussed in this thesis use two circular rails which are parallel and equidistantly connected at all times by welded cross-ties. This chapter explores the engineering side of coaster structure design: recommended load calculation methods, various track and support cross-sections used by different manufacturers, some common support structure shapes, the co-operation of track and spine structure, flange connections, aesthetics, foundations and external effects that sometimes need to be considered.

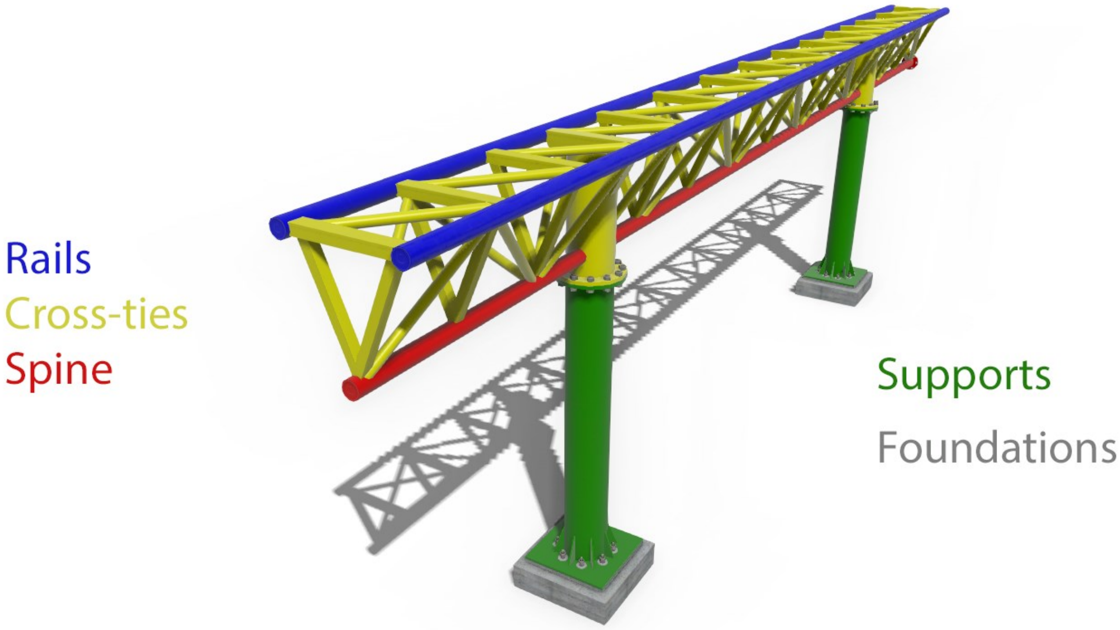


Figure 22: Coaster superstructure with color-coded division

4.1 Calculating loads

Like all structures, roller coasters have a designed and finite lifespan. As slender, dynamic and bare steel structures, they are subjected to a lot of swaying, fatigue and environmental conditions. They share similar requirements with all structures regarding permanent and variable loads, but due to their special dynamic nature have their adaptations [2 §5.3]. The dynamic nature of the loads caused by coasting trains cause major stress fluctuations, which require fatigue analyses rather than simple rupture limit state check [2 §A.1]. Structures subjected to fluctuating stress which are likely to be exposed to more than $n=10^4$ stress cycles during their expected service life shall be dimensioned by calculation of fatigue strength [2 §5.6.1].

The required calculations for a coaster structure according to Eurocode [2] are ultimate limit state (ULS), fatigue limit state (FLS), stability limit state analysis, verification of safety against overturning, sliding and lifting off and dynamic analysis. Verification of deformation limit states can also be required (e.g. long spans). Unlike inhabited buildings, coasters allow swaying and vibrations much more; i.e. serviceability limit state (SLS) doesn't need to be considered and thus the utilization of material is not limited by deformations like in most slender steel structures. This can even lead to visible swaying and oscillation of some parts of a structure during operation, while it is still verified for operation. In the case of Kirnu at Linnanmäki, the original superstructure had only four columns in total and coasting trains caused the structure to visibly and audibly sway and oscillate. Two additional supports (shown in Figure 23) were added to Kirnu and all similar models for next season to prevent this oscillation.

Figure 23: Kirnu in 2007 (left) and with added supports in 2008 (right)

The loads subjected on a coaster track include self-weight, environmental loads (wind, snow and seismic loads) and dynamic loads from the coasting train. A single car can weigh more than 1700 kg [3] while holding four people (4 x 120kg = 480 kg) making the self-weight of the train up to 70% of its total maximum mass. The extreme loads to the track are calculated using fastest speed with overloaded train (each passenger weighs 120kg), but even then, the gs cannot be exceeded [6], making the maximum local load roughly 5 times the train's total mass. All loads are then combined, calculated locally and divided to each axle, bogie and wheel to make sure that not only the superstructure holds, but the sub-structure of the track (and train) as well.

Minimum load cycle requirement for a constructional detail in a coaster is [2: Table 6]:

$$N_{min} \geq x_1 * 5 * 10^6$$

where N_{min} = number of load cycles
x_1 = multiplier for the number of times the train crosses over the detail

Beside maximum loads, fatigue has a major effect in dimensioning. Example: a continuous track loop coaster has a dispatch time of one minute, which leads to 60 cycles in an hour and 480 cycles during an 8-hour operating day. This leads on to 3360 cycles in a week and 80 640 cycles after six months. A total of 25 years (or seasons) like this accumulate to over 2 000 000 cycles from the trains only (plus vibrations, sway and wind-loads). The high amount of load cycles means all deformations caused by the running trains in the structure need to be elastic in order to remain under control and prevent fatigue damage. This is called infinite-life design [46 §2.2.1]. Because of the high number of cycles and often hard-to-reach and -inspect structures, allowing plastic deformations would open a possibility for a failure with unstable growth that could remain unnoticed. However, it’s not uncommon to have small repair welds done on a coaster or any other ride during off-seasons [3].

4.2 Track cross-section

As shown in Figure 22 the track cross-section consists of rails, cross-ties and spine structure. The cross-ties not only support and keep the rails equidistant, but also combine the rails and spine into a sub-structure. Most coasters use tubular rails (CHS), but RMC has also recently developed a method to utilize an I-box track with welded sheets of metal, as shown in Figure 24. As most coasters use three-wheeled bogies (see Figure 3), the cross-ties holding the rails can only be welded on one side of the rails. The cross-ties themselves can be of any cross-section: tubular, square or flat sheets of metal etc. (different variations presented in Figure 25). Besides cross-ties connecting the rails with spine, additional rods on the same plane as rails (i.e. between the rails) can be added to form a Z-shape (see Figure 22) to gain more lateral rigidness. The spacing between cross-ties can be adjusted according to the loads caused by trains. Unlike steel coasters, wooden coasters usually have a layered structure supporting flat rails along their whole length.

Most manufacturers have nowadays switched to only using tracks that utilize side wheels running outside the track. Having side wheels inside the track allows lowering the heartline as trains can travel partly inside the track, and thus the track shape is easier to calculate by hand. However, with advanced CAD technology it has become easier to set the heartline to any chosen height and have the computer calculate the final shape of the rails, which has led to the popularization of outside side wheels due to their benefits. These benefits include easier maintenance access to the side wheels (resulting in a smoother ride experience), less used material in track manufacturing and a structurally sturdier track with less critical fatigue points. Vekoma [47] (and Arrow Dynamics – bankrupt in 2001) has a long history of using a track with side wheels running inside the track, but as previously stated, has recently also switched to outside side wheels. Chance Rides [48] is the only major manufacturer to have recently built a coaster with side wheels running inside the track $^{\text{(Lightning Run – Kentucky Kingdom)}}$.

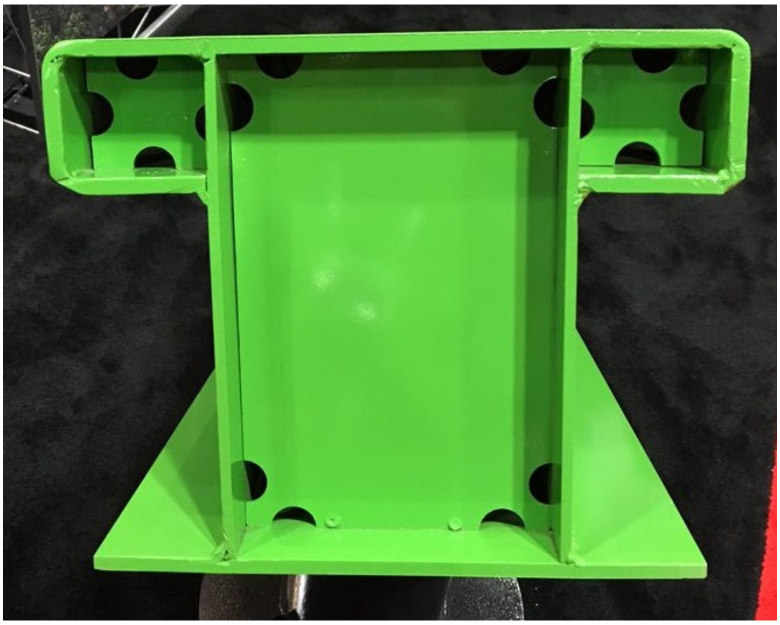


Figure 24: RMC I-Box track cross-section [Fig. 16]

The length of unsupported track between two supports (span) is dependent on the track's mechanical properties and applied loads. Because having a support on every cross-tie of the track is not efficient, the span can be increased by increasing the mechanical properties (bending and twisting strength) of the track. Changing material to increase strength is not preferable due to manufacturing costs, so most manufacturers rather adjust the cross-section shape and area [4]. Since the train travels on one side of the rails (in this thesis, trains run above the track), more material can only be added on the opposite side (below) i.e. spine to increase the mechanical properties – mainly second moment of area – while also ensuring that the cross-ties don't interfere with parts under the train during tighter concave radii of the layout.

Methods of improving the mechanical properties, i.e. shape of spine, vary between manufacturers. Figure 25 presents current common spine types by manufacturers; Intamin, Gerstlauer and MACK all use a variation of a 3-pipe truss track. B&M [49] uses a hollow steel box spine with varying dimensions and Vekoma uses single-spined 3-pipe track. Intamin recently developed a single/double spine track (shown also in Figure 31) to accommodate their new wing coaster trains $^{\text{(Skyrush – Hershey Park, Flying Aces – Ferrari World)}}$ and MACK has also developed a thicker spine to improve their 3-pipe track to allow longer spans (shown also in Figure 26).

As the track's cross-section becomes more complex, it also becomes more expensive to manufacture due to increased amount of material and welding. A spineless 2-pipe track with simple cross-ties is easy to manufacture, while a 3-pipe truss track takes a lot more material, preparing and welding to finish its multiple diagonals. MACK uses flattened ends on otherwise round diagonal rods (shown in Figure 26) in their 3-pipe truss. This makes preparing the welds easier while retaining the rods' tensile properties, but compression needs to be calculated separately because of this procedure's effects on buckling.

Choosing the track cross-section mostly comes down to favored calculation and manufacturing methods and hence cost savings, but it can also be affected by aesthetics, especially with guests and park representatives. It's also common to have special spines on brake runs, lift hills and other straight pieces of track. Because straight pieces don't have big dynamic loads, it's much easier to replace a truss spine with a simpler beam structure, also allowing more room for machinery between the rails (brake or lift equipment).

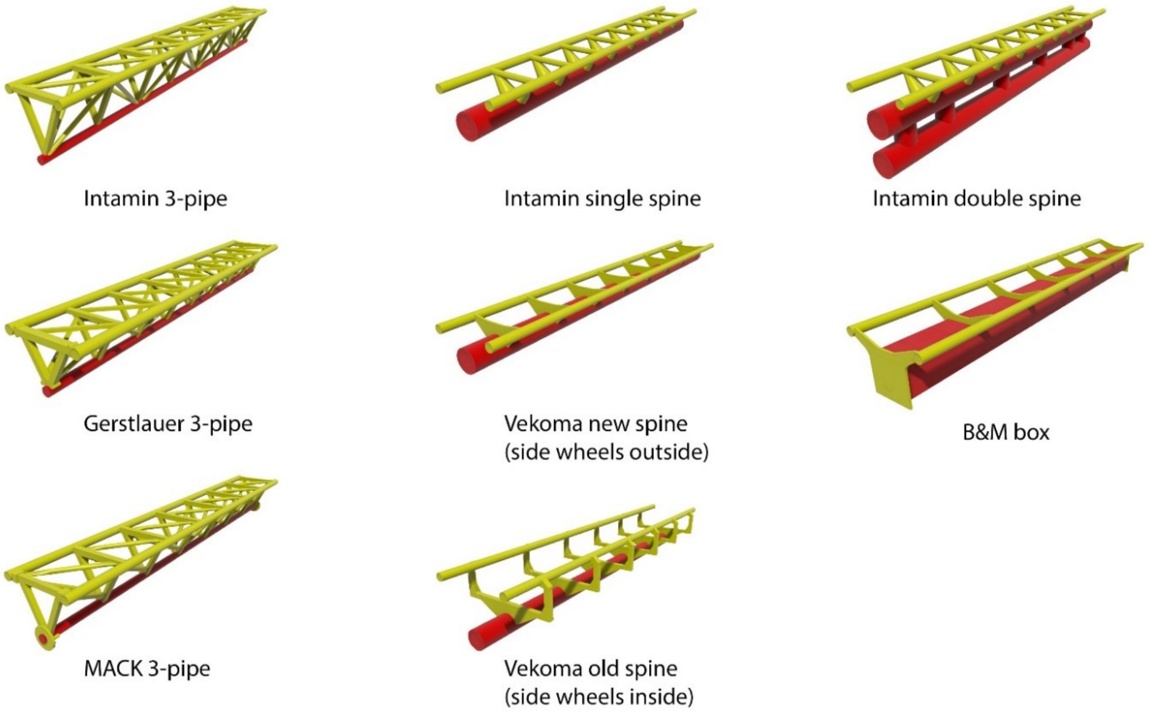


Figure 25: Common spine types by manufacturers

Figure 26: MACK flattened diagonal ends and thicker spine (background) [Fig. 17]
(DC Rivals HyperCoaster – Warner Bros. Movie World)

4.3 Supports

The loads caused by coasting trains are conveyed from the track substructure to supports via track connectors. Because the track is often shaped and banked in a way to eliminate lateral gs on riders, the track needs most supporting in a vertical direction in relation to the track. The g-limits presented in Table 1 also have the greatest extreme values in positive vertical direction. However, this local direction is rarely aligned with global axis (Earth's surface). Thus, the local load can be divided into global vertical and global horizontal load as presented in Figure 27.

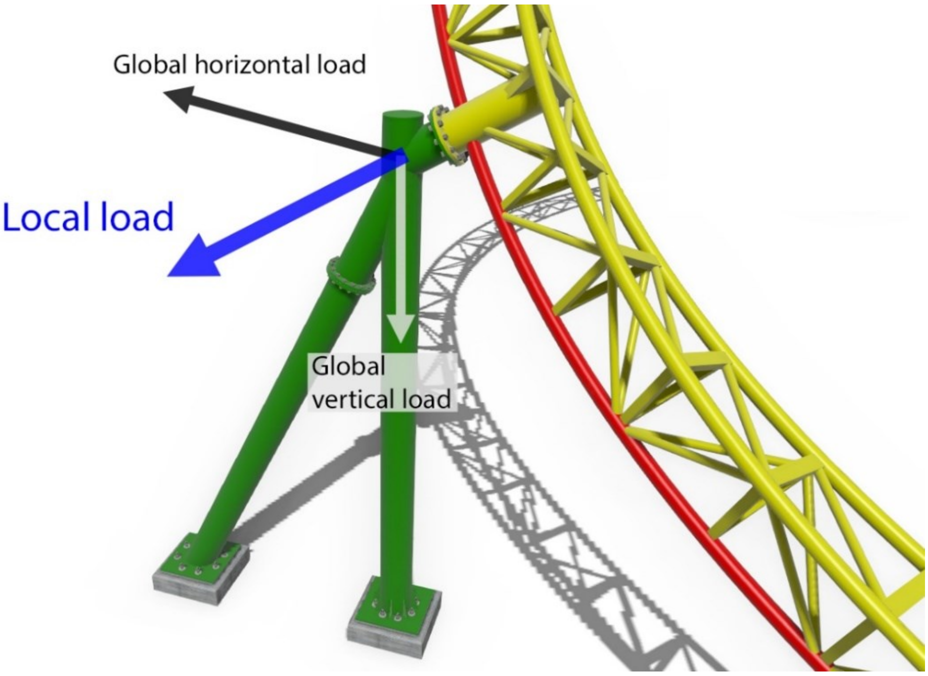


Figure 27: Local load divided into global components

At low heights, a simple vertical or slightly angled column is often enough to support both vertical and horizontal global loads. Slightly taller structures can use a simple A-frame with either one vertical and one angled support, or two angled supports. Depending on the loads, track and column rigidity, the A-frame may require additional bracing. Tallest structures may require changing the A-frame into a truss or another special structure. A truss can be in one plane or 3D. Figure 28 displays these common basic support structure shapes. Sometimes the support structure needs to avoid certain areas (e.g. paths, structures or other rides) and custom solutions are needed.

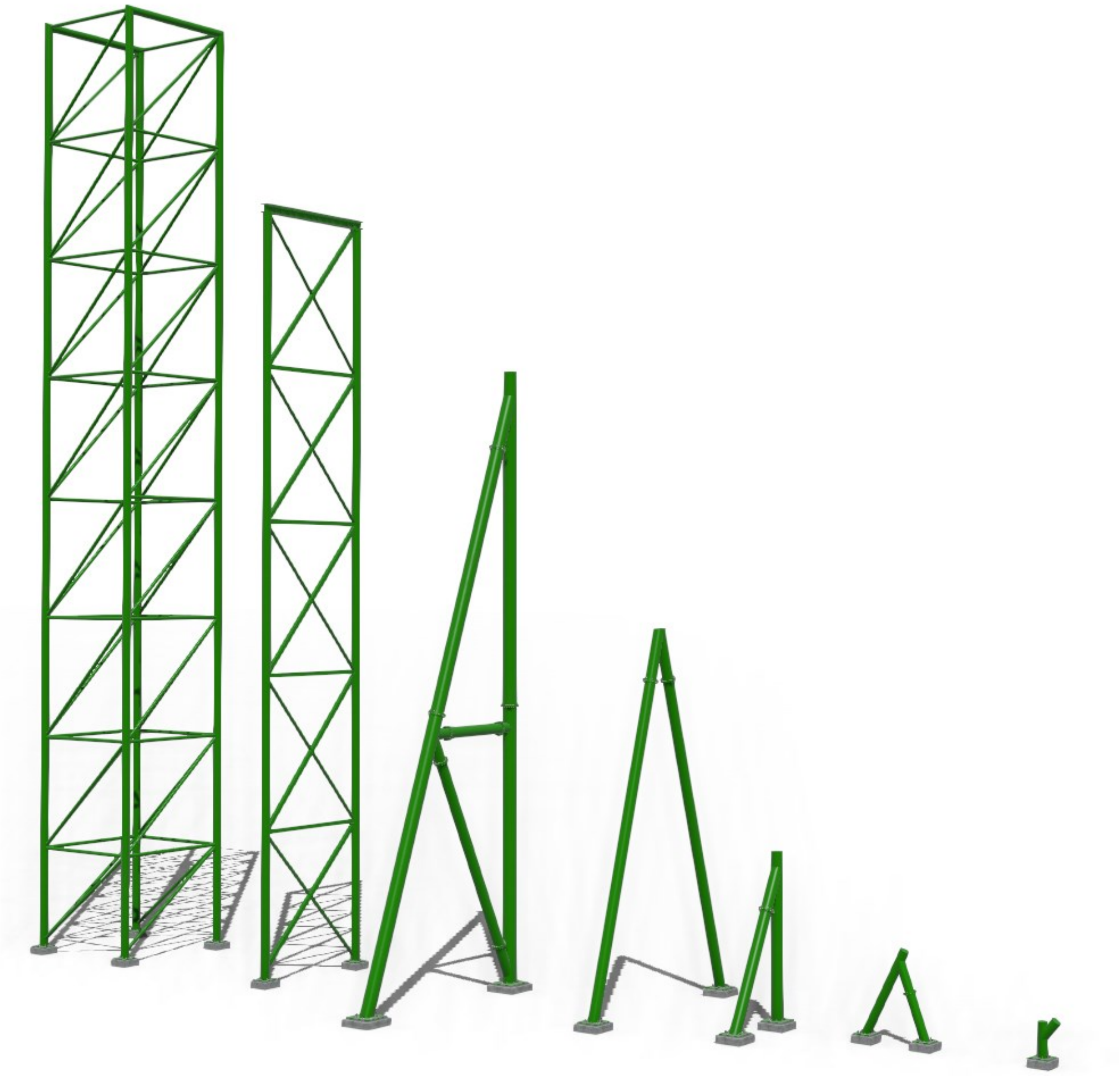


Figure 28: Common basic support structure shapes

The cross-section and shape of the support columns varies between manufacturers and third-party engineering companies. The most used shape is a round hollow steel tube (CHS) with miniature spiral wings to prevent vortex shedding and other unwanted dynamic phenomena. Round shape is easy to manufacture and as symmetrical it has certain structural benefits e.g. regarding buckling. Round column joints are most often welded, which makes them a bit more troublesome and expensive to manufacture. I- and H-profiles as well as box profiles that use bolted joints have also been used in several cases (iSpeed - Mirabilandia, Juvelen – Djurs Sommerland). Bolted joints are especially favored in traveling coasters that are constantly relocated and re-erected (Olympia Looping – Barth Schaustellerbetriebe).

The support design is a major factor cost-wise since it is very flexible and can be optimized very effectively with each project unlike trains or track cross-sections that are more complex to re-iterate multiple times. Adjusting the track cross-section affects directly the support span as mentioned before; simple supports are very cost efficient, even to the point when it's cheaper to have a spineless track and supports more frequently than having a track with spine and less supports. This can be especially efficient if the track only has pitch change since it doesn't need much lateral support or twisting rigidness. An example of this case is presented in Figure 29.

When designing coaster elements that are tall – e.g. over 30m – the cost of supports starts to grow almost exponentially [4]. While the local loads caused by the train remain inside the same g-limits, the rigidness and stability of the supports themselves becomes a major factor as the columns become longer. Simple mast stiffening may not be enough and additional bracing might be needed, even to the point of having a truss structure. Because of this, with especially tall support structures it is beneficial to connect the larger (truss) structure to simultaneously support multiple pieces of track.

The supports are connected to the track spine and/or cross-ties via bolted connections. These connection points are subjected to major shear loads, so they are often reinforced with additional material as shown in Figure 30. Connecting the support to both rails and spine adds rigidity to the joint.

Figure 29: Spined track and spineless track on the same coaster [Fig. 18] (Kawasemi – Tobu Zoo)

Figure 30: Support connections by Intamin (left) (Expedition GeForce – Holiday Park) and MACK (right) (Helix – Liseberg)

The increase in support material and column joint manufacturing cost with tall support structures can be reduced by improving the track cross-section, mainly spine, to enable longer spans and fewer supports. While making a complex track cross-section raises manufacturing costs, it can save money in reduced supports due to increased spans. Figure 31 presents an example of elongated spans with more rigid track; concave elements often have lower loads compared to convex elements, which makes it possible to use the arc shape to have the track support itself for a longer span. However, this (and any) unsupported segment is susceptible to sway caused by wind and lateral loads, which need to be considered. As stated in Chapter 4.1, the allowed sway is much higher than in most steel structures, but uncontrolled swaying may still affect both the structural integrity by adding fatigue load cycles and the riding experience by creating uncomfortable vibrations or even lateral gs. In the case of Lost Gravity – Walibi Holland, a small airtime hill in the layout is travelled at high speed creating strong ejector airtime. Negative vertical gs with a concave track shape were utilized in the original design to have a long unsupported span. However, quickly after initial test runs a visible sway on the track was noticed that continued oscillating even after the train had passed the element [50]. The oscillation was deemed harmful and additional support was added afterwards (see Figure 32). Because the track's movement became restricted, the lateral loads that initially caused the sway are now projected to riders as the track isn't able to absorb them anymore [51].

Figure 31: Rigid spine and concave shape allow long spans [Fig. 19] (Skyrush – Hersheypark)

Figure 32: Airtime hill without (left) [Fig. 20] and with added lateral support (right) [Fig. 21] (Lost Gravity – Walibi Holland)

4.3.1 Flanges

After the track and support designs have been finalized, flanges are added to divide the pieces for manufacturing and transportation purposes, either due to their length – up to 14 meters to fit on a standard flatbed truck – or 3D-geometry. These pieces are manufactured and welded indoors where the environment can be controlled much easier to reach the required quality of welds. It’s also much easier to use special rigs indoors that allow rotating the parts to gain access to all welding locations. The pieces are assembled on-site using bolted flange connections shown in Figures 33 and 34. Splicing the pieces with flanges also allows more flexibility in assembly order. With round support columns, the flanges are easier to add/manufacture perpendicularly into a straight column piece – this means the joints between beams and columns are welded and the flange is added at a distance from the joint. This also helps with assembling because the distance between the jointed column and flange is designed to fit tools in-between. Support flange connections have multiple bolts to make them more rigid and less vulnerable to failure caused by a single flawed bolt. By design choices and depending on the support structure, it may be possible to have a flange only transmitting axial force rather than shear force by choosing the flange location. Usually this is in portals or A-frames. Connections between two track pieces (Figure 34) have bolts near rails and, depending on the track cross-section, spine. Rails can only have bolted connections on one side due to their three running surfaces (see Figure 3), so they may also utilize additional male-female connections inside the rail tubes.

Figure 33: Flanges in supports with bolted connections (Hype – Särkänniemi)

Figure 34: Bolted connection between track pieces (Junker – Power Park)

4.4 Aesthetics

While having a functional structure is the top priority, parks may also value the aesthetics of a coaster, as it is iconic as a silhouette and can be used to draw crowds from distance. These aesthetics can include non-disruptive layout lines (e.g. first drop silhouette), or minimal support structures as supports are often considered visually unpleasant, unlike the track. A park/buyer may even favor or exclude manufacturers that use certain track profiles. Having less supports is usually considered better (it saves material costs as well) giving advantage to sturdier track cross-sections. However, a sturdier track often becomes more solid (see Figure 25) and thus prevent seeing through it, unlike a truss-track that is see-through. The support-span-track ratio can have visual similarities to bridges, but slender structures can also work in favor of increasing the feeling of insecurity and intensity.

4.5 Foundations

The foundations on a coaster are usually rectangular or round reinforced concrete footers that act as weight anchors [2 §5.5.2.1]. Supports and foundations have bolted interfaces: threaded rods are partially submerged inside the concrete in a pattern and columns have flanges with holes matching the pattern of the rods. Nuts are then used to tighten the column flange with the top level of concrete and grouting between them. The hole pattern usually has some extra gap for adjustments to help the assembly on-site, but with washers these gaps can be neutralized. These bolted connections withstand tension loads and bending moments and small I-beam sections in the bottom of each column (shown in Figure 35) inside the concrete withstand shear loads. Compression loads are conveyed automatically through contact between the flange and concrete/grouting. Reinforced concrete then transfers the loads into the soil/bedrock below. Ultimately the size and shape of a footer depend on the loads and soil conditions.

Figure 35: Shear force support beneath contact plate [Fig. 22] (Lost Gravity – Walibi Holland)

Because soil conditions and building regulations vary worldwide, the foundations are in most cases made by a local third-party company. For example, the ride manufacturer may provide the coaster until ‘bottom of steel’ and give the coordinates and loads for the required foundations as well as the support connection details. An engineering company then uses their local knowledge to design foundations that withstand the loads and fit the support counterparts. [3] [4]

Because pouring simple concrete structures (like footers) is generally cheaper than manufacturing complex supports, a coaster that has been previously designed to another location, can be re-adjusted to a new location with customized footers. This way the previously made drawings and calculations can be mostly used as they are without having to re-engineer the steel parts. An example of this is presented in Figure 36.

Another foundation method beside reinforced concrete is to have a horizontal steel structure laid on the ground, which connects multiple supports into a lattice (shown in Figure 37). This method is often used in traveling coasters as well as locations that don’t allow pouring concrete foundations like piers.

Figure 36: Custom concrete footers used in a copied layout [Fig. 23]
(Crazy Coaster – Loca Joy Holiday Theme Park)

Figure 37: Steel lattice used as foundations [Fig. 24] (Formule X – Drievliet Family Park)

4.6 External aspects

Coasters operating in extreme or fluctuating temperatures may require additional design methods. Thermal expansion causes stresses and deflections that can be countered with special spring-like rail pieces (Red Force – Ferrari Land) which lengthen or contract while trains can still pass over them. Cold operating temperatures present challenges especially due to increased friction from grease viscosity. This can be countered by having heaters under the maintenance bay or station area to warm up wheels and grease on trains or even upgrading the launch speed on a launch coaster (Taron – Phantasialand).

Some amusement parks operate in areas that have operational regulations for the park, like Alton Towers (Alton, UK) with noise and building height regulations due to nearby housing or Kolmården (Norrköping, Sweden) with noise regulations due to proximity of zoo animals. As a coaster train rolls along the track it can create an echoing, in some cases even "roaring" noise via the hollow rails, spine and supports. This noise can be reduced by filling the rails and supports with sound dampening material such as sand or gravel [3] [4]. The wheel material has also a big effect on this sound, as softer materials like polyurethane create less sound than harder ones like nylon. Some mechanical parts can also create loud sounds like the lift hill chain, motor and anti-rollback ratchet system. Silent anti-rollback systems have been recently developed that use either friction (Tulireki – Linnanmäki) or eddy currents (Wildfire – Kolmården) to reduce sounds; while the train is moving forwards, the anti-rollback mechanism remains in a position where it doesn't touch the ratcheting anti-rollback teeth shown in Figure 12. As soon as the train stops or starts moving backwards the anti-rollback mechanism engages. While the screaming of riders cannot be prevented, it can be muffled by building a wall or a tunnel around the reach envelope (Wicker Man – Alton Towers, Balder – Liseberg, Silver Star – Europa Park) as shown in Figure 38.

Figure 38: Noise protection wall added several years after opening [Fig. 25]
(Silver Star – Europa Park)

5 Making a Roller Coaster into a Ride Experience

A coaster is rarely just a steel structure of rails and supports etc. Depending on resources and desires of the park, there can be several other buildings/structures and functions that are connected to the ride: most coasters have a station building, a queue and a maintenance shed. While these can be very simple and unsophisticated, there is a possibility for added value in their design not only in guest experience and increased capacity, but in saved operation costs as well. For example, a coaster train without any shelter will suffer from weather during day and night, while a station and heated maintenance building provide cover not only during nights, but during off-season as well. Train maintenance is a key factor regarding the lifespan of a coaster and having sufficient maintenance areas helps not only by having the needed equipment available, but it can act as a motivational booster for maintenance staff as well. This chapter explores the design of station area, queue and theming both from guest and operator point of views. Virtual Reality (VR) coasters, a recent trend in the industry, and augmented reality (AR) in amusement parks are also discussed. Lastly, some aspects regarding investing in a new ride are presented. Figures 40 and 41 show examples, variations and some details included in station design that are discussed throughout this chapter.

5.1 Station design

Stations are used to get guests both on and off the ride. Station area design is a combination of effectiveness and safety; since there are a lot of people moving around, unwanted and unsafe areas need to be fenced off, but at the same time ride attendants need to be able to move around and communicate effortlessly. As the guests only spend a short time in the station area (and even then mostly distracted by the ride), the station floor plan needs to be simple and effective to enable smooth operations and traffic.

A coaster station is rarely at ground level due to required maintenance access and room for equipment below the station. Having a ramp rather than stairs leading to the station platform on at least one side (preferably on the exit side) is beneficial; not only is it more enjoyable to walk up/down a ramp than stairs, but it allows easier access for disabled customers and freight transportation. For guest access the slope must not be greater than 1 in 6 (= 9,5°) according to Eurocode [2 §6.1.3.2] but local legislations may also have additional conditions.

5.1.1 Design from riders' point of view

Station design from riders' point of view focuses on simplicity and comfort. For example, showing the station area before guests need to board the train can speed up the loading and unloading process, since the queueing guests can assess the station area beforehand and learn what they are expected to do by watching the previous riders' actions [41 p.481].

Before boarding the train, guests are most often held behind closed gates until a train is in the correct loading position to prevent collision with the moving train. These gates can vary from a simple rope at the end of the queue to splitting into specific smaller queue gates for each row (Figure 40) and even to large show-doors (Schwur des Kärnan – Hansa Park). With designated queue gates for each row in the station guests can choose their seats in advance. While it can enhance the guest experience by giving them the freedom of choice, it often leads to differences in row popularity, especially regarding the first and last rows. Placing the end of the queue to the back or middle of the station enables the queue for the first row to be longer without blocking other rows. Having exit at the front of the station enables the guests to see the exit before stepping out of the train, and thus save a little time when guests don't need to search for the exit. When the train is being loaded or unloaded, riders should be prevented access to wandering off the station area alongside the track, especially when the station platform is elevated, to prevent accidents.

In station areas the track creates a gap in the station floor, especially when a train is not present. These edges are often highlighted as they are a falling and tripping hazard, especially if there is a height difference between the station floor and train floor. A recent trend in train and station design is to take this into account as a part of guest experience and safety; newer train designs are more open and have unobstructed floors that are level with the station floor as shown in Figure 39, and riders need to only take a small step to board or exit the train (Helix – Liseberg, Taron – Phantasialand). These open train designs also affect the restraint checking; with these kinds of trains the ride attendants can simply walk along the platform and ergonomically push the restraints down to waist height while standing upright instead of crouching or reaching.

Figure 39: Open train design with floor level matching the station's floor (Helix – Liseberg)

While a train is moving in the station area it's possible for riders to extend their arms or feet outside the train. Thus, the reach envelope (Figure 7) applies in the station area just like everywhere else, affecting especially the placement of queue gates, walls and staff locations in the station area. This clear area required by the envelope also gives the attendants some room to walk beside the train while checking restraints.

Guests often have loose items with them including backbags, handbags, cell phones, wallets etc. Loose item policy regarding rides can be divided into five main categories: no loose items allowed on the ride at all even in the queue, all loose items need to be taken onto the ride, a cloakroom with staff in the queue, one-sided storages in station and two-sided storages either in or before station. One-sided storage means a shelf where guests input and output their items from the same side, and two-sided means the input and output happen on opposite sides. Both one-sided and two-sided shelves can have doors to allow access only to certain shelves, most often assigned to one train at a time. Two-sided shelves allow guests to pass through more quickly and not gather on the station unload area thus blocking the next guests from accessing the storage, but they require more space and spatial planning. When designing a station (or multiple stations) with separate load and unload positions, the method and location of loose item storages should be considered to enable smooth flow of people.

5.1.2 Design from operations' point of view

Station design from operations' point of view focuses on efficiency and capacity. The actual capacity of a ride decreases if a train can't be dispatched when the designed dispatch time has been reached. The delays caused by slow guest or staff actions should be minimized through effective station design.

The theoretical capacity can be increased by utilizing a 'flush station' design and/or multiple stations. A flush station has load and unload on opposite sides of the train. This increases slightly the capacity as the loading (i.e. opening the queue gates) can begin before the station area is completely empty, unlike with stations that have load and unload on the same side. Multiple stations can be used to simultaneously load more than one train or have the load and unload positions separated. These designs vary from two consecutive trains on the station (Maverick – Cedar Point) to branching tracks that use a switch to distribute incoming trains to available parallel stations (Tatsu – Six Flags Magic Mountain, Storm Runner – Hersheypark) and even their combination (TRON Lightcycle Power Run – Shanhgai Disneyland). Examples of these variations are presented in Figure 40. The width of the exit path also plays a role in efficiency; if the exit path is very narrow or otherwise slowly navigated, it can create congestion in the station platform area thus stalling the load/unload procedures, and sometimes even blocking the staff movement. It is also noted, that multiple and more complex stations that require more staff to operate naturally also increase operating costs due to larger number of hired people.

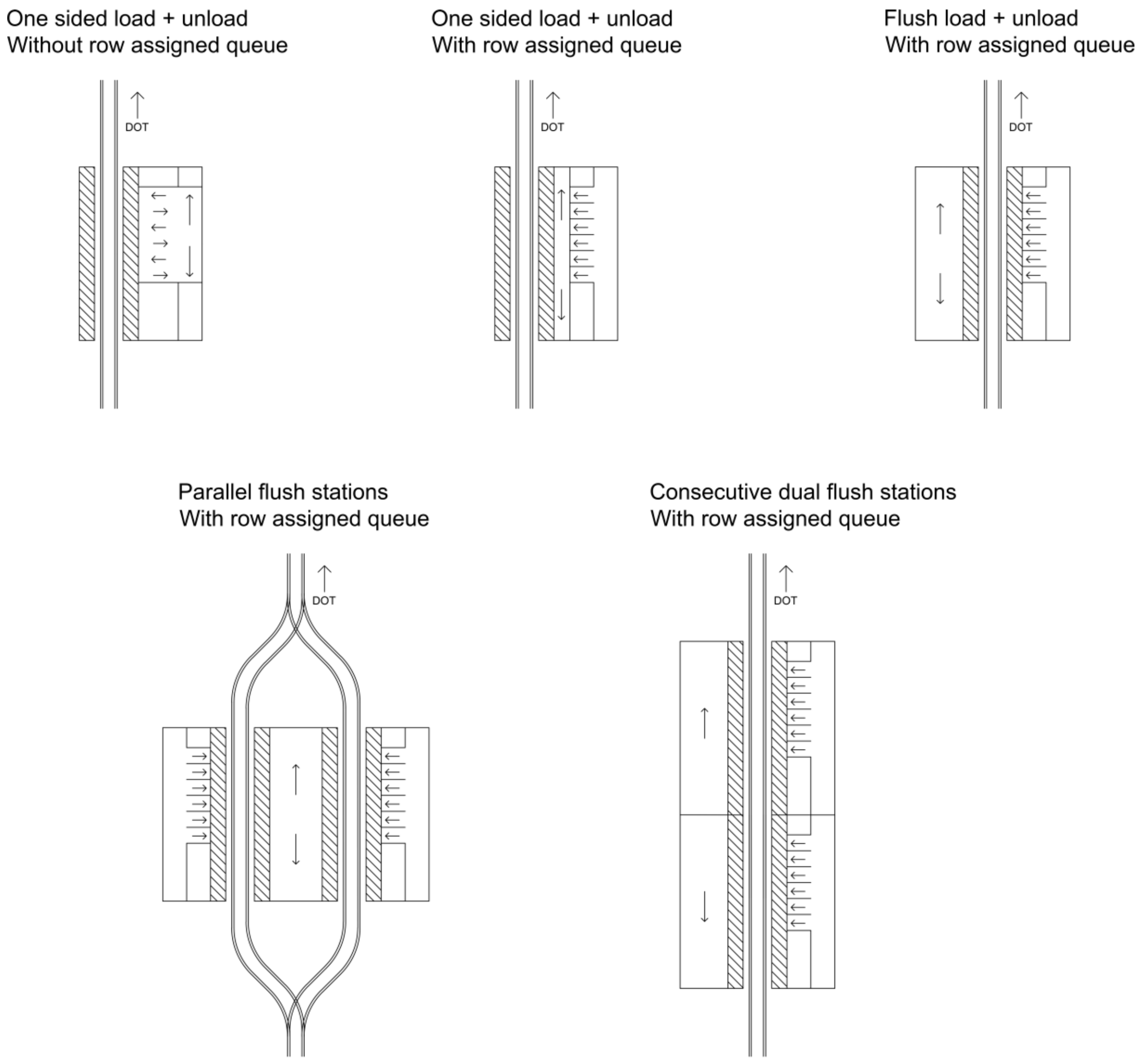


Figure 40: Station type variations

Some coasters have multiple control panels in the station area and require more than one panels simultaneously having a button pressed down to dispatch a train. This is common especially with bigger coasters that have more riders per train. The aim of having multiple panels is to ensure that the train is safe to dispatch by having more staff on the station area for surveillance. These safety conditions include, for example, having all guests seated properly and their restraints checked, ensuring the station area is free of obstacles and people, and the next block in the layout is free allowing the train to advance through the course [2 §7.5]. The location of all control panels required for normal operation should be considered in the design of the station area, since they are also the locations for staff during dispatching [2 §6.4.2.5.1]. The main control panel should have a line of sight over the whole train in load area and the other control panels. Thus, it’s often placed in a raised and isolated booth (also referred as control booth or operator booth) nearby the station to enable easy communication with the ride attendants in the station area without headsets etc. Unauthorized access to the operator booth should be prevented by keeping it securely locked during non-operation hours [2 §7.4.7.5]. The subordinate panels are often placed on the opposite side of the coaster track in relation to the main panel to ensure more visual coverage on the train and station area. A clear line of sight should also be provided between all panels. While all panels should be located outside the reach envelope there should still be a method of protecting the staff from the moving trains by either having enough distance or placing a barrier (e.g. railing, window or electrically monitored gate) between them and the train. All staff positions should also be adequately illuminated [2 §6.4.2.5.1].

Fire safety is regulated by local authorities. Exits and exit routes must be wide enough to provide safe escape for the designed amount of people in the station area at all times. Thus, the number of people in the station area may be controlled or limited during operation. In enclosed structures, emergency lighting needs to be considered to illuminate exit routes, staircases, changes in level and signs. Doors and obstacles should not be locked or fastened in a way that they cannot be easily and immediately opened form the inside. [2 §7.8.4.1]

5.1.3 Ride operators and attendants

Ride operators and attendants are staff trained to safely operate the coaster including loading, unloading and checking passenger restrictions such as height and weight limits or medical conditions. They also know procedures for breakdowns, defects or unusual occurrences and cases of emergency stop. [2 §7.4.3.3].

The ride operators' and attendants' main tasks in station area during normal operations are to prepare the right number of guests for boarding the next train (batching), load the train and check safety restraints, dispatch the loaded train, advance the following train back to the station for unloading, and finally guide guests to the exit. With a single operator, these tasks are simply performed one at a time, but with multiple operators their role, placement and communication becomes more important. Communication with speech is usually enhanced with hand gestures and if necessary, with headsets.

In case of multiple operators, usually one of them is placed in the control booth at all times (ride operator) while others work more closely with guests in the station area (attendant). The ride operator should have an overview on the whole ride either visually or with CCTV, and if the main control panel is located in the control booth, they have most control over the ride. While the operator rarely interacts directly with guests (excluding announcements via speakers), the attendants in the station area do it constantly. Their task is to load and unload guests into and off the train and then enable dispatching with subordinate operating panels.

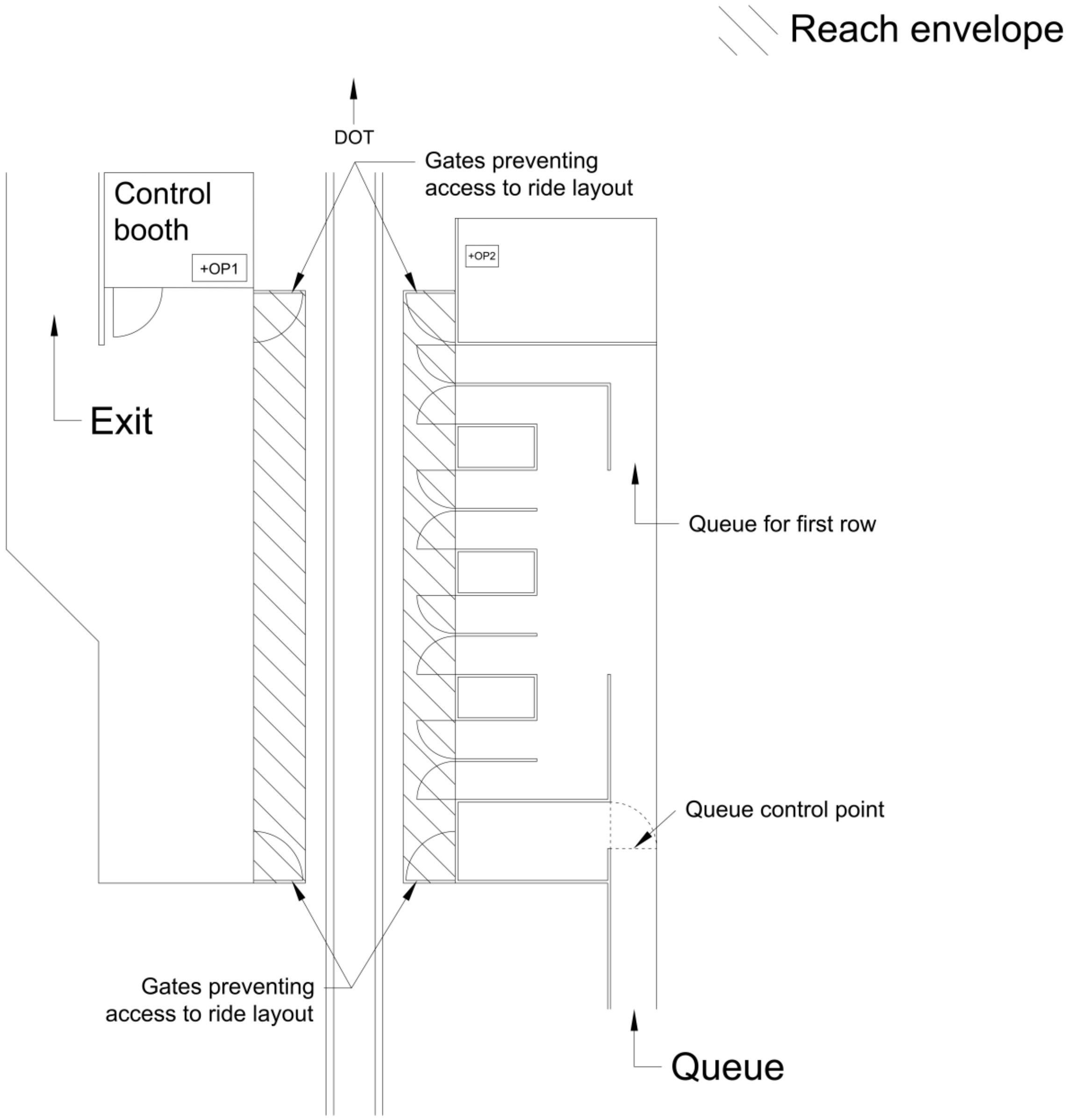


Figure 41: Example station layout with row assigned queue gates

Due to the nature of their job, ride attendants are constantly walking nearby hazardous areas, and thus a detailed risk assessment of safe working procedures for staff should be assessed in the station design [2 §6.4.2.5.1]. Biggest risks in the station area are to get overrun by the moving train or get stuck between the train and platform.

Station design from ride operators' and attendant's point of view include not only safety, but work satisfaction as well. A station with multiple operators can switch and rotate the staff to include variance and thus help with monotony. Giving capacity incentives or demands can increase the actual capacity of the coaster, but it's benefits can be debatable; the ride attendants are a key factor as they are responsible for each restraint to be checked properly and rushing that could open up a window for catastrophic mistakes.

5.2 Queue design

Because the capacity of a coaster is usually more than the number of people wanting to ride it simultaneously, there is a specific area for the customers to wait for their turn called queue. The station can also be located quite far from the closest park path due to various reasons (such as maintenance access), so the queue also works as an approach without the need to be a wide path since the traffic is one-way only. It's also the purpose of a queue to prevent congestion in other park paths by directing people to these queue areas. While the width of the queue can vary, it's advisable to have it wide enough to allow two people passing each other comfortably, but not too wide to cause problems with guests' placement or accidental cutting in line. [41]

The start of a queue located by a park path should be clearly marked and preferably close to visible elements of the ride to prevent guests from accidentally entering wrong queues and thus wasting their time. If the ride itself is not visible, a sign or another method of cuing the ride's nature should be displayed. [41]. The queue can be outdoor, indoor or mix of both. Outdoor queues often have shades or roofing to provide cover for both sun and rain thus improving the guest experience. A cover for falling items may even be required if the queue travels under the ride itself. Indoor areas have the same safety regulations as any buildings that are used for housing people; for example, the width and number of exits in case of a fire is stated by local authorities. Because the number of people in queue buildings is often very high, these regulations can create great demands for the building. Indoor areas also require ventilation and lighting, which raise not only building costs but the operation costs as well.

Another safety factor that should be considered in queue design is crowd control. With multiple, perhaps unhappy and queue fatigued people crammed in a tight space, the possibility of a disturbance requiring security intervention grows larger. Thus, the queue area should be observable and preferably also accessible for staff to prevent and remove obtrusive guests.

Total length and thus capacity of the queue is a key design problem: too much queue results in wasted space and building costs, but too little and the line of people spills into the park paths. Many queues have gates that can be used to create shortcuts, so on low-attendance days the walking distance to the station is shorter. While this doesn't really affect the building costs, it still affects the guest experience and thus adding these shortcut possibilities should be considered in the queue design.

Due to the nature of the queue, it's subjected to high pedestrian wear and tear. Not only are numerous guests walking on the paths and touching all the railings, they are also touching and reaching even into things they shouldn't, just to help them fight boredom and pass time. This emphasizes not only the placement of additional objects around the queue, but their material selection as well. While more durable materials can have bigger purchase prices, they might require less upkeep and maintenance during the ride's operation lifetime. An unkempt queue area can discourage guests from entering the queue and lower their perception of quality thus having negative effects on the park's image.

Waiting in line is often considered boring, especially when the waiting times can exceed 2 hours. To help with this, many parks have added some enjoyment to the queue areas, like physical theming props, music, video screens etc. (theming is further discussed in Chapter 5.3). Some guests are prepared to pay more to reduce the waiting time and parks have adopted various means to do this; there can be special tickets allowing either limited or unlimited re-rides per day through a shorter, separate queue or a certain return time allotted to the rider when they can skip the regular queue. Virtual queues that use devices like Q-bots [52] create a virtual version of the guest, allowing them to "virtually" wait for a ride while they are physically free to do something else – even visit other rides. Single rider queues can also be utilized to fill every seat on each train. If a special queue method is used, it should be separate from the regular queue area and have a staff member at its entrance or merge point to prevent misuse.

5.3 Theming

While a coaster is usually enough to attract more crowds by itself, the guest experience can be enhanced by creating a more immersive and thematic experience around the ride by adding symbolic and narrative elements throughout the guest route. Methods of presenting these vary from physical and/or interactive sets to lights, sound, special effects and even virtual reality. When successful, the guests are immersed in a created fantasy world, which is what people sometimes seek via escapism by visiting an amusement park [41].

Ultimately, it's the goal for a park to have as many guests to ride a coaster as many times as possible during its lifespan. Having high re-rideability makes a ride stay popular after its first years, keeping guests coming back to the park year after year and thus creating revenue. High re-rideability not only requires smooth and enjoyable ride from mechanical perspective (gs, vibrations, seats, restraints etc.) but from a thematic perspective as well. In the best-case scenario, an interesting theme or concept has guests discovering new details after each ride making them want to ride again. Also having a ride experience that is not always the same (e.g. spinning cars) keeps the experience from coming stale. Interactive elements have also been introduced especially in dark rides to increase re-rideability [53] [54].

Other reasons for theming a coaster include differentiation, perception of quality, targeting specific audiences, increasing secondary spending and decreasing queue fatigue. Differentiation via theming allows parks to buy copies of existing rides but via theming make them seem unique. Adding theming and making the coaster aesthetically pleasing increases the perception of quality and attracts guests to spend their money. Themed rides often draw more crowds due to their storytelling nature and choosing a specific theme can attract guests, who wouldn't ride the same ride unthemed. Merchandise and food options with the ride theme (e.g. ride logo/name on a t-shirt) can be utilized to create additional revenue from the ride. Often the ride exit in major rides leads directly to a shop to encourage purchase. Having themed environments and scenes along queue decrease the perceived length of time spent queueing, which helps keep guests happy during the most mundane part of riding a coaster. [41 p.5]

Creating a theme for a ride can be a demanding task but using an existing Intellectual Property (IP) guests can be attracted more easily due to their popularity (Universal Studios, Disney etc.). Familiar IP can make a new ride more marketable since it can attract guests that are more familiar and interested in the IP than the bare ride itself. An existing IP also gives a bit of freedom in creating the story elements during the ride, since designers can expect the riders to have some knowledge of the story already and don't need to explain every detail. However, using an existing IP can be criticized for lack of originality and feel "shoehorned into an inappropriate setting, especially if done with low quality". [41 p.64]. License expiration can also cause problems forcing a re-theming. For example, Terminator Salvation: The Ride at Six Flags Magic Mountain opened in 2009 but was re-named and re-themed as Apocalypse the Ride in 2011, continuing operation without the Terminator-movie IP.

Storytelling-wise queue theming methods and scopes include: receding (guests are gradually immersed in the new story-world through a slow transitioning), suggestion (duration of time spent in queue allows story element suggestion to enhance the experience), previewing (story element is shown and revealed to guests as they progress through the attraction), spectatorship (seeing the attraction and its riders having fun from new angles to prepare the guests for the ride – also beneficial in station design) and interactive elements. [41 p.475]. The queue can also include one or multiple pre-shows, which can be used for storytelling.

Besides the queue, theming elements can be added on the ride itself. Often the trains have at least a color or a paintjob matching the ride's theme, but they can even have custom shaped body elements on the front, side and back of the train, as shown in Figure 42. The station or other parts in the beginning of the layout can have show-elements, which will play after riders are seated and the train has been dispatched. This method of beginning the ride with a spectacle can raise the excitement and expectations of the riders to heighten their ride experience. The layout may also have other scenes during the ride both in gravity run and transport sections and they can utilize sensors that trigger events when a train is detected. Scenes during the layout can also utilize show doors or other obstacles that block the view of the track ahead and wait for a dramatic reveal. Dark sections in the layout where the track can't be seen increase intensity since the riders can't prepare themselves for the coming curves ahead. Trains can also have onboard audio i.e. built-in speakers (Hollywood Rip, Ride, Rockit – Universal Studios Florida, X2 – Six Flags Magic Mountain).

Themed elements are not the only way of adding thrill on a coaster; all close-call objects either above ("head choppers") or next to the track – including the ride and its supports – increase the feel of speed and danger. While these objects are outside the reach envelope (Figure 7), they appear to be close enough to hit the riders adding a precarious feeling to the ride experience. These objects close to the track have a great angular displacement from the riders' perspective, which makes it difficult for the eye to follow and brain interprets this rapid movement as faster motion. At a certain speed the eye can no longer move fast enough, and the objects become blurred. [55].

Figure 42: Themed train and zero-car [Fig. 3] (Taron – Phantasialand)

5.4 Digitalization in Amusement Parks

Digitalization in amusement parks can be done to improve the guest experience, attract guests with new technology and even gather research data about guest actions during their visit. Common examples of digitalization include virtual and augmented realities both on-ride and offride, and special wristbands.

5.4.1 Virtual Reality Coasters and Augmented Reality

Since its debut in 2015 (Alpenexpress Enzian – Europa Park), adding Virtual Reality (VR) -technology on a coaster has been implemented on (at least) 35 coasters [56]. This means the riders wear a VR-headset display onboard that replaces their visual field of the real world with a virtual one. The headsets have built-in accelerometers to match the viewed media with the rotation of guests' heads and thus enhance immersion – hence the term "virtual reality". The most popular VR-technology used at the moment is Samsung Gear VR, which uses smartphones installed inside a headset. The VR-content/environment is stored in the phone's memory and displayed to each eye of the rider through lenses to provide a 3D-effect [57] [58]. The ride layout is integrated into the content to mimic the movements of the train, but its dimensions can be manipulated to create a greater sense of movement and exceed spatial limitations.

To synchronize the movement of the train and the VR-content, a load wheel on the coaster train is equipped with a speedometer (e.g. a pulse sensor) to adjust the timing. As the train is rolling along the track, speed (and thus location) data is transferred to an emitter on the train and wirelessly further to all headsets [57]. This way the presented VR-content matches the movements of the train better, as the coaster's speed can vary with each run. This also separates the virtual reality from a 3D-movie. To further enhance immersion and reduce nausea, each display's position in the train (car/row) can be adjusted to better match the car's position and movements – this is especially helpful in coasters with long trains, where gs and sensations of movement can have great differences depending where the rider sits on the train. [3]

The sought profit from adding VR into an existing coaster is usually a boost in attendance and a possibility of an enhanced, very immersive rider experience. Linnunrata Xtra at Linnanmäki opened with VR in 2016 and the park immediately received numerous positive reviews [3]. There's also a possibility of added revenue if the VR-experience costs extra. Most of the VR implementations so far (including Linnunrata Xtra) have been made on family-sized coasters that are more than ten years old and had started to lose some popularity due to their low-thrilling nature and age.

Since its introduction, some challenges of this rather rapidly adapted new technology have also emerged; the capacity of every VR coaster has decreased even to less than 100 pph due to elongated dispatch times: riders have problems wearing and adjusting the headsets and a staff member is often required to assist each rider individually. Staff is also needed to clean the headsets after each use as they touch directly the guests' faces. [3]. Wireless headsets have also some other weak points: they have batteries that need recharging and the software can malfunction. Riders can either accidentally or purposefully vandalize the headsets by dropping or stealing them. A broken or missing headset needs to be replaced so there must be extra headsets available and their price can be quite high due to required technology. A modular headset would help with wear and tear allowing each part to be replaced separately to reduce spare part costs. Like everything in an amusement park, the VR-headsets are subjected to high wear and tear with thousands of cycles daily and as many riders using them. The headsets can also suffer greatly from exposure to weather and some rides only run the VR experience when it's not raining. A huge safety factor is that the headsets can – either accidentally or on purpose – fall from the ride. They weigh several kilos, and as the tallest operating VR coaster at the moment is more than 60m tall (Big Apple Coaster – New York, New York Hotel & Casino), a falling object presents a major safety risk. Multiple rides (Kraken – SeaWorld Orlando, Shaman – Gardaland et al.) have already removed the VR from operation due to issues regarding operation, negative effects on capacity and staff costs.

Because the VR headset completely replaces the visual field it can induce nausea in some riders and even unintentional bruising as the riders may be unable to prepare for any quick turns in the coaster layout. Thus, the VR-experience is best used in a low intensity rides (e.g. powered coasters) and perhaps with the VR content showing the rough ride layout to give riders some ability to prepare for changes in direction. The hardware benefits if the ride is indoors in a secluded area to prevent weathering and falling equipment harming anyone.

Replacing Virtual Reality in Coasters with Augmented Reality (AR) could greatly reduce motion sickness during the ride, since the riders would be able to see real environment. It would also allow riders to interact with each other better since they could sustain visual connection. Even though VR and its current gear doesn't restrict talking, the experience can still feel a bit secluded and detached from other riders. Because AR requires electrical equipment to display virtual content (optic screens or video screens [59]), arranging it for a coaster would be possible in a similar manner as VR is currently done. However, aligning the virtual content with real environment requires a lot of fast computational processing to sustain the immersion, and the coaster trains' movements and possible high speeds with riders' head movements provide challenges for the hardware to be light and powerful while remaining economic.

One method of AR is already widely used in themed attractions with a technique called projection mapping. In projection mapping an existing, often 3D surface is used as a projected video screen, giving possibilities e.g. for illusions of movement. The shape of an object is spatially mapped with a software, which is then used to fit the video material to match the 3D shape of the object. [41 p. 531]. This projection method could also be utilized with interactive elements without the need for additional viewing devices. Other uses of AR (especially displaying virtual 3D objects) in the park would need either large stationary screens, mobile devices that can be borrowed or rented from the park, or the use of guests' smartphones and downloadable applications. One way to integrate AR technology in amusement parks could be to use smart phones as video screens to display the virtual content using tags placed in the park environment.

5.4.2 Special Wristbands

In 2013, Walt Disney World (USA) implemented MyMagic+ system which combines several guest service functions with wearable technology and mobile applications to enhance the guests' visit at the theme park. This wearable technology, called MagicBands, is wristbands that can be used as keys and tickets as well as to collect memorabilia photographs and activate other interactive showpieces inside the amusement park. The interface doesn't require any plugs etc. due to RFID technology, which makes their use very simple and durable: a ring light around the RFID scan area will emit a color for a successful/unsuccessful transaction. A staff member is also placed nearby to help with problem situations and prevent misuse. While the guest is wearing their MagicBand, data about their visit is gathered to benefit both the guest and the park. The park gets valuable data for analyzing guest behavior patterns during their visit, which can be used to create more revenue in form of targeted marketing and adjust/improve existing services. The guest gets the feeling of a personalized amusement park experience when long-range scanners read their wristbands and enable them to automatically receive onride photos, see personalized advertisements and even receive tailored services such as food served at table without additional requests. [60] [61]. This type of RFID wristband payment system has also been implemented in numerous other instances around the world such as waterparks (e.g. TapuTapu™ system in Universal's Volcano Bay [62]) and festivals.

Disney is not the only park to utilize special wristbands. Barcode, QR-code and RFID wristbands (or other tickets) can act as the tickets required to get onboard the rides, in which case their validity is usually checked at every ride entrance. This scan system can be utilized to gather visitor data similar to Disney, but the lack of long-range scanners prevents as effective targeted marketing, as the guest needs to purposefully scan the wristband to have any effects, unlike at Disney World.

5.5 Investing in a Ride and Future of Amusement Parks

To remain competitive with other types of entertainment, amusement parks need to constantly evolve and improve, but because of the limited space amusement parks often have, they need to maximize their utilization of physical space [63]. In the future, more parks will probably adapt to adding rides that are integrated with other existing rides to allow more rides being built. As more rides and buildings are eventually added, layout designers will face more spatial limitations but with modern 3D-environment scanning and CAD-modeling, more effective solutions and functioning layouts can be found [3]. With limited space, the most effective solutions become even more valuable and desirable, causing the need for designers to further improve their designs and skills.

When designing new rides, re-rideability is a major key factor. If no-one wants to ride several years after a ride has been built, it could be considered a loss. A ride should remain popular throughout its lifespan to be deemed profitable and cover its maintenance costs. This is also why amusement parks should invest in future-proof concepts that are not quickly outdated during following years, making the original investment redundant. This aspect applies especially to consumer electronics, where new technologies are commercialized constantly. Although each new technology becomes stale and timed at the moment it is released, a study made in 2016 [63] with several industry people suggested that Augmented Reality has huge future potential in amusement parks. [63]

Investing in a new multi-million ride is always a risk, as its effect on attendance cannot be exactly predicted. To have a positive effect on attendance, an amusement park should provide experiences that cannot be achieved anywhere else, especially at home [63]. This is why massive roller coaster structures are not usually found in backyards, but mainly in amusement parks. Though some individuals could have enough finances to build a coaster, maintaining a ride takes a lot more than just money. Building a coaster is an investment not only in money but in time and effort as well to keep it running.

Amusement parks attract more guests mostly by buying new rides from manufacturers. The seasonal nature of amusement park opening times favor relatively short construction periods, but with ever longer and even year-round operations and bigger construction projects becoming more common, the need for proper scheduling grows. If a park is open while there is also a construction site, it needs to be safely secluded from the open areas that guests can access. This is when BIM could be utilized to visualize the time span during construction. Further implications of BIM may also include the maintenance of rides. Though some parks remain open even during winter, these parks still have low and high attendance days, enabling them to plan and rotate the maintenance of rides.

Building new rides sometimes means an existing ride needs to be removed. Reasons for removal can include low popularity, high maintenance costs, high wear or even loss of structural integrity. Rides can also be relocated or sold to other parks. Renewing via removing rides is very common, and while removing popular rides may have a short-time negative effect on public opinion, the removal can also be used to boost attendance to encourage guests to come ride it before it is removed.

Amusement parks as environment also have their unique features since they need to highlight safety even more than usual. Everything guests normally do during a park visit can be held responsible by the park, and the emphasis on safety is particularly high with rides, since they usually have motions that are otherwise not included in normal human life, like falling.

6 Discussion

During the last decades amusement parks have thrived and the industry has been growing steadily with no slowing in sight. Due to more people having access to healthy and safe life, the need for amusement has grown, increasing the number of existing parks and rides. The amusement industry has benefitted from the advance of technology not only making rides safer and better designed, but also making the ride experiences more sophisticated. Some concepts used in roller coaster design can be improved and are more essential for layout design, while others are already rather optimized and don't have immediate need for research and improvement, or don't affect layout design directly. This chapter analyzes development potential for each concept previously presented in this thesis, which are summarized in Table 2, as well as their effects to layout design. Lastly, a very general proposed order of actions to minimize the number of iteration cycles for designing a roller coaster is presented.

The bogie system has been widely accepted and has been a standard approach due to its reliability and efficiency, and almost no innovations or alternative concepts have been researched after its popularization. Because of the nature of roller coasters, the trains are rolling on a track rather than sliding and using wheels provides a smooth and more durable method of traveling along the track. The bogie design very little affects the layout design as it only requires a small reach envelope applied around the rails.

Train design and especially seating configuration are constantly going through new innovations and re-iterations as they directly affect the ride experience. New seating configurations can also be used in marketing as well, especially if they offer new sensations. Not all experiments are flawless though, and only successful designs are continued. The most popular seating type through time, sit-down, is the most used seating type even today as it has multiple benefits and it can be easily designed and optimized regarding material use, manufacturing, operations and maintenance. The train type greatly affects the track design, as the heartline is defined by the rider chest position, along with the width of the train impacting the maximum allowed roll rate.

Related to the seating configuration, rider safety restraint has a big role in rider comfort during the ride. Obtrusive restraints can not only limit the rider perspective, but even cause physical pain in extreme cases. However, riders need to be safely secured during the ride, which proposes continuous research to improve the restraint design to not only have comfort but safety as well, while still enabling all shapes and sizes of people to ride. Not allowing riders onboard due to their physical appearance can be considered extremely exclusive (even if it is done to promote safety) which is the opposite of what amusement parks try to achieve. The recent trend of having only a lapbar quickly became a new competition tool which also relates to the growing demand of rider comfort. While the shapes and materials of restraints keep evolving, so do the mechanisms that hold the restraints closed. The restraint design may limit the layout to exclude inversions or other extreme maneuvers especially in family rides, but in extreme coasters the restraint itself is not limiting the layout design, as it can hold the riders secured during any movements.

Reach envelope is not a concept that could have much development but is rather a constant due to its key role in the design phase. Transport devices and brakes on the other hand can be nearly infinitely improved regarding their effectiveness, power usage and reliability. Most of the current low-speed propulsion methods favor friction-based devices due to their simplicity and power efficiency, but as technology advances are made, they may get replaced with other technology. Regarding brakes the key factor is reliability, which is why magnetic brakes were developed and have been popular ever since. Every new propulsion and braking method still needs to have a back-up solution to safely evacuate the train, and the development could be aimed towards safer and reliable methods that are also easy to manufacture and maintain.

Block systems are controlled by computers which have vastly improved in computing power but because the monitored reality (rolling trains) can have a lot of variety, time buffers need to remain in the system which prevent infinite optimizations. However, the software can be made more sophisticated, reliable and easy to use, and even include functions to improve maintenance and troubleshooting [3].

Daily operations in amusement parks have a lot of variance and differences. While manufacturers state their requirements for the rides' daily operations and maintenance, there can still be a lot of different methods to operate a coaster even inside a single park. While manufacturers need to follow regulations in design and operation manuals to improve the safety of the rides, the human part in daily operations may still remain uncontrolled. The industry has had multiple design innovations regarding the safety in terms of engineering and design – most of which have been standardized – but a common frame for operations is still lacking. To prevent accidents caused by human errors, a global system resembling driver's license could be developed. For example, much like with a driver's license and multiple car manufacturers which have unified signal equipment, the amusement industry has already very similar operating panels throughout all ride manufacturers and the ride attendants' positions during dispatches are also already considered in station design, so the step wouldn't probably need to be that big to unify panels and their locations via a standard. The actions of ride attendants could be unified to include similar maneuvers throughout all rides to include all necessary safety functions. Because the role of ride attendants checking the restrains is important, having a standard to use during training could reduce the amount of accidents caused by human error related to restraint checking before dispatching. Most parks already utilize a test or proof of capability for staff regarding ride operations, but an official standard could improve the quality of training and workmanship, especially in problematic and unclear situations. However, the biggest implementation would probably be to control that the standard would be implemented in all amusement parks. The governing officials would probably need to be IAAPA (International Association of Amusement Parks and Attractions) to have enough credibility, and additional resources may be needed for effective control actions. Daily operations affect the aimed capacity, the location and type of station(s) and maintenance areas in layout design.

The layout design software discussed in the beginning of Chapter 3 is probably one of the biggest candidates for rapid development. As a software, it can be quickly modified and improved with the ever-growing availability of computation power. As stated in Chapter 3, the layout design software is the key difference between manufacturers as it is the sole responsible unit behind the ride experience – thus it can and should be updated as time passes, and technology advances are made. The current force design method of designing layouts automatically controls the most influential factor of the layout: accelerations. While the limits regarding gs and track radii remain, the ride experience is formed by these accelerations. If the same formulaic elements and rates of accelerations as transitions between elements are used similarly in different rides, riders may notice repeating patterns in coasters from the same manufacturer or designer. Repetition can create unsurprising and predictable experiences, which can lessen the excitement making a ride meaningless if it's meant to excite. Thus, changing the software or mixing some values in it can create varying rides, which all feel unique and thus maintain the excitement [4]. The software can also be improved to make speed calculations more accurate as the modeling methods of real life phenomena are researched and developed. CAD-softwares used for 3D-modeling the track and supports are already at a sufficient level needed for manufacturing, and with 3D environment scanning methods also being used, there probably isn't as big of a need (besides UI improvements) for track modeling development as there is for the layout design software.

The basics of layout design may change as time passes by; for example, shuttle coasters or powered coasters may become more dominant and new methods of transport and braking devices may not require restricting the track design. Special switch tracks may also become more common, breaking the most common closed loop layout designs. However, gravity runs will still need to have the train make it through. Upgrading the station types to enable higher capacities may also be studied more in detail, especially since it has been proven that multiple stations improve capacity. Maintenance areas and switches may have new designs, though current designs have also been proven effective numerous times.

Wheels and greases can be improved through material technology and better (more effective and durable) versions are constantly developed even outside amusement industry. Better wheel and grease materials allow less speed losses resulting in faster rides with smaller lift hills/propulsions and thus they greatly affect layout design. Especially materials that are able to withstand temperature changes would be beneficial for roller coasters, since more parks are extending their operation seasons outside summer.

The current g-limits are based on numerous tests to keep the riders conscious and unharmed. Unless the average human body develops a common mutation to enhance blood circulation and spine structure, the current g-limits will remain as they are. Jerk limits may become standardized in the future like gs already are, because they affect the ride experience and comfort as well. Together with advanced mathematics, physics and force design, the shaping of elements can be made more exact and controlled to further prevent unwanted gs, jerks and vibrations. The gs and jerks naturally affect the layout design, as they set the maximum limits for accelerations during the ride. Though g-limits are the same for all manufacturers, choosing and shaping the elements and their order varies a lot as it is a form of expression by the designer. New elements are constantly developed to induce new sensations during the ride to provide even more thrill, and because of this they are probably the most varying components in coaster design. Pacing and thrill are linked to human psychology, and as the understanding of what happens in the brain during excitement and thrill and how to induce them improves, the layout designers will have more tools to increase the amount of excitement during a ride.

If the buyer/park makes exact assessments before tendering a ride, the possibility of the ride matching their needs and initial plans increases. Of course, it is up to the buyers whether they want to demand exactly certain elements or just accept what they are offered through bidding. This can be affected by having staff with knowledge of both roller coasters as well as amusement industry and their recent trends. The initial data provided in the beginning of the tendering process sets the starting points for layout design. From the layout designer's point of view designing for less-demanding clients might be easier as they require less, but it could also feel less fulfilling if there are no incentives to improve the design after first drafts.

Engineering and dimensioning a coaster superstructure provide nearly limitless possibilities especially regarding track cross-section, spine and support structures. There can be multiple variations of making a structure hold a track, all of which can be equally sufficient as long as the structural integrity is achieved. While calculation and manufacturing methods improve, the structures can be optimized ever further. With recent and more accurate calculation methods the support spans have started to become longer, which has caused swaying to become problematic and thus new methods for preventing sway could be studied. The spine and support design don’t affect layout design, but the other way around. The layout states the loads (gs) and reach envelope stating the needs for structural capacity and areas avoided by supports. Likewise, the foundation design is flexible as long as it is able to withstand the allocated loads. The current method of using spliced track and supports favor current manufacturing, transporting and erecting methods, which are based on real-life limitations. New innovations regarding track manufacturing may very well rise, since it’s only limited by manufacturing methods, which can also be researched and developed. Due to complex and difficult on-site assembly processes, the splice method will probably remain in use as the main erecting method. Use of prefabricated pieces could be studied, although each coaster is usually a highly customized product.

External aspects like noise reduction have become more important during recent years, as they can affect both the park guests’ experience as well as nearby residents. Some methods to muffle the echo through hollow structures are already used, but more effective and cheaper alternatives could be found through research. More silent mechanisms are also more often favored, since they improve not only the rider experience, but non-rider experiences as well. Thus, with the development of new propulsion and braking methods, the sounds they make during operation could also be considered during development. Noise reduction methods don’t affect the layout design, but they may have some influence in engineering and dimensioning the structure.

Station area design is another aspect in coasters and rides that has a lot of variance and differences. While the coaster layout states some requirements, the queue and flow of people can have multiple different routes and designs. Placement of guests and staff can affect both the capacity and the ride experience. Some effective solutions have already been found which are used widely, although ideal solutions are not always possible due to spatial limitations. The loose item storage systems can also affect the ride experience, which is why it should be considered as a part of station area design. Station area design may not affect the coaster layout design unless special requirements have been made by the buyer/park e.g. regarding the placement of queue or exit.

Queue design has improved both with regular queue and alternative methods. However, using alternative queue methods may require guests to plan their visit beforehand, which may reduce the feeling of spontaneity and decrease enjoyment. Since the amusement industry is constantly growing, the average queue times can be expected to increase as well. Because of this, not only alternative queue methods should be researched, but the capacity of each ride should also be considered and improved already in the design phase to reduce the need for alternative queue methods. Like station area design, queue design and theming don't influence the layout design unless special requirements have been made by the buyer/park. The theming of a ride can however influence the layout design if it utilizes one or more signature element(s) in the layout or certain sensations are wanted (e.g. flying or chasing).

Adding Virtual Reality on coasters has so far always been a retroactive decision after their initial opening and thus it has not affected the layout design of any coaster, excluding the renovation of Eurostar – Europa Park, which will have an additional and separate station devoted to VR-experience [66]. If VR coasters are to be used in the future, the issue of low capacity should be addressed and considered from the beginning of either retrofitting or designing a new ride to improve the capacity. As the technology of VR keeps evolving and improving, so can its use in coasters as well to have lighter, more durable and more powerful gear. When effective use of Augmented Reality (AR) can be commercialized like VR, it will probably have a similar wave of initial interest in amusement parks, as it is a new form of entertainment. Like all new technology, its novelty can be used in marketing and attract guests to amusement parks due to its (probably) high price making it not available for everyone to have at home. Regarding layout design, VR (and AR) gear is designed to remain secured to the riders' head at all times, and thus it doesn't affect the layout design itself, excluding special station arrangements.

One possible topic for future research could be to focus on the social experience during roller coasters and other ride experiences. While most of the time the experiences are heavily focused on individuals because they are caused by sensations of motion, during less intense parts of the ride there is a possibility for social interactions. Before the ride waiting in queue and station area as well as onboard the ride waiting for dispatch, during slow parts of the ride e.g. lift hills and brake runs social interactions are possible because the senses are not occupied by the movement of the ride. Most people probably even prefer to have a friend or someone they know to talk to during these parts that otherwise could be boring. A research could study how the seating arrangement affects these social interactions and thus the ride experience.

While new innovations are constantly required and "World's First" is a common phrase used in amusement marketing, all designs regardless of their field should still follow a standard to make sure they are applicable and safe to operate. This causes additional pressure for authorities to keep up with each new design and patent and upgrade the standards correspondingly. Amusement industry is unique in the sense that new innovations are required more rapidly e.g. than in other civil engineering, in which new innovations are profitable but not vital. Thus, more resources are probably needed in the future to keep the standards updated in time.

Table 2: Possible focuses of development for concepts used in roller coaster design

Potential for development	No direct need for development
Train design	Bogie system
Rider safety restraints	Reach envelope
Transport devices	Block system
Braking devices	Track structure modeling software
Ride control software	Maintenance areas and switches
Daily operations	G-limits
Layout design software	
Station types and configurations	
Wheel materials	
Greases	
Temperature tolerance	
Layout elements and their shaping	
Pacing and understanding thrill	
Shaping of individual ride elements	
Distribution of roller coaster knowledge	
Track cross-section and support engineering	
Prevention of excess track sway	
Noise reduction	
Station area design	
Queue design	
Alternative queue methods	
VR and AR Coaster technology	

Designing a roller coaster is an iterative process, where multiple phenomena and features are interlinked. For example, simply changing the number of cars per train affects the station and brake section lengths, the chain and launch motor drives and the train speed throughout the entire gravity run, which then might require reprofiling certain elements, which then affects the track and support types and flange placement also possibly moving foundations. Because of chain reactions like this, the following order of actions based on this thesis is proposed for the general design process of a roller coaster to reduce excess amount of re-iteration:

1. Define starting points for the ride
    a. area (incl. location or access to station and maintenance)
    b. budget
    c. capacity
    d. demographic
    e. external limitations and legislations (height, noise etc.)
2. Create the heartlined track spline
    a. follow radii limits caused by trains
    b. calculate gs and speed variation (lowest speed and fastest speed)
    c. define block sections
    d. calculate station, propulsion and brake section lengths
3. Engineer track cross-sections and supports throughout the layout
    a. splice track sections and supports with flanges
4. Engineer foundations
5. Design station and queue
    a. integrate theming

7 Conclusions

Amusement parks and roller coasters have reached a strong position in modern culture and will continue to provide thrills that are unobtainable anywhere else in a safe environment. As technology advances are made, the methods to induce thrills will improve to include more excitement in more comfortable ways, while also further improving safety.

Designing roller coasters has started to become standardized, but due to ever growing competition, the standardization processes need to evolve along as well. Some of the currently favored concepts in roller coaster design have already been optimized, but most concepts still have potential to be further developed.

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