“Escape from Kronos”

Independent Study: Ride Engineering & Design
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Abstract

This paper outlines the process and outcomes of the Independent Study project "Ride Engineering & Design," a dark-ride theme park attraction consisting of an engineered rollercoaster and various show set design elements. An alternate, spine-chilling take on the Greek myth of Kronos, guests travel through a grandfather clock in a journey to escape time itself. The ride story is realized through concept art, engineering calculations, and three-dimensional digital and physical models, with special attention to the switch track mechanism that highlights the climax of the guest narrative.

This project was supervised by Professor Daniel Harris.

Introduction – Methods and Intent

The themed entertainment industry – from Disney to Universal, Six Flags to the newly opened Ghibli Park – is one that uses engineering to shape magical, story-based guest experiences. With the increasing demand for physical immersive environments in response to the emergence of digital worlds and artificial intelligence, the industry is rapidly growing, not only in the United States, but also globally.

The industry divides their technical work into multiple teams, from ride vehicle engineering to track engineering, to safety and show-set animatronics. This project considers aspects of every team on a smaller scale, modeling the collaboration a larger attraction might require – for example, considering the ride vehicle when accounting for the time limit of the moving mechanism, the track in understanding the manufacture of each part, and the safety of the materials placed under stress.

"Escape from Kronos" is an attraction that combines a dark ride with a rollercoaster. Typically, dark rides are story-focused, engineered within an enclosed building with special lights, sounds, and sets as guests are moved from scene to scene. Recently, they have been combined with sudden movement and guest interactions to create new experiences; however, historically, they began as "Tunnels of Love" rides. On the other hand, rollercoasters may or may not follow a narrative. Instead, they consist of "trains" that move along a track, and focus the engineering around inclines, drops, and loops to provide a thrill for riders. By combining the two experiences, as seen in current attractions like Space Mountain at Walt Disney World and Revenge of the Mummy at Universal Orlando, designers and engineers can maximize the guest experience.

For this independent study, research of past student projects were conducted to identify which areas of engineering are the most significant to highlight, due to the confidential nature of the industry; current ride technology, to identify how past attractions could inform where the industry may be headed, pinpointing guest need; and patent research, to further study the technology and assets that currently exist. Altogether, this method allows for the implementation and advancement of more efficient models.

The final deliverables include concept art; patent research; calculations relevant to the study of current models; calculations relevant to the design of the attraction; an engineering package with engineering drawings of CAD models, ride state diagrams, and ride operational flowcharts; structural analysis via simulations and the subsequent design iterations; and physical prototypes and scale models of the ride experience.

Inspiration

Because of the narrative-based nature of current theme park attractions, it was integral to develop a story to serve as the project's backbone, determining the detailed technology to fit each scene as done in the industry. The following constraints were considered: the final narrative does not use existing intellectual property (IP), the narrative would be realized as an indoor dark-ride roller coaster, and the narrative must fit within the thrill or horror genre.

As a designer, I find nursery rhymes particularly cryptic, and thus used the method of "dark spin on a nursery rhyme" to fuel my ideation process. After some research, I came across "Hickory Dickory Dock":

> Hickory, dickory, dock,
> The mouse ran up the clock;
> The clock struck one,
> The mouse ran down,
> Hickory, dickory, dock.

From this, I imagined a large grandfather clock, where guests were taken on a journey through time, weaving in and out of the gears and mechanisms that its interior might provide. Its connotations of signaling the end of time allowed for the exploration of its symbolism, which led me to the famous Romantic painting *Saturn Devouring His Son* by Spanish artist Francisco Goya (App. C, Fig. 1), which depicts the Greek titan Kronos mid-action, eyes wide, as he bloodily devours the limb of his newborn. Though there are several interpretations of the Greek myth and Goya's painting, one of the most common is that, like Kronos, time devours all.

Story Development

High Concept

"Like Kronos, time devours all." As riders journey through an ancient grandfather clock in search of time, the story takes a dark turn as they come face-to-face with Kronos.

Guest Experience

The Queue: Guests walk through the ruins of an old house. Dimly lit, guests are surrounded by eerie framed portraits, analog clocks showing different times, and flickering candles as they approach the towering grandfather clock (inside which the roller coaster is located).

The Ride: In the first show element, riders are introduced to Kronos, who ostensibly welcomes them to the environment, but is quickly revealed as the antagonist. This sparks the chase; riders quickly weave in and out of the cogs and inner mechanisms of the grandfather clock in an attempt to escape. As the ride vehicle approaches the large "window" looking out from the inside to the outside, guests believe the escape to be successful (App. B, Fig. 1). However, the clock's pendulum swings, controlled by Kronos, knocking the ride vehicle backwards onto the track. After traveling further, the ride ends ominously, leaving guests to realize that they must escape Kronos' clutches one moment at a time.

In this project, the high concept is generally outlined, but in the future, the ride's narrative would be further fleshed out by collaborating with writers.

Story Chart

Duration	Ride Cycle: 2.5 minutes Load/Unload Time: 43.2 seconds
Story	As riders journey through an ancient grandfather clock in search of time, the story takes a dark turn as they come face-to-face with Kronos.
Guest Emotion	Thrill, apprehension, adventure, relief

Ride System Research

Going Backwards

In order to implement the narrative's climax, where guests are ostensibly approaching the end of the ride, then pivoted in a different direction in surprise, a mechanism that allows for the rollercoaster train to move forwards, then backwards on a different track, became the focus of this project.

On some occasions, roller coasters move backwards on accident. This can be due to a variety of factors: high winds can decrease launch velocity, the time of day (morning) can decrease the conductivity, and cold weather can decrease the amount of heat needed for launch. When there is not enough initial force to make the hill, the event is referred to as "rollback." In order to account for these rare cases, engineers and designers incorporate secondary mechanisms to ensure the safety of the riders.

However, on other occasions, the backwards-moving is intentional and results in rides with incomplete circuits (most roller coasters are designed to have complete circuits, where the track is one continuous loop with different curves and spirals within). One example of an incomplete circuit is a "shuttle coaster," which allows riders to enjoy a coaster forward, then again backwards on the same track. Because of the nature of this type of coaster, only one train can operate at a time, often making the attraction low-capacity and ride-time short. While there are many variations of the shuttle coaster, a main example is the Boomerang model by Vekoma, seen at various Six Flags parks. Another model of an incomplete circuit is a "drop track," where the entire ride vehicle and its track falls vertically, leading to another path. The mechanism operates similarly to drop towers, where structures support the ride vehicle to drop a designated distance, seen in rides such as *Guardians of the Galaxy – Mission: BREAKOUT!* at Disneyland California Adventure or *Polar X-plorer* at Legoland Denmark. The last example of a ride with an incomplete circuit is the "switch track," which allows riders to move forward on one track, then move backwards onto a different track.

Because of the narrative of the roller coaster and its goal to accommodate for the largest guest capacity, the switch track mechanism was determined the most compatible. In order to analyze the technology, the following attractions were researched:

The Revenge of the Mummy (Hollywood)

The Revenge of the Mummy opened in 2004, and has different versions at Universal Hollywood, Orlando (Florida), and Singapore. However, the only attraction that features the switch track is the Hollywood version, which has a darker take than the other two, as opposed to a comical one. Because the Hollywood attraction replaced an older E.T. Adventure ride, which still operates at Universal Florida and Japan, the dark ride roller coaster was designed to fit the restrictions of the smaller space.

In this attraction, guests board a minecart into the tomb of Imhotep. However, an ancient curse is awakened, leading guests in a thrilling ride through the journey of their escape. The show set of the queue features actual props from *The Mummy* films, complete with animatronics and hieroglyphs on the walls warning of danger, and this theme is carried throughout the ride. The backwards portion occurs as the climax of the roller coaster; as guests pause at a scene where they believe the ride to be over, the cart is thrust backwards onto the track in total darkness. Though it is clear that the switch track mechanism operates while the roller coaster train is parked, the technology itself is unclear. However, from the ride's track layout, it is clear that the forward and backward portions of the ride are different (Fig. 1) [1]. At the end of the ride, a turntable configures the roller coaster track into the correct direction before passenger unloading.

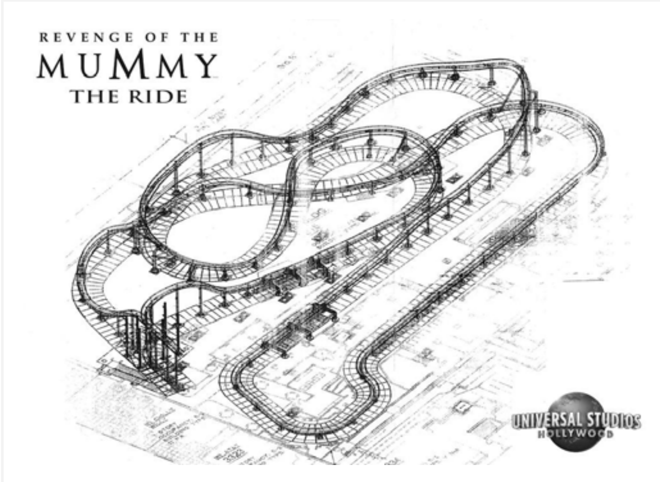


Figure 1: *The Revenge of the Mummy* Track Layout

This steel roller coaster, with a track of about 581 meters and a ride length of 2 minutes, is launched with Linear Synchronous Motors with single-sided linear induction motors (SSLIM), which allows the roller coaster train to hike 45 feet uphill in 1.5 seconds, then drop below ground level. In total, there are seven near-zero-gravity moments, several high-speed, 80-degree turns, and a maximum speed of 40 miles per hour, which adds to the thrill of the ride. Because this attraction is a dark ride roller coaster, meaning that it combines a high-speed roller coaster with a low-speed dark ride attraction, it implements a variable-frequency drive for speed and thrust control, instead of operating at a standard of 60 Hz. Each roller coaster train is timed during its initial launch using proximity sensors that observe the position and velocity of the vehicle, and communicate with the control system using a servo feedback loop [2]. This determines the weight and launch force needed throughout the ride, allowing ride operation to run smoothly [3]. In addition, the vehicles are recharged during passenger loading, and, because the attraction is within an otherwise-empty warehouse, the tracks are filled with sand to reduce noise.

The Revenge of the Mummy also features multiple braking systems to ensure the safety of the guests. Pinch-style coaster brakes hold the vehicle in place, whether that be as "anti-roll devices," which prevents accidentally rolling backward, or "block zone separation," which prevents vehicles from running into each other when the previous train has yet to finish a show scene. Platen-style brakes have a similar purpose, separating each train from the previous, and operate by pressing against the vehicle's underside to stop. Lastly, passive and active magnetic brakes lower vehicle velocity, reducing the energy proportional to the vehicle's speed without contact. This is particularly important for heavy vehicles, as it decreases the force needed to stop the vehicle when the pinch-style brakes engage [2].

Expedition Everest

Expedition Everest – Legend of the Forbidden Mountain is an outdoor roller coaster at Disney's Animal Kingdom Theme Park in Orlando, Florida. The ride explores the mountains of the Himalayas, but encounters a Yeti along the way, throwing guests into a thrilling expedition. The switch track component occurs during the middle of the ride, where guests encounter a broken and twisted track during the escape from the Yeti, causing the train to fall backwards into a cavern [4].

Each train of the steel roller coaster consists of 6 cars, allowing for 34 riders per train; in total, the attraction's ride capacity is about 2,050 riders per hour. The ride track is 1,184 meters and lasts about 2 minutes and 50 seconds. This attraction operates via chain lift hills, mechanically bringing the trains up before each drop. Its switch track model features two tracks on opposite sides of the same section, which rotates automatically as the vehicle is held in place by a series of rubber tires (Fig. 2). However, because of this older model, guests must wait for a few seconds before going backwards as the switch mechanism operates, somewhat breaking the illusion of a thrilling chase [5].

Figure 2: Rotating Switch Track Mechanism, *Expedition Everest*

Hagrid's Motorbike Adventure

Hagrid's Magical Creatures Motorbike Adventure is one of Universal Orlando's newest attractions, located within the Wizarding World of Harry Potter – Hogsmeade. In what Universal refers to as a "story coaster," the attraction features seven total launches, integrated within multiple show set scenes, with a total of 1540 meters of track and a 2 minute, 55 second ride time. Each train consists of 7 cars, with 2 riders in each car; at maximum capacity, 12 trains run with 27.3 second dispatches, accommodating up to 1700 riders per hour [6]. Through this rollercoaster, guests follow Hagrid through the Forbidden Forest on "motorcycles" or "sidecars," until they reach a dead end "spike" veiled by mist, when guests "run out of power" and are immediately thrust backwards [7].

Hagrid's, which opened in 2019, incorporates three new technological innovations. Instead of the chain lift hills seen in *Expedition Everest* or the older LIM technology, the ride uses INDRIVETEC Linear Induction Motor systems (LIM) and Linear Synchronous Motors (LSM), which works by using proximity sensors to sense the train throughout, activating the drive tires, moving the train towards the launch area, activating the linear motors, and turning on the redundant brakes until the train safety clears the launch. For the switch track, the ride uses high speed live transfer technology. In the time that the train ascends the spike and descends due to gravity, a table-like structure slides to the other track to allow the train to go backwards onto a different route (Fig. 3). Together, with the linear synchronous motors, brake fins, and tire drives, the live transfer switch tracks create a unique experience improved from earlier roller coasters. Afterwards, the train travels backwards into a cylindrical building, which houses the drop track. Guests then free-fall 17 feet, supported by a pneumatic cylinder, magnetic brakes, and sensors [8].

The ride vehicle itself is fairly simple, with a chassis of wheels, basic spine, seat frame, and fiberglass outer. Instead of over-the-shoulder restraints like other high-speed roller coasters, Hagrid's has lap bars. In addition, if timed correctly, the attraction itself can run up to 7 cars at the same time; because "block zones," of which the ride has about 14 (Fig. 4), prevent trains from interacting with one another, some scenes can be extended or shortened to accommodate for slow unloading or loading times, or if a car doesn't clear a track section. To account for the varying amounts of stress, the track changes shape throughout the ride, from a simple straight path to a triangular shape with support beams [8].

Figure 3: High Speed Live Transfer Switch Track

Figure 4: *Hagrid's* Track Layout & Block Zones

Through the technology research with a focus on the switch tracks, a few points of improvement were identified. For example, while all of the models work to serve their purpose, the rotating track seen in Expedition Everest is the most compact in space and inconspicuous; however, guests are forced to wait for the mechanism to lock into place. On the other hand, the sliding live transfer method is convenient to accommodate for switch times, but can be obvious to guests moving backwards and can take up a large amount of space. For this project, to fit into a limited space, as well as allow for a seamless transition and guest experience, the rotating switch track mechanism technology was combined with the intermediate accelerating motors and increased distance between the track and the spike. In addition, the current attraction and technology research informed rough numbers to estimate with and aim toward.

Patent Research

To further understand the current technology of roller coasters, a few patents were investigated in detail:

Universal City Studios LLC, US Patent No. 7,997,540 B2 – Fast Track Switch [9]

The invention is a fast track switch: a singular path on one side feeds into the switch track, and follows into one of two directions (Fig. 5). In older models of track switches, a piece of heavy steel track is shifted over a large distance, taking upwards of eleven seconds. On the other hand, this new design features two pieces of track on the same part, rotating about a single axis (Fig. 6, 42), which accommodates multiple vehicles in short amounts of time. The axis is fueled by a rotating motor, referred to as a “pivot actuator.”

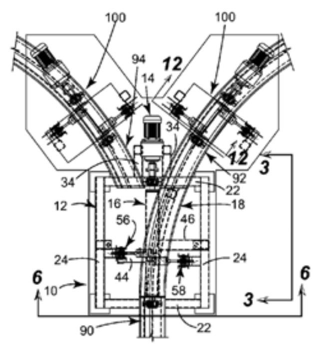


Figure 5: Universal City Studios LLC, US Patent No. 7,997,540 B2 –Fast Track Switch, Top View

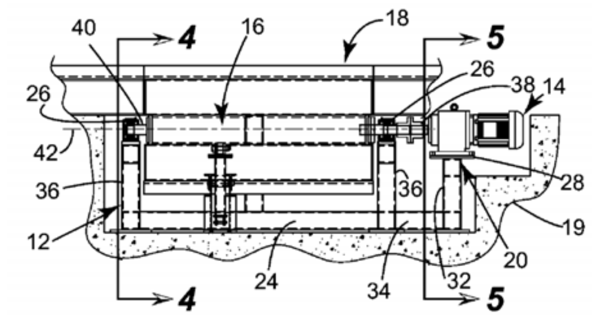


Figure 6: Universal City Studios LLC, US Patent No. 7,997,540 B2 –Fast Track Switch, Section View

Figures 7 and 8 highlight the difference between the lock and unlock positions of the rocker arm (Fig. 7 and 8, 58) – seen upright in the locked position, and seen diagonally rotated in the unlocked position. As seen in the figures, the track only rotates about the same 180 degrees (Fig. 7 and 8, 98), rather than the entire 360 degrees, supported on each side by the support posts (Fig. 7 and 8, 52 and 53) and the extension leg (Fig. 7, 46). Together, these elements prevent movement when the ride vehicles travel over it.

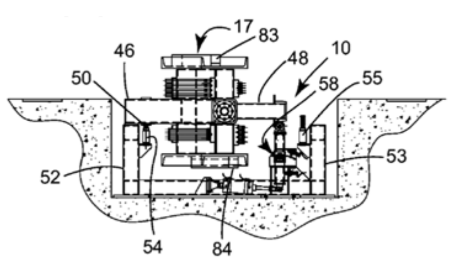


Figure 7: Universal City Studios LLC, US Patent No. 7,997,540 B2 –Fast Track Switch, Section View along the Axis

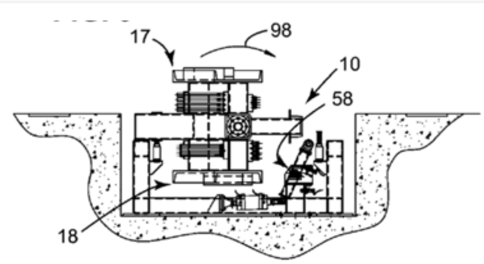


Figure 8: Universal City Studios LLC, US Patent No. 7,997,540 B2 –Fast Track Switch, Section View along the Axis

The patent mentions that it is able to relock "within a range of between about 1.2 and 2.5 seconds, and in one specific embodiment about 2.0 seconds." Based on these estimations, this technology could be used in a rollercoaster with both forwards and backwards movement, featuring an upwards spike that changes the movement from forwards to backwards. This is similar to Disney's *Expedition Everest*, but can eliminate the riders' wait time of a few seconds at the top when paired with an extra track in between the switch track and the point of shifting direction.

In addition, other patents informed how accelerations of a roller coaster train are changed during a ride cycle:

Vekoma Rides Engineering, US Patent No. 10,556,511 B2 – Amusement Ride with Speed Trim System [10]

Speed Trim Systems in amusement rides, by using an assembly of induction blades and magnet arrangements, decrease the speed of a ride vehicle, especially crucial when passengers are on the attraction vehicles. During regular operations, the systems slow down vehicles approaching the unload station, and during irregular operations, when weather conditions affect how the ride operates (for example, if the steel has not warmed up earlier in the day, or if there is rain or wind), the trimming provides safety and consistency. The invention is specifically designed to reduce speeds of rail-bound vehicles, rather than entirely stop them.

Fig. 2

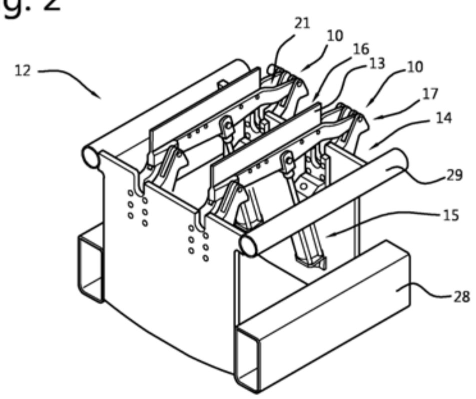


Figure 9: Vekoma Rides Engineering, US Patent No. 10,556,511, Isometric View

Fig. 7

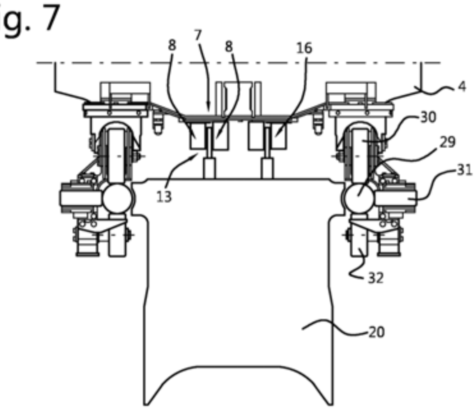


Figure 10: Vekoma Rides Engineering, US Patent No. 10,556,511, Section View Along Rails-Axis

Sensors in the speed trim zone measure the velocity of the ride vehicle as it approaches the system of induction blades (Fig. 9, 13) and trim brakes (Fig. 9, 10). If the speed is above a certain threshold, the trim brakes change to the active position, allowing the braking edge (Fig. 9 and 10, 16) to engage with the magnet arrangements (Fig. 10, 7) on the ride vehicle (Fig. 10, 4), effectively slowing it down. When the speed reaches the target threshold, the blades adjust to the inactive position. The active and inactive positions of the blade are driven by the actuator (Fig. 9, 15) along the pivot axis (Fig. 11 and 12, 17), as seen in Figures 11 and 12. The patent recommends a pneumatic cylinder as the actuator, pivoting the brakes from active to inactive.

As the ride vehicle passes through the speed trimming zone, the braking edge of the track system passes through the gap between the two rows of magnets on the ride vehicle, creating a magnetomotive force. By creating two magnetic fields that oppose one another, the system acts as a braking force, reducing the speed of the passing vehicle. The maximum braking force is determined by the length and the number of induction blades, and the length and the number of magnet arrangements on the vehicle.

This magnetic technology is an implementation of Lenz's Law, as seen through demonstrations where a magnet falls through a copper tube or pipe, or the magnetically levitated bullet trains in Japan.

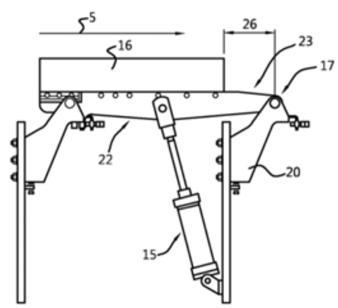


Figure 11: Vekoma Rides Engineering, US Patent No. 10,556,511, Section View of Active Brake

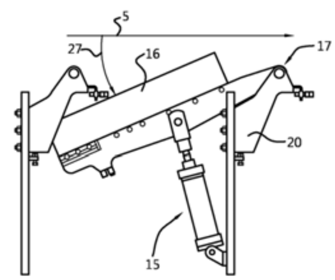


Figure 12: Vekoma Rides Engineering, US Patent No. 10,556,511, Section View of Inactive Brake

Vekoma Rides Engineering, US Patent No. 10,766,502 B2 – Amusement Ride with Booster Drives [11]

Similarly, Vekoma developed a booster drive system to increase the speed of ride vehicles. In regular operations, these systems can move a vehicle forward in small increments, whether that be pulling from the loading station, moving around a show scene, or restoring speed in between changes in elevation.

The booster drive system is designed to be mounted directly onto the ride tracks. A "drive fin," (Fig. 13, 10) installed on the bottom of the ride vehicle, feeds into two booster wheels (Fig. 13, 11, and Fig. 14 and 15, 21). As the wheels rotate, the fin is pinched, accelerating the vehicle. This drive fin is usually a length of 1.5 to 3 meters, ideally installed along the entire longitudinal length of the train, and is made of a material stiff enough to withstand the propelling force. The wheels are driven by two separate booster drive motors (Fig. 15, 22), which are recommended to be high performance AC or DC motors. In the case that the ride vehicle does not need a boost, an additional motor or actuator moves the two booster wheels towards and away from each other, allowing the vehicle to pass without interacting.

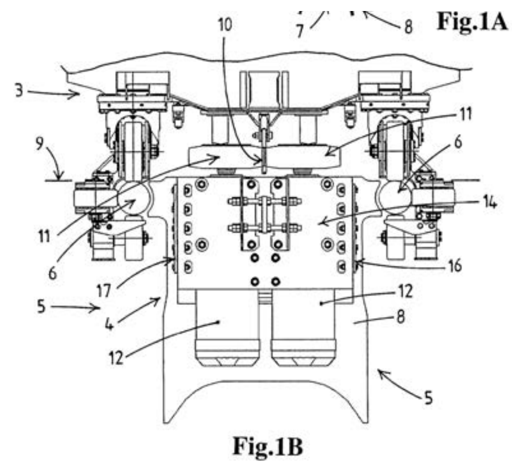


Figure 13: Vekoma Rides Engineering, US Patent No. 10,766,502 B2 – Amusement Ride with Booster Drives, Track Cross Section

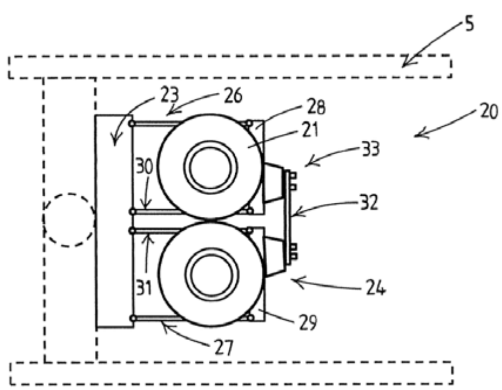


Figure 14: Vekoma Rides Engineering, US Patent No. 10,766,502 B2 – Amusement Ride with Booster Drives, Booster Drive Configuration 1 Top View

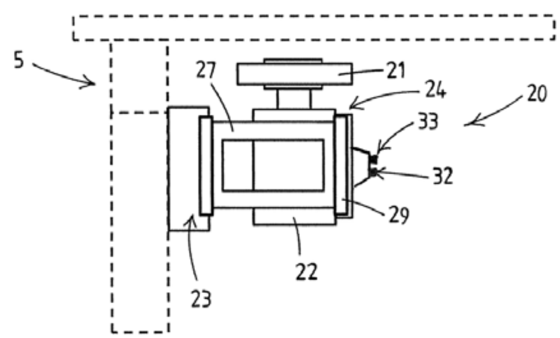


Figure 15: Vekoma Rides Engineering, US Patent No. 10,766,502 B2 – Amusement Ride with Booster Drives, Booster Drive Configuration 1 Side View

The patent also provides alternative configurations of the booster wheel invention, with variations in the supports, frames, and the carrier arms. These booster drives, together with the speed trim systems, allow rollercoasters to both decelerate and accelerate, even during ride operation.

Other related roller coaster engineering patents can be found in Appendix D.

Revisiting the Story Post-Research

Informed by the attraction studies and technology patents, the story was revised and further detailed to understand the project from an operational perspective. The operational flow chart (Fig. 16) outlines each stage of the ride, splitting it up into show elements, lifts, drops, boosts, and load/unload. The show elements sections communicate the narrative of the attraction, spaced in between the various lifts and drops to not only make chronological sense, but also to allow the ride control team to keep track of each train during irregular operation. The lifts and drops indicate an increase of velocity from the low speed of moving around a show set, around 3 to 4 feet per second, to a velocity of a typical roller coaster, transitioning the guest experience from narrative to thrill. The boosts, similarly, increase the speed of the ride; however, they transition from one drop to another without the need for another lift. While most of the other attraction sections are automatic, the unload and load section (Fig. 16, 16 and 1) is where the operational team helps manage the flow of guests.

These sections of the operational flow chart are condensed into the block zone diagram (Fig. 17), which simplifies the ride into sections which allows multiple trains to run simultaneously. The lifts and drops combine into the numerical "launch blocks," while the show elements are designated as "brake" sections, as the ride vehicle's speed must be decreased to fit the pace of the show set elements. The diagram has an added prestation waiting period at the conclusion of the ride, a block zone before guests unload at the station area block (Fig. 17, 1). The ideation process for the guest experience can be found in Appendix B.

Figure 16: *Escape from Kronos* Operational Flow Chart

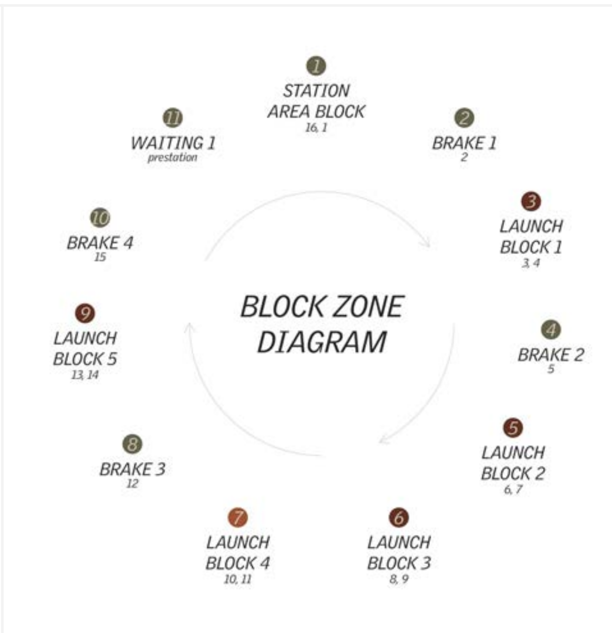


Figure 17: *Escape from Kronos* Block Zone Diagram

Ride System Calculations

Analyzing Hagrid's Motorbike Adventure

To best understand the timing and technological requirements, the switch track and upward hill of *Hagrid's Motorbike Adventure* was analyzed. Theoretically, with the specifications of a spike placed at a 70-degree angle with a height of 65 feet, assuming that the vehicle uses the entirety of the height to reach a stop (and thus transition backwards), the velocity of the vehicle at the base of the pike was calculated to be 64.7 ft/s (44.1 mph), taking 2.14 seconds (App. A, Fig. 6). Thus, in total, the time for the vehicle to rise and fall on the spike is around 4 seconds. However, based on observation, the above assumptions are not entirely accurate. In reality, there is a section of track in between the switch track and the spike's base; the ride vehicle travels most, but not all, of the height; and, in between the switch track and the spike, there could be booster wheels or speed trimmers to increase or decrease the speed of the ride vehicle. By observation, there are actually about 6.34 seconds of ride time between the switch track and the spike, giving the switch track mechanism about 12 to 13 seconds to lock into place [12].

Thus, for the estimations to be closer to reality, the times and velocities were recalculated to add the extra section between the switch track and spike and a 5-foot height buffer for the spike. Assuming that the vehicle travels at a constant speed across the added track, the velocity at the spike's base should be 62.163 ft/s (43.53 mph) to travel upwards for 2.05 seconds, meaning that there should be around 270 feet of added track to meet the 6-second quota. However, a theme park may not have this space; thus, given the same spike-base velocity and time of 4 seconds, alternate track lengths and vehicle accelerations were calculated. After a few iterations (App. A, Fig. 7), it was determined that a track extension of 200 feet, which allows the vehicle of velocity 37.84 ft/s to accelerate at 6.08 ft/s^2 (1.85 m/s^2) to reach the base of the spike.

Hagrid's also features a dip before the spike, after the track extension, causing the ride vehicle to drop before climbing. However, because the starting and ending heights are the same before and after the dip, it does not impact the energy of the vehicle, and, thus, was not considered in the project. Based on the physics, the dip is likely an added element to increase the thrill and catch riders off-guard, rather than to impact the vehicle's velocity.

Ride Vehicle Calculations & Design

The constraints of the ride vehicle were determined based on the Humanscale 4/5/6 Manual, which was originally published by the design firm Henry Dreyfuss Associates between 1974 and 1981. These documents outline the average measurements of the human body, providing a general standard for the seats of the ride vehicle to accommodate for the wide variety of riders.

The ride vehicle consists of these main parts: the seat, the chassis, the wheel system that adheres the chassis and seat to the tracks, and the restraint system. Based on the manual's standards, the ride vehicle design has a seat width, left to right, of 20 inches; a seat depth, from front to back, of 16 inches; a seat height, from floor to seat, of 17 inches; and a seat back height of 23 inches. With two seats per car, each car has a 45" width, a 40" height, and 58" length. When adding 10" spacing between the cars, and with six cars per train, the train's total length is 33.1 feet, accommodating 12 riders.

Based on these measurements and the overall train length of 33.1 feet, the times were recalculated to account for the position of the train's center of mass at 16.55 feet. Maintaining the extended track length of 200 feet and acceleration of 6.08 ft/s^2, the ride vehicle now has a velocity of 25.13 ft/s entering the switch track, estimating the forward time to be 6.44 seconds total. Given the backwards velocity down the hill is constant, at 53.5 ft/s, the total backwards time is 5.2 seconds (App. A, Fig. 8). Combined, the total time to switch the tracks is 11.64 seconds, which is plenty of time for the switch track mechanism to operate from one side to the other, based on the patent research [9].

The physical design (Fig. 18) was based on the attraction's narrative, modeled after Greek racing chariots and those featured in myths, from Hercules to Dionysus to Apollo. While riders typically stood in the chariots for this dangerous sport, with the barrier in between the rider and the team of horses, some depict the people seated, with the taller half supporting the riders' back, as in the *Chariot of Venus* by Pietro da Cortona (App. C, Fig. 2). The details of the chariot's backside is inspired by the ornamentation found in illustrations during the mid-1800s of ancient Greek stories (App. C, Fig. 3 and 4). For racing, the chariots were typically made of wood to lighten the weight, but for parades and other elaborate occasions, the chariots were made of a combination of bronze, iron, and leather [13]. Though a few iterations were considered, including a chariot-design that featured barriers on both the front and back, the asymmetrical one-sided design is truer to the original Greek chariot silhouette and better suits accessibility standards (App. B, Fig. 3).

Figure 18: *Escape from Kronos* Ride Vehicle Design

Project Deliverables: Modeling

CAD Modeling, Assemblies, Drawings, Animations

After identifying the components of the switch track assembly, each part was separately modeled via Solidworks. The final assembly – the images, drawings, and animations – can be found in Appendix A.

The computer-aided design (CAD) process was done with the manufacturing process in mind. For example, subassemblies were created to further categorize the parts of the large assembly, parts intended to be welded together were modeled separately, and easily accessible, non-custom parts (eg. the bolts, hex nuts, needle roller thrust bearings, swivel joints, and electric actuator) were imported into the program. For custom parts, all of the measurements were specified. For example, for the curved-track model, the bend was defined using a circle's radius and overall track width. In addition, for both the base axis and locking mechanism, the supports were modeled to house swivel joints to support the rotating shafts; thus, revolved cuts were used to allow bowed rings to slot in after the swivel joints, preventing lateral movement. During the assembly process, elements were combined using both standard and advanced mates. Specifically, "width mates" were most helpful in aligning the part centers automatically, which remained consistent when some of the dimensions were altered. Furthermore, calculations were done in the intermediate steps in order to size the necessary pre-manufactured components. For example, shear yield stress and its resulting safety factors were calculated to estimate the diameter of the bolts needed to attach the electric actuator to the locking mechanism (App. A, Fig. 9). By understanding the material properties and the relevant forces, the assembly's design was further thought-through, making it more relevant to real world applications.

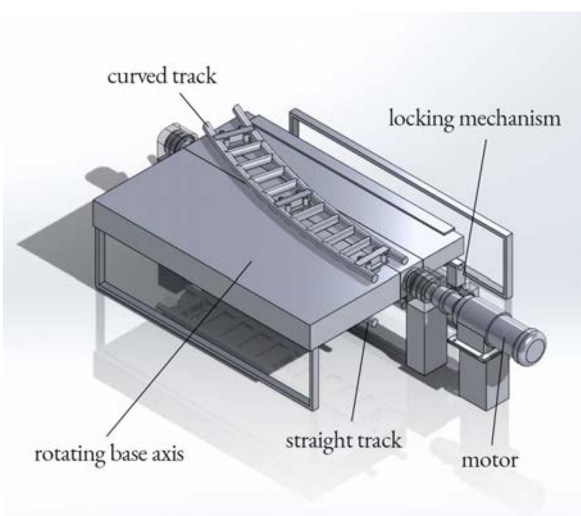


Figure 19: Switch Track Assembly CAD Model, Isometric View, Full Animation Videos Linked in Appendix A, Figure 17

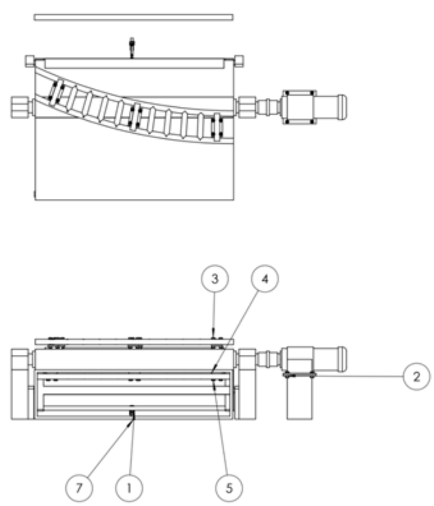


Figure 20: Switch Track Assembly Engineering Drawing, Subassemblies: Locking Mechanism (1), Base (2), Curved Track (3), Straight Track (4), Screws (5), Nuts (6), Overall Support (7)

3D Modeling & Prototyping

After digital modeling through Solidworks, the parts were 3D printed with PLA on a 1:50 scale. 3D printing does not always mimic the actual manufacturing process, as 3D printing is additive through printing layers, while, realistically, parts are made by removing volume from a large mass or cutting a pre-existing part to the right size. However, through this rapid prototyping process, the physical assembly was simulated, making sure that all of the parts are intuitive.

Figure 21: Switch Track 3D Printed Prototype
Curved Track Side, Isometric View

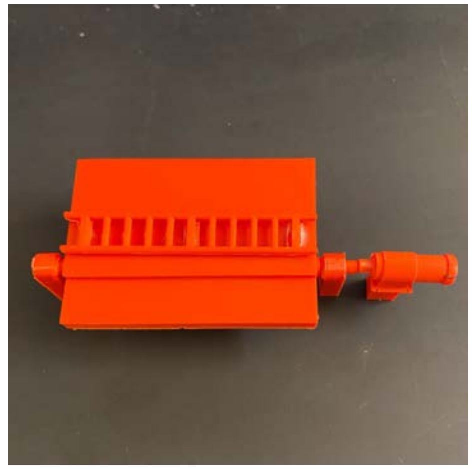


Figure 22: Switch Track 3D Printed Prototype
Straight Track Side, Top View

To push the project further, a 3D print with SLA (resin) combined with a step motor would improve the accuracy of the model, allowing it to more easily assemble together, and move as the switch track would in reality.

Project Deliverables: ASTM Calculations

The American Society for Testing and Materials (ASTM) outlines the standards for materials to ensure the safety in their use. For the themed entertainment industry, which is the second largest section after concrete, ASTM defines the expectations for all aspects of amusement rides, from restrictions on the seat back angle of go-karts to the characterizing of rides based on testing with ballast weights. For the switch track mechanism in this project, the following ASTM Standards were considered:

ASTM F2291-22a: Standard Practice for Design of Amusement Rides and Devices [14]

8.22 Load Combinations For Strength Using ASD (Allowable Stress Design):

8.22.1 The following nominal loads are to be considered:

Dead load: Permanent load due to the weight of the structural elements and the permanent features on the structure

To understand the nominal dead load of the structure on its environmental surroundings, the gravity and body force were calculated. With the material set as steel alloy for all components, the switch track, as provided by the Mass Properties on Solidworks, was 11727.78 lbs., or the equivalent of 5.86 US tons (App. A, Fig. 10).

7.1.4 Sustained acceleration duration limits are shown in this section (see Figs. 6-8). The following definitions apply:

7.1.4.1 Acceleration units are "g" (32.2 ft/s/s or 9.81 m/s/s).

7.1.5 Simultaneous combinations of single axis accelerations shall be limited as follows:

7.1.5.1 The instantaneous combined acceleration magnitude of any two axes shall be limited by a curve that is defined in each quadrant by an ellipse. The ellipse is centered at (0,0) and is characterized by major and minor radii equal to the allowable 200 ms g limits. Graphical representations of this requirement are presented in Figs. 10-17. Combined accelerations that exceed the limits for less than 200 ms in duration shall be excluded.

As the ride vehicle moves across the switch track, the velocity is constant, meaning that there is no acceleration in the X-direction (defined by ASTM as "eyes front" or "eyes back"). On the curved track, however, riders experience acceleration in the Y-direction due to the centripetal force. Because the curved track has a length of 144 feet and a radius of 360 inches (28.33 feet), and the ride vehicle travels at a velocity of 25.13 ft/s for 5.7 seconds, the riders experience a Y-direction acceleration of 22.29 ft/s^2, which is the equivalent of 0.693g (App. A, Fig. 11).

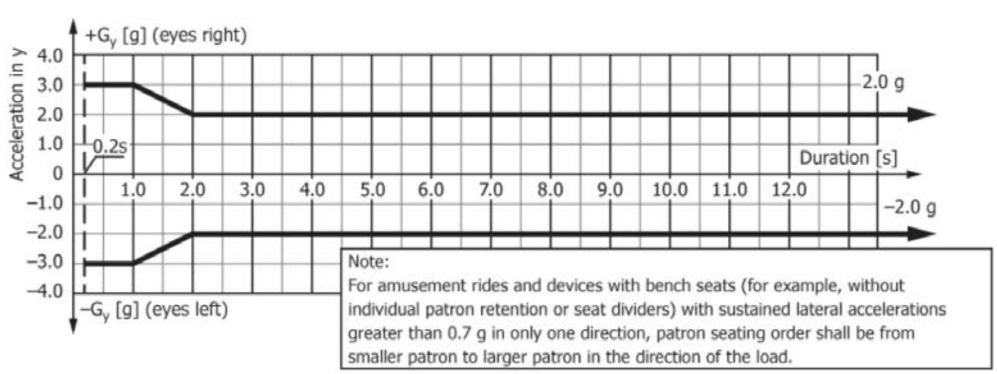


Figure 23: Acceleration-Duration Limits for Gy (Eyes Right and Eyes Left) – Labeled Fig. 7 in F2291-22a

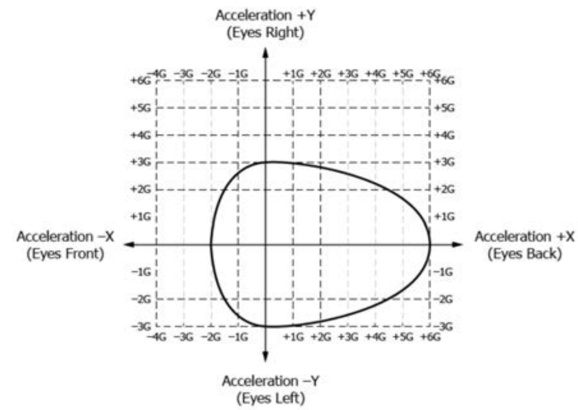


Figure 24: Allowable Combined Magnitude of X and Y Accelerations – Labeled Fig. 10 in F2291-22a

Thus, based on Figures 23 and 24 (labeled Figure 7 and 10 in the standards), the acceleration does not exceed the limits set by the standards.

8.3 35,000 Operational Hour Criteria:

8.3.1 All primary structures of an amusement ride or device (for example, track, columns, hubs, and arms) shall be designed using calculations and analyses that are based on the minimum 35,000 operational hour criteria. The designer/engineer shall verify that the calculations and analyses meet or exceed this minimum operational hour requirement. This requirement is intended to ensure that all primary structures within an amusement ride or device are designed for at least a minimum fatigue life.

Calculation to Determine the General Reduction for Load and Unload Time:

$$\left(\frac{\text{(Total load/unload time for one ride cycle)}}{\text{(Total load/unload time for one ride cycle)} + \text{(Time for one ride cycle)}}\right) = \text{General reduction for load/unload time}$$

Calculation to Determine the Operational Hours to be Used in the Applicable Design Calculations and Analyses for the Amusement Ride or Device:

$$[(35\,000 \text{ Operational hours Criteria}) \times (1.00 - \text{general reduction for load/unload time})] = \text{Operational hours}$$

Figure 25: Equations to Calculate the 35,000 Operational Hours Criteria and General Reduction for Load/Unload Time

If *Escape from Kronos* were aiming for about 2000 riders per hour, with 12 riders per train, a train must leave the station every 21.6 seconds. Though this is not realistic, as it takes longer for riders to load, assuming peak efficiency, the ride must operate for at least 27174 hours based on the equations given by Figure 25 (App. A, Fig. 12). As defined by materials engineering, this would require about 4.5 million cycles. Based on these conditions, the endurance stress limit for steel is 29 ksi, or around 2.0e8 N/m^2 (Fig. 26).

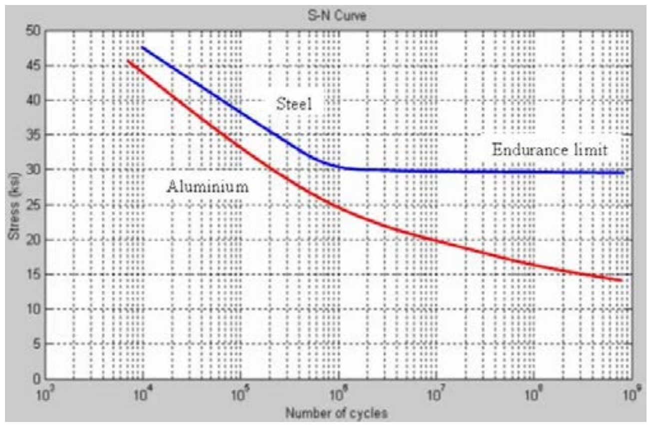


Figure 26: Fatigue Life of Steel, in blue, with Number of Cycles on the x-axis and Stress (in ksi) on the y-axis [15]

Project Deliverables: Structural Simulations & Finite Element Analysis (FEA) Calculations

With the previous calculations in mind, Finite Element Analysis (FEA) was performed in order to establish the structural stability of the base axis part. This part consists of a large, irregularly shaped rectangular prism, in which the two tracks are intended to be welded to, and a center shaft that allows for rotation. Because the safety of the ride vehicle relies solely on this part, it was integral to understand how stress over time would impact the material and geometry.

The part was simulated under a static load, which was concentrated in three circular areas in which the track would be welded. This was done in Solidworks by applying a split line via a new sketch, then treating these mapped areas as separate faces. Because the curved track had more mass than the straight track, with a weight of 1139.46 N, combined with an estimation of the average loaded roller coaster train at 4903.325 N, the base axis was simulated with a total force of 6042.785 N (App. A, Fig. 13).

In the first simulation, the entire Base Subassembly (App. A, Fig. 3 and 13) was simulated, with fixed base axis supports. Thus, when the three external loads were applied, the stress was concentrated on the shaft of the base axis part, producing a maximum of 1.303e6 N/m^2 (Fig. 27). In the second simulation, the base axis part was simulated, keeping only the parallel end planes of the shaft fixed. When the loads were applied, the most stress showed at the shaft ends, near the fixed areas, at 9.753e5 N/m^2 (Fig. 28).

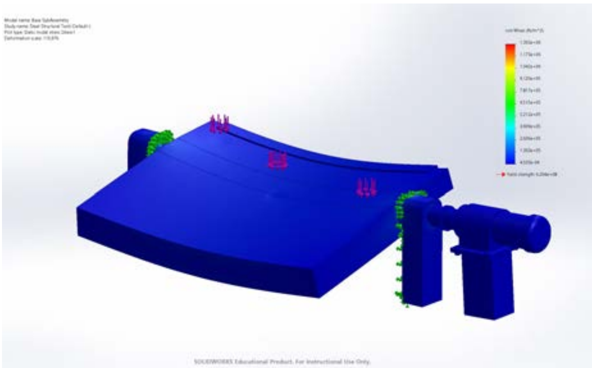


Figure 27: Iteration #1, Simulation #1, Steel Structural Test on the Base Subassembly, Keeping Supports Fixed

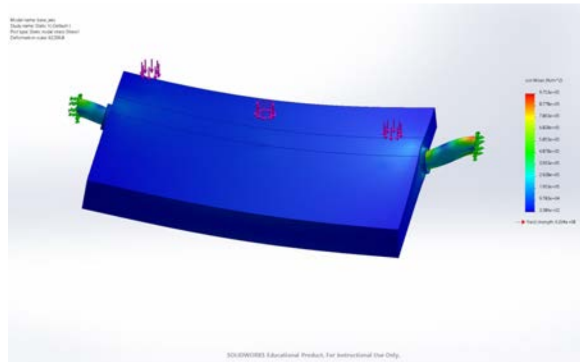


Figure 28: Iteration #1, Simulation #2, Steel Structural Test for the Base Axis Part, Keeping Planes Fixed

Because these two simulations revealed that the area with the highest stress was the seam between the shaft and irregular rectangular prism, the seam was given more volume to further help support the stress.

In the third simulation, the base axis part was simulated with the shaft fixed on both sides. When the loads are applied, the maximum stress of 4.172e5 N/m^2 also appears most at the seam, but less dramatically (Fig. 29). Realistically, the results are likely to be in between the second and third simulations. The material's safety factor, based on the operational stress limit based on the fatigue life of steel in the above section, was calculated to be 479.38, revealing the part to be over-engineered (App. A, Fig.14). Even the first simulation, which produced the largest stress at 1.303e6 N/m^2, has a safety factor of 153.49.

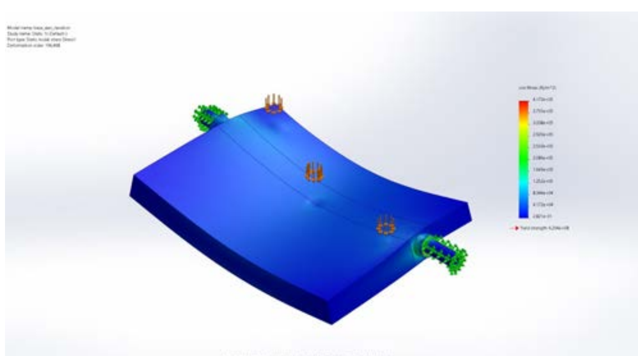


Figure 29: Iteration #1, Simulation #3, Steel Structural Test on the Base Part, Keeping Shaft Fixed

Thus, in the following iterations, the designs attempted to reduce the amount of material – and, thus, the part's weight and cost. The design criteria based on the previous simulations were the following: the part's material should be removed with the points of external force in mind to maintain the structural integrity, the geometry (its width and length) must be maintained, and the position of the shaft must not change.

In the second iteration, material was removed via two rectangular cut-outs in the z-direction. This increased the material's maximum stress to 5.307e5 N/m^2, but, based on the safety factor above, it does not impact the structural integrity of the part (Fig. 30). However, at around 1984 kg, there was a 40.37% decrease in mass. The third iteration removed material in the x-direction by making the rotating platform partially hollow. However, though the stress results for this simulation was lower than that of the second iteration, there was only a 37.22% decrease in mass.

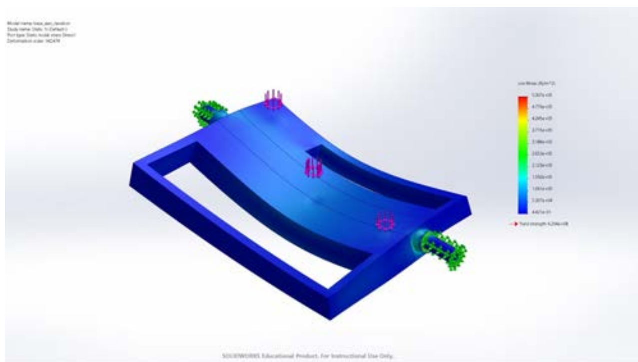


Figure 30: Iteration #2, Steel Structural Test on the Base Part with Z-Direction Cut-Outs, Keeping Shaft Fixed

In addition, the change in displacement due to the external loads were compared (App. A, Fig. 15). The simulations concluded that the first iteration had a displacement of 9.28e-5 in, the second had a displacement of 1.28e-4 in, and the third had a displacement of 1.11e-4 in. Although the second iteration has the largest displacement, the values are not large enough to impact the structure. Thus, when prioritizing the mass reduction, the second iteration is the best option. If this project were to be advanced further, this redesign would be further considered, optimizing the geometry to reduce the stress, displacement, and mass so that all of the parts fail at similar times.

With this redesign, the nominal dead load consideration provided by ASTM F2291-22a, 8.22.1 was recalculated. The new assembly weight was found to be 8744.31 lbs, or 4.383 US tons, which produces an overall weight reduction of 25.2% (App. A, Fig. 15).

Conclusion

Through the process of designing and engineering a portion of a roller coaster for *Escape from Kronos*, I was able to mimic the engineering process seen in the themed entertainment and theme park industry. This ride engineering and design independent study was a direct application of the knowledge taught on other courses at Brown, from materials engineering, seen through the structural simulations and bolt sizing calculations; computer-aided visualization and design, in the use of Solidworks and finite element analysis; statics and dynamics, in calculating the acceleration's impact on riders and the torque needed to rotate a shaft; and electricity and magnetism, in understanding how relevant mechanisms interact with a ride vehicle to adjust its velocity. By combining this new engineering knowledge with my existing knowledge of creative design and storytelling, I modeled how engineering can be applied in atypical settings and niche industries beyond those well-known (eg. aerospace, biomedical, civil).

In order to further advance this project, I would continue to iterate on the base axis design, applying additional simulations to inform the decision-making process. I would also explore more possibilities for prototyping, working toward models more reflective of reality. With a larger team, the project could expand further, whether that be to detail the ride story, the ride vehicle engineering, or the track design. These future steps would develop a larger understanding of the guest experience, as well as how teams in the themed entertainment industry work together on large-scope projects that impact millions of people worldwide.

References

[1]
https://blog.discoveruniversal.com/attractions/complete-guide-to-revenge-of-the-mummy-at-universal-studios-hollywood/
[2] https://www.designnews.com/automation-motion-control/revenge-mummy
[3] https://www.themeparkinsider.com/columns/robert/11.cfm
[4] https://disneyworld.disney.go.com/attractions/animal-kingdom/expedition-everest/
[5] https://www.youtube.com/watch?v=KTji1hOICEI&t=104s
[6] https://coasterpedia.net/wiki/Hagrid%27s_Magical_Creatures_Motorbike_Adventure
[7]
https://www.universalorlando.com/web/en/us/things-to-do/rides-attractions/hagrids-magical-creatures-motorbike-adventure
[8] https://www.youtube.com/watch?v=GuTn6MW_szA
[9] https://patentscout.innography.com/patent/US7997540B2
[10] https://patentscout.innography.com/patent/US10556511B2
[11] https://patentscout.innography.com/patent/US10766502B2
[12] https://www.youtube.com/watch?v=TdGbsggU2dg
[13] https://www.metmuseum.org/art/collection/search/247020
[14] https://compass.astm.org/document/?contentCode=ASTM%7CF2291-22A%7Cen-US
[15] https://fractory.com/material-fatigue-strength/

Appendix A: Engineering Package

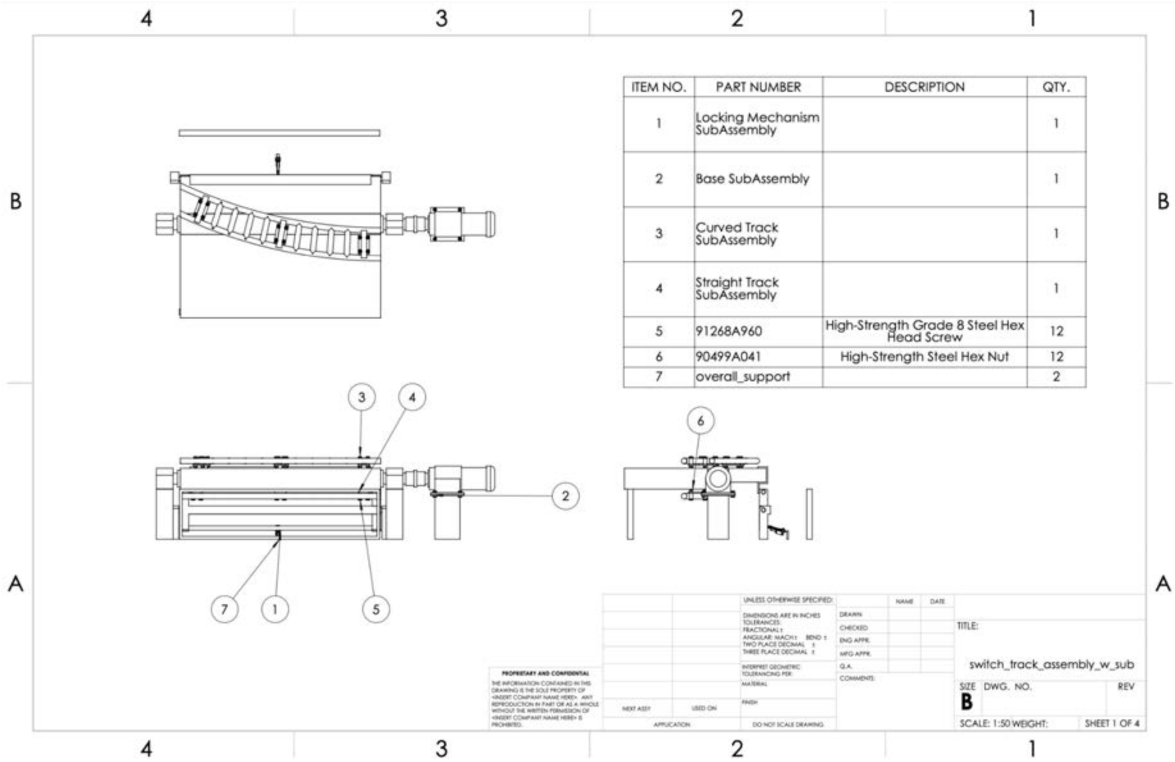


Figure 1: Switch Track Assembly, Engineering Drawing

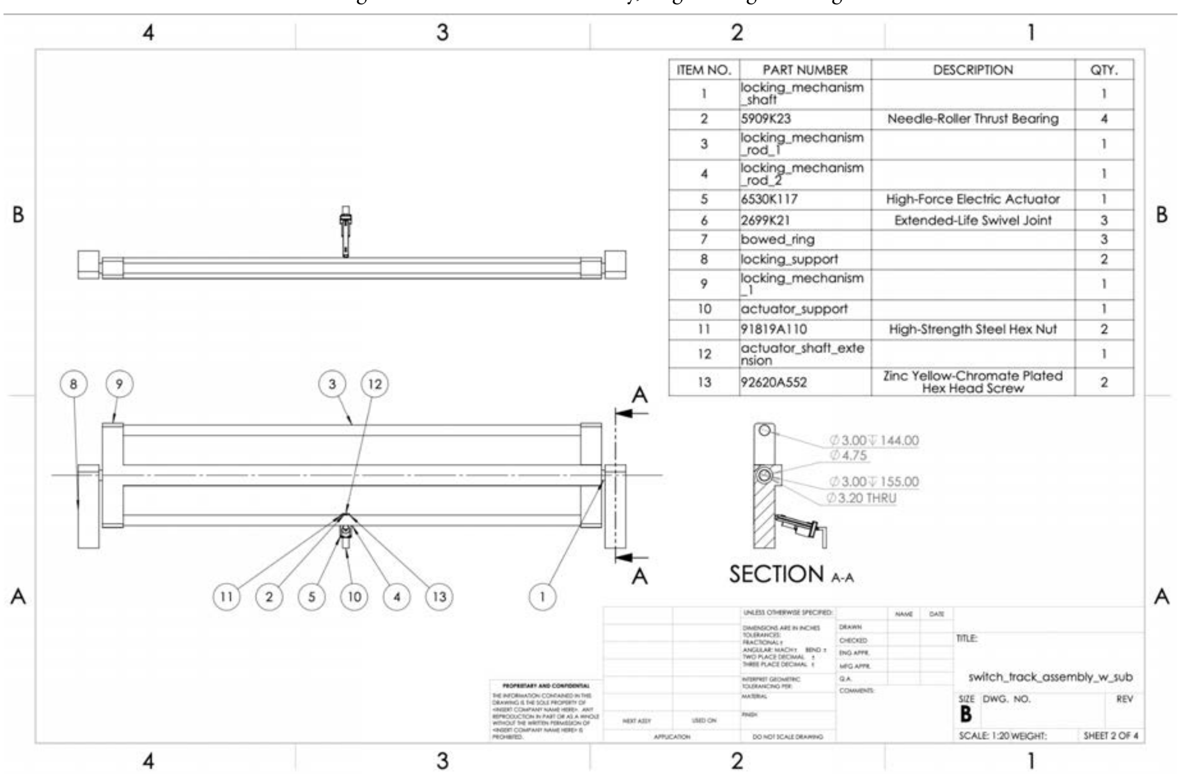


Figure 2: Switch Track Assembly, Locking Mechanism Subassembly Engineering Drawing

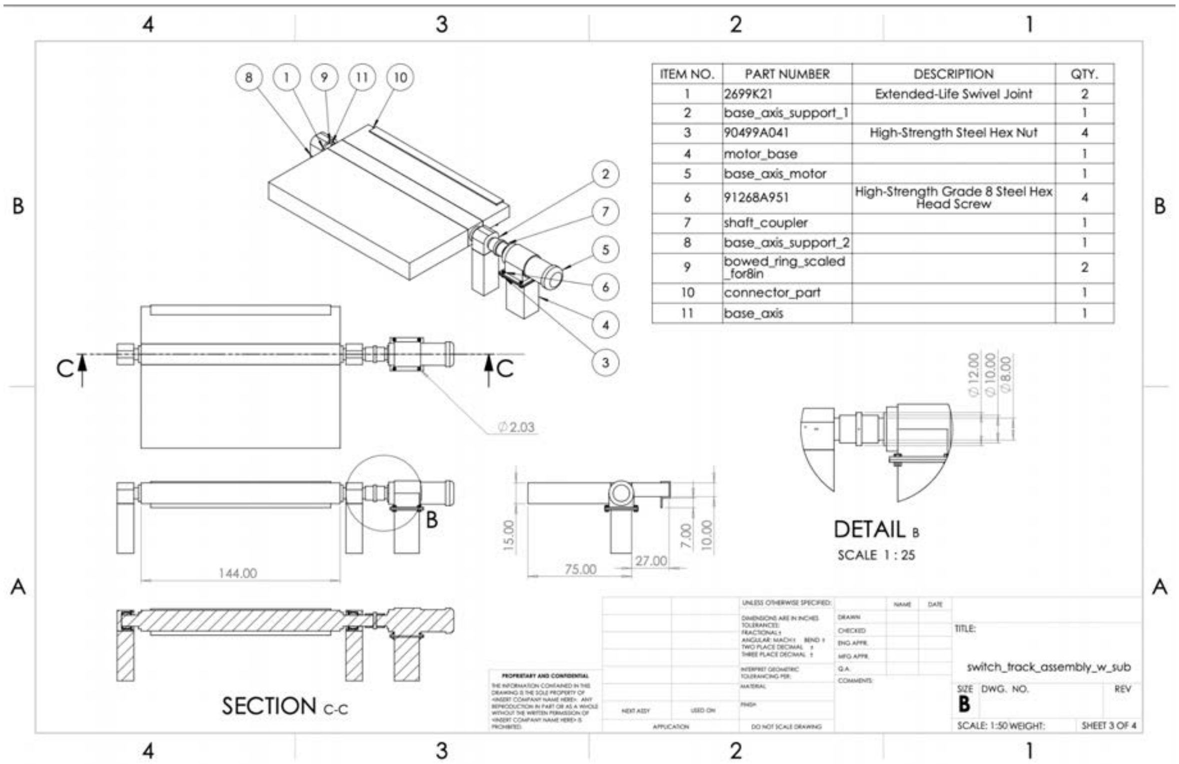


Figure 3: Switch Track Assembly, Base Subassembly Engineering Drawing

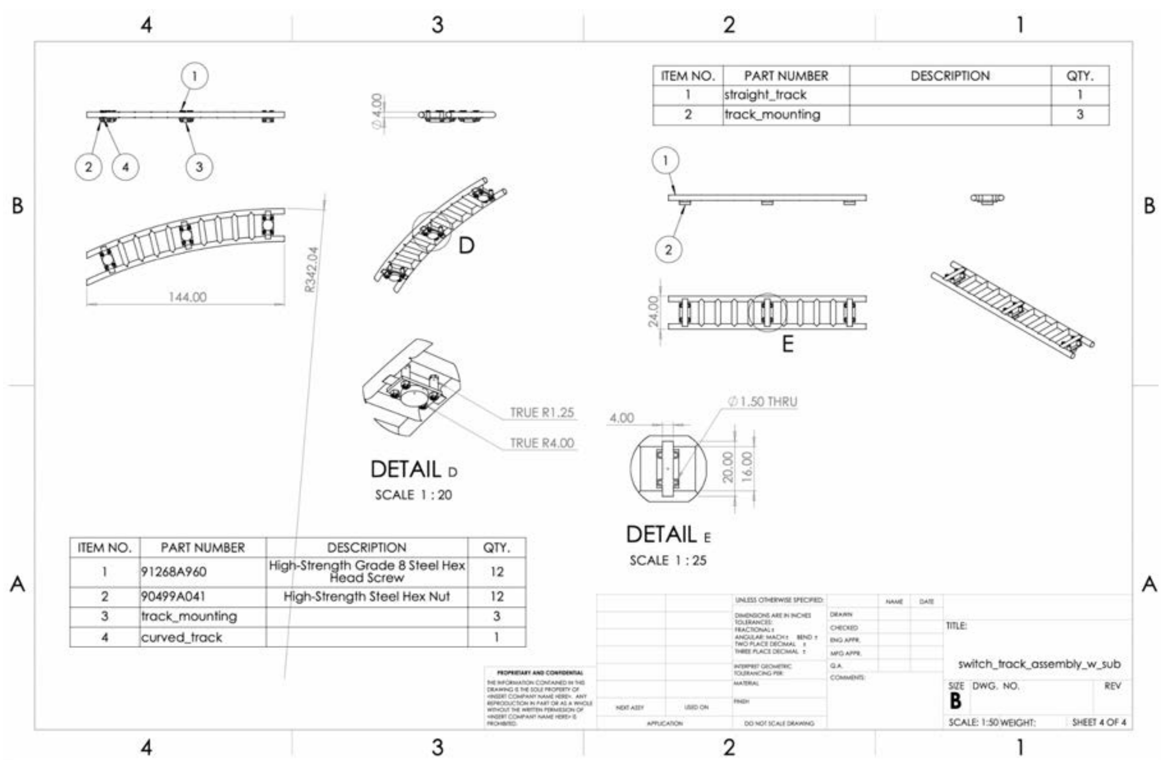


Figure 4: Switch Track Assembly, Curved Track & Straight Track Subassembly Engineering Drawing

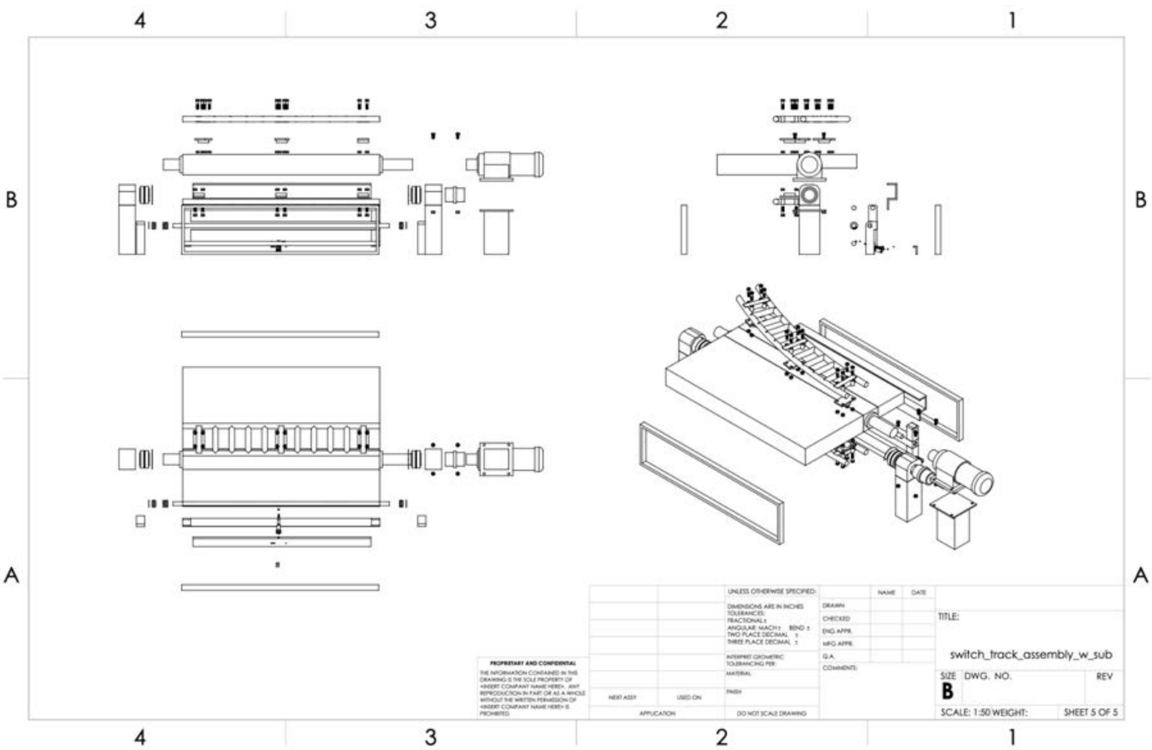


Figure 5: Switch Track Assembly, Engineering Drawing, Exploded View

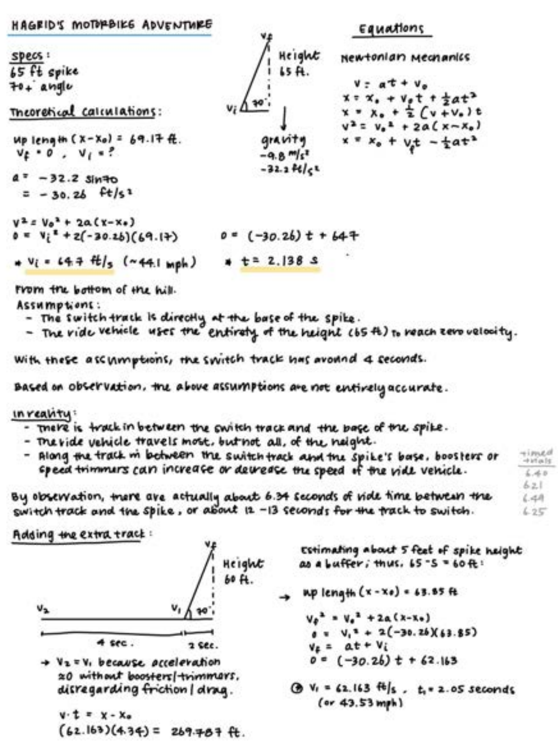


Figure 6: Engineering Calculations, Time Estimations

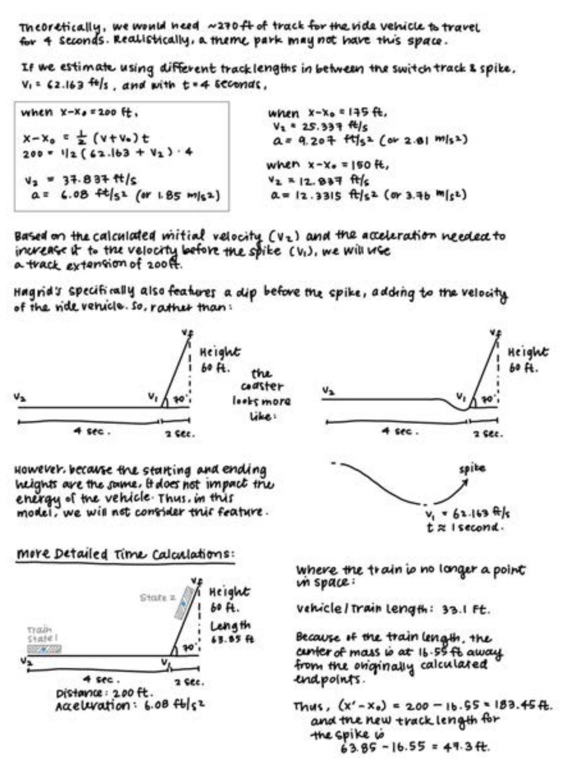


Figure 7: Engineering Calculations, Time Estimations

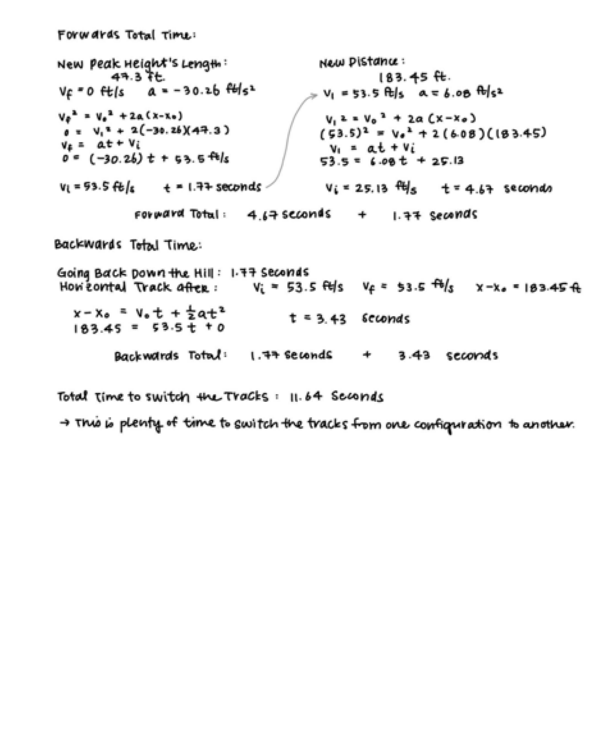


Figure 8: Engineering Calculations, Time Estimations

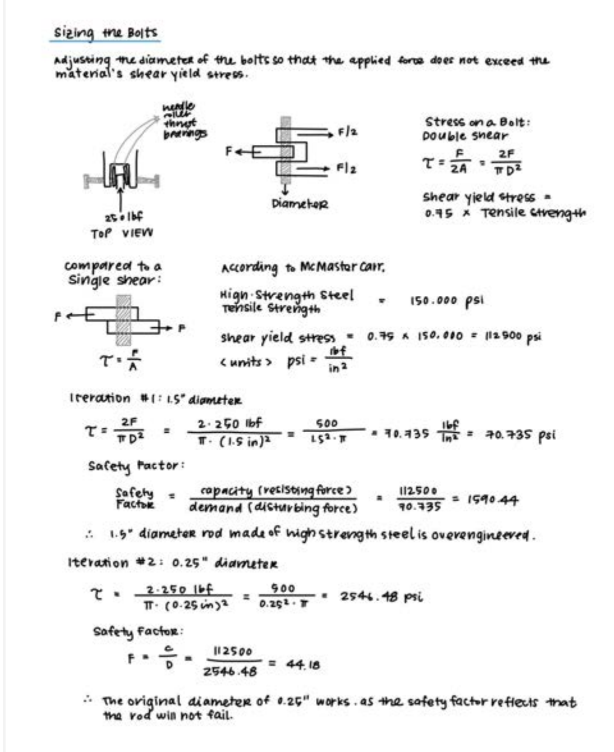


Figure 9: Engineering Calculations, Sizing the Bolts

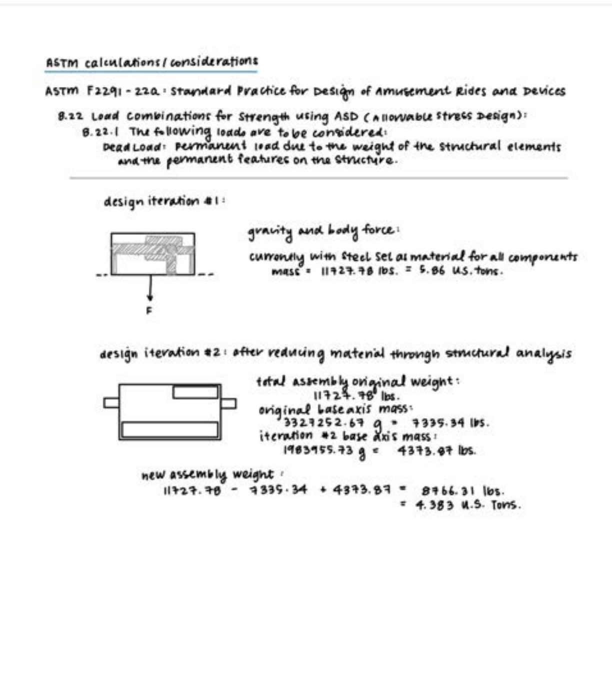


Figure 10: Engineering Calculations,
ASTM F2291-22a, 8.22

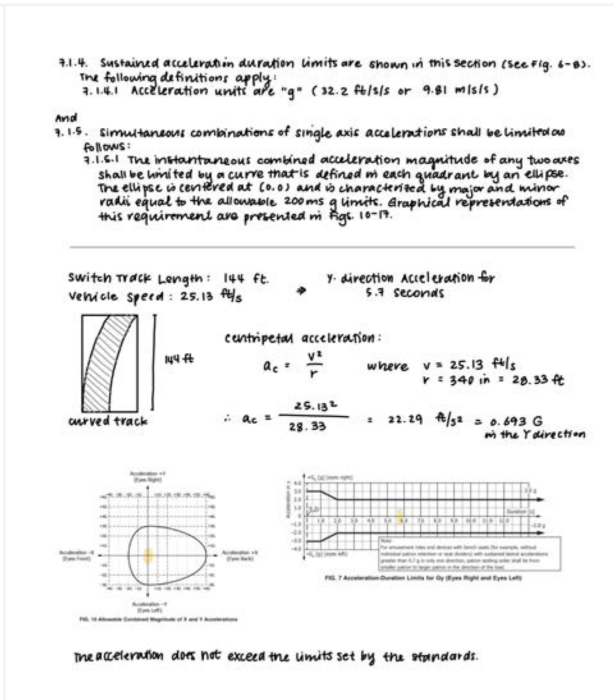


Figure 11: Engineering Calculations,
ASTM F2291-22a, 7.1.4 and 7.1.5

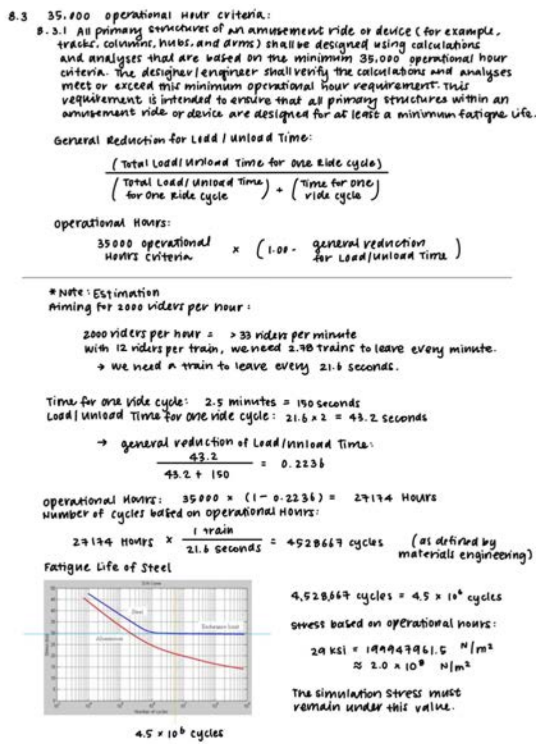


Figure 12: Engineering Calculations, ASTM F2291-22a, 8.3

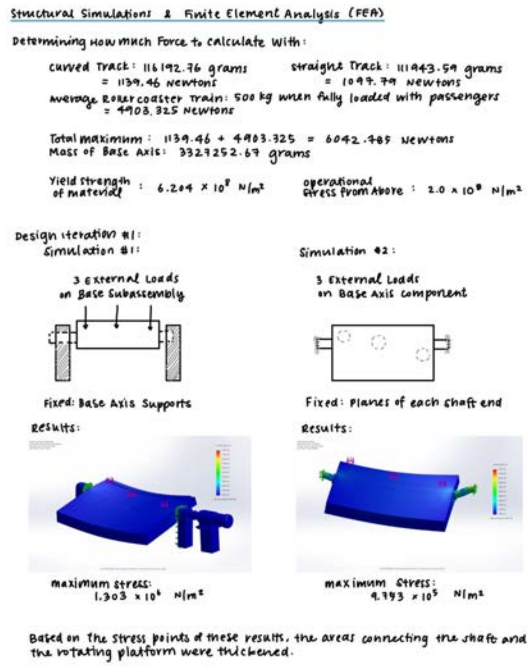


Figure 13: Finite Element Analysis (FEA), Iteration #1

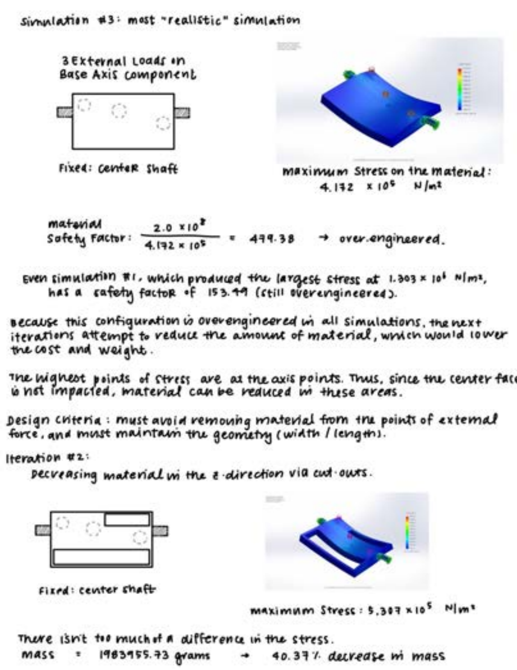


Figure 14: Finite Element Analysis (FEA), Iteration #1 and #2

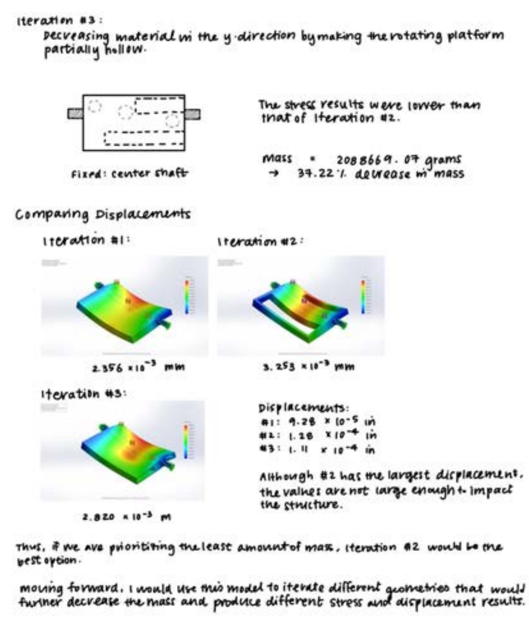


Figure 15: Finite Element Analysis (FEA), Iteration #3

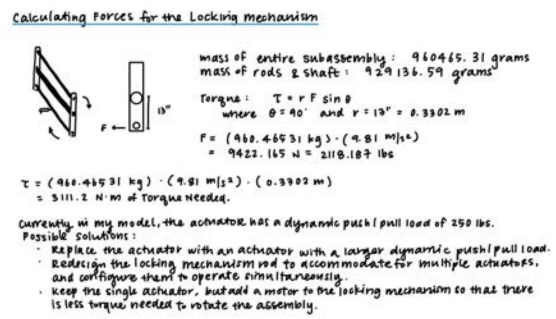


Figure 16: Engineering Calculations, Locking Mechanism Forces

Figure 17: All Animations (https://drive.google.com/drive/folders/1qTicBYqBgS_NnkZN9TVdM-XK_Xn5qro_?usp=share_link)

Appendix B: Ideation & Process Drawings

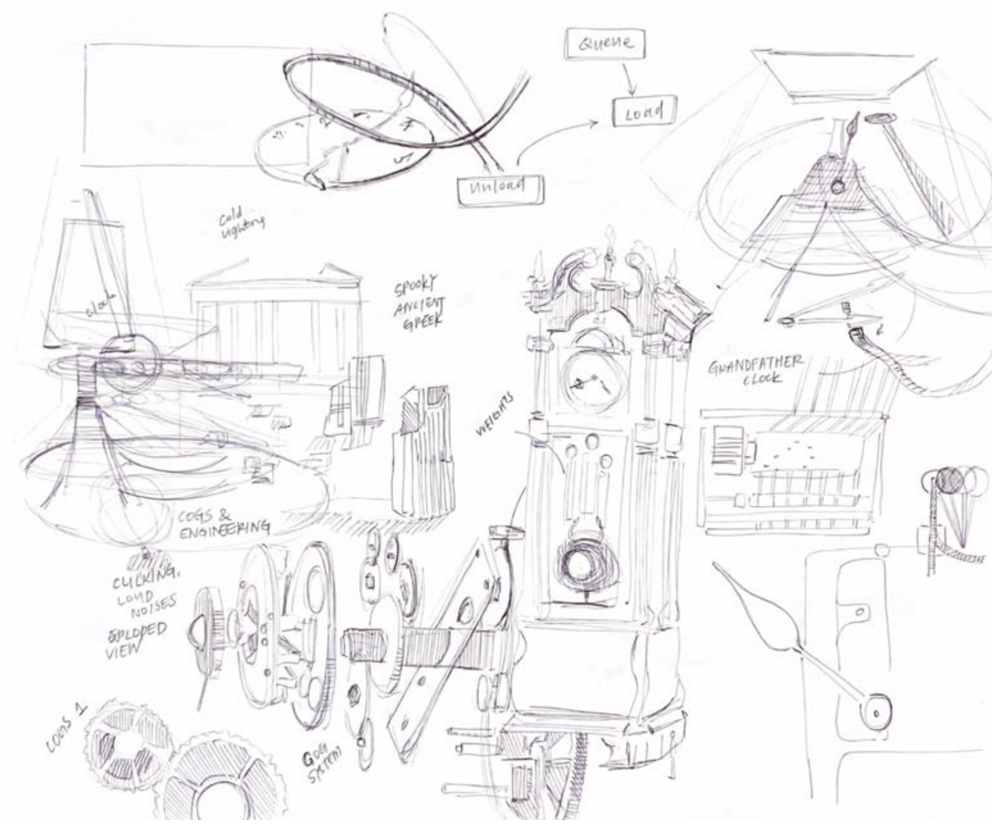


Figure 1: Concept, Narrative, and Guest Experience Ideation

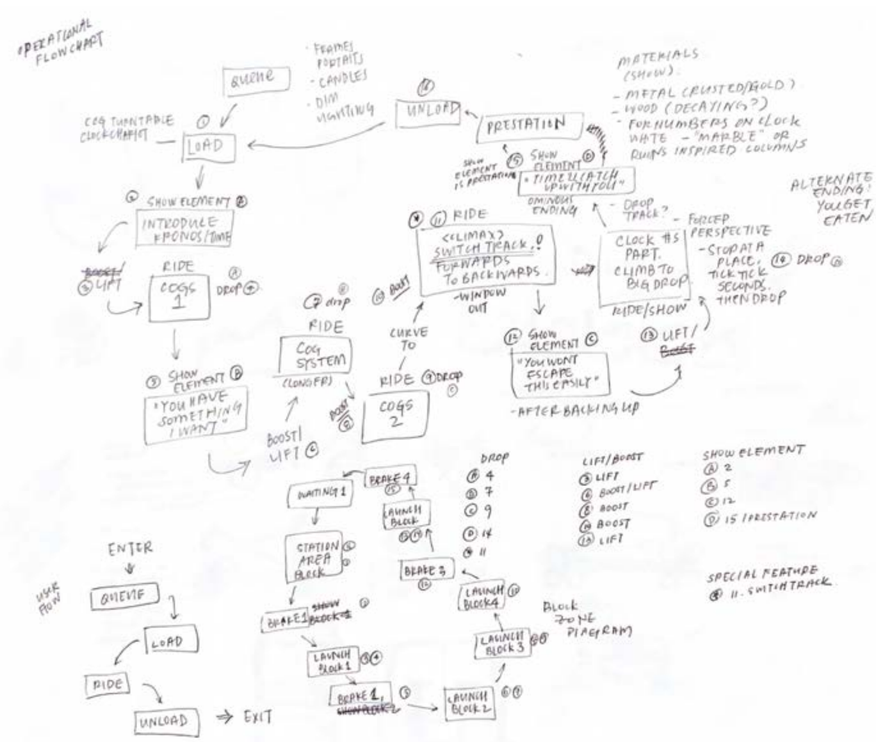


Figure 2: Concept, Narrative, and Guest Experience Ideation

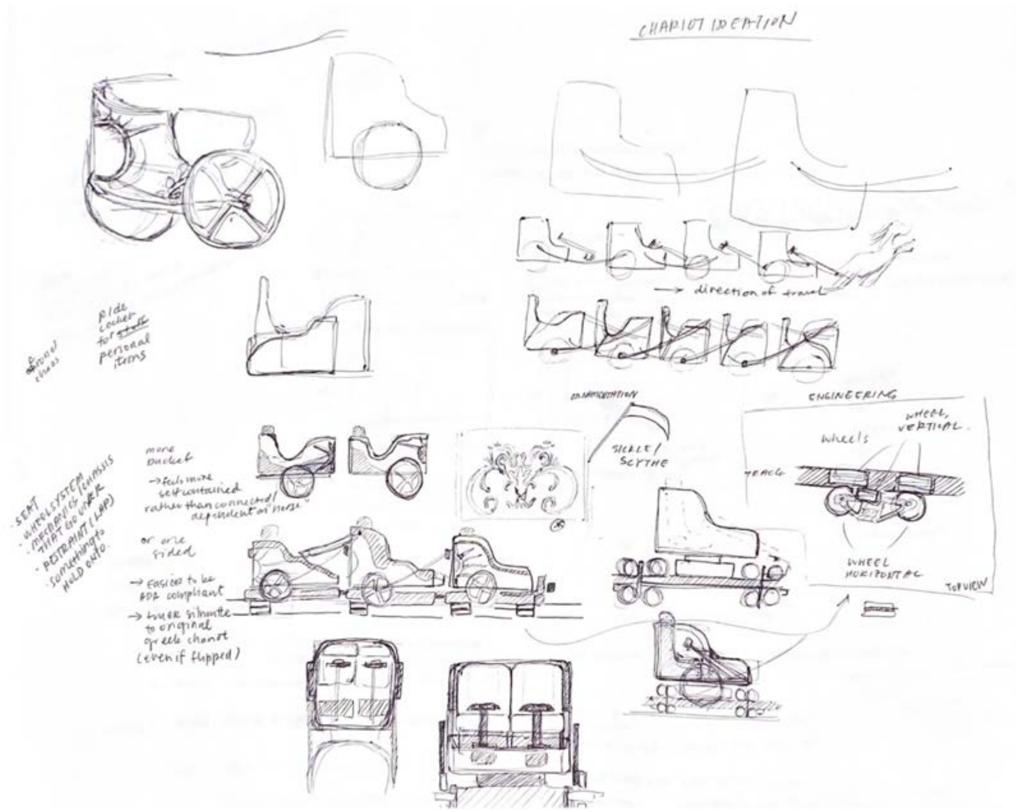


Figure 3: Ride Vehicle Design Concept Ideation and Engineering

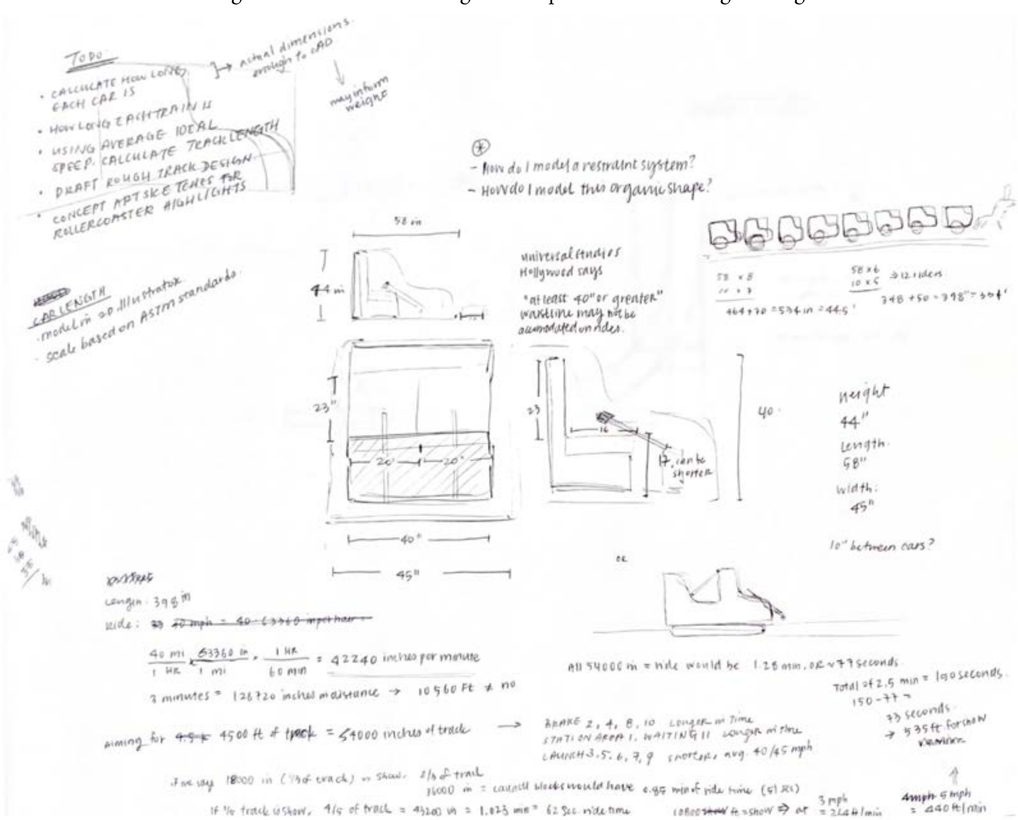


Figure 4: Ride Vehicle Design, Engineering, and Calculations

Appendix C: Reference Images

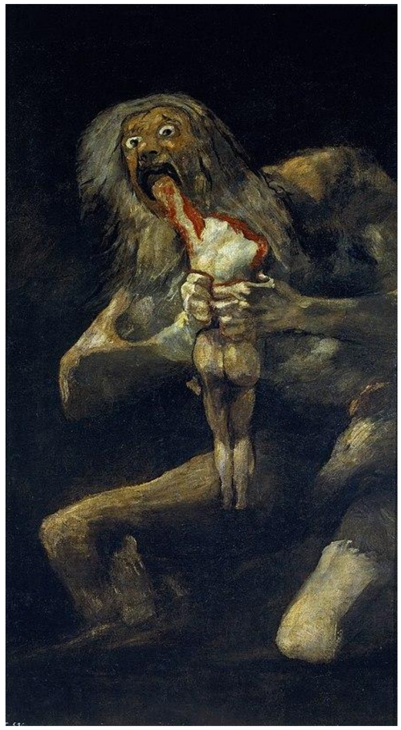


Figure 1: *Saturn Devouring His Son* by Francisco Goya (1819–1823)

Figure 2: *Chariot of Venus* by Pietro da Cortona (1622)

Figure 3: Copperplate engraving by Angelo Monticelli from Giulio Ferrarios Costumes Ancient and Modern of the Peoples of the World, Il Costume Antico e Moderno, Florence, 1842

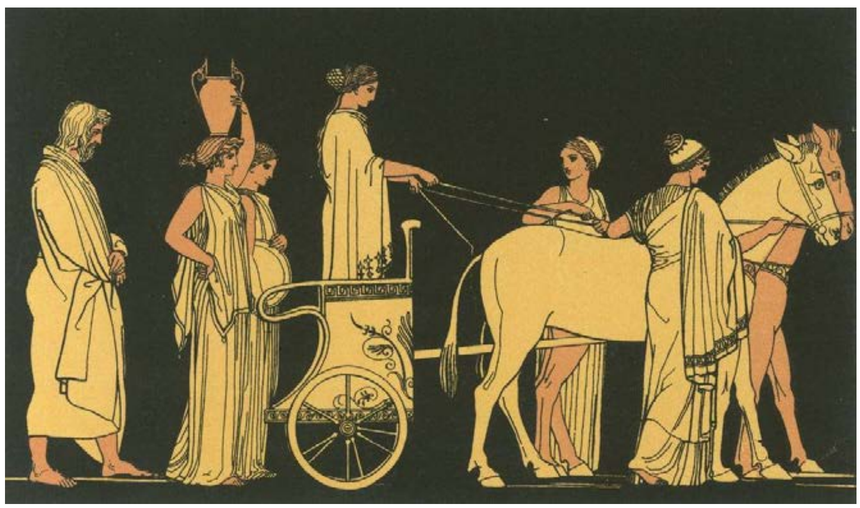
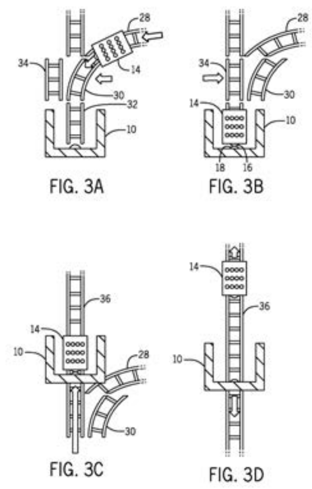
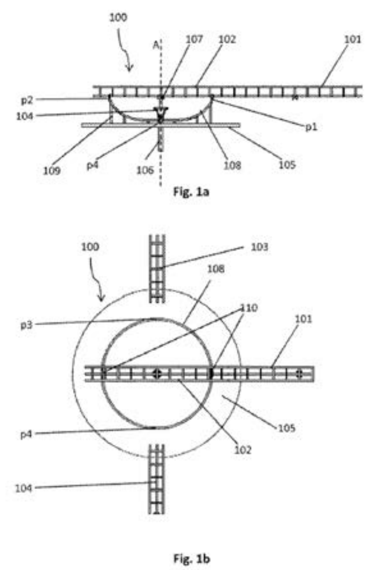
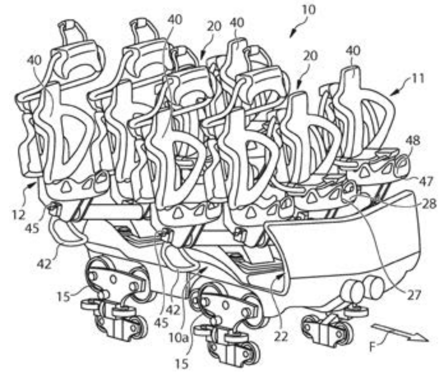
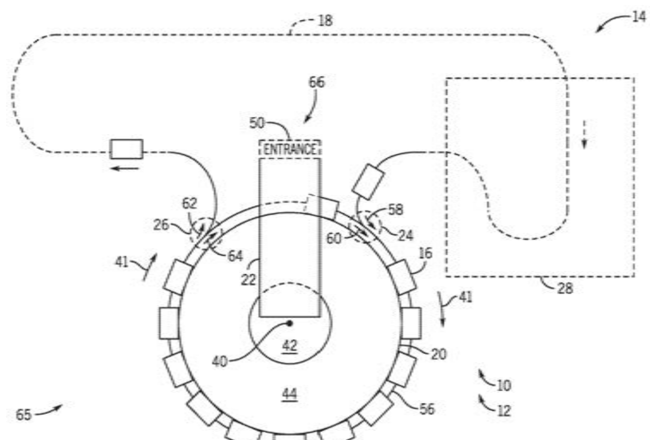
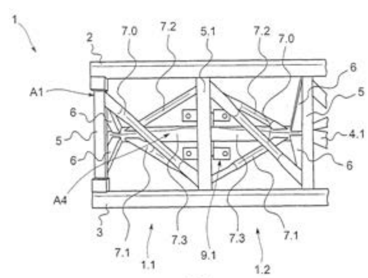
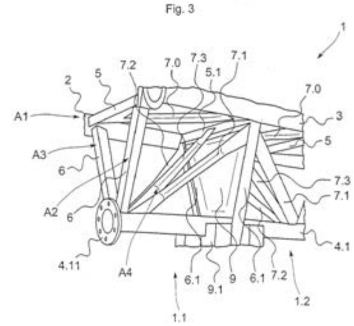
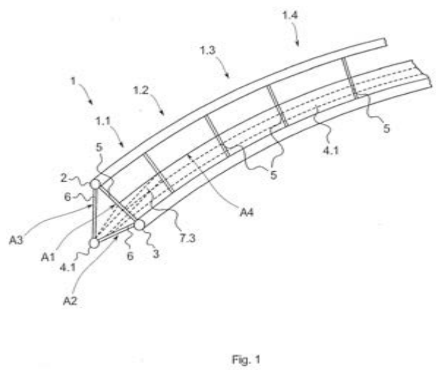
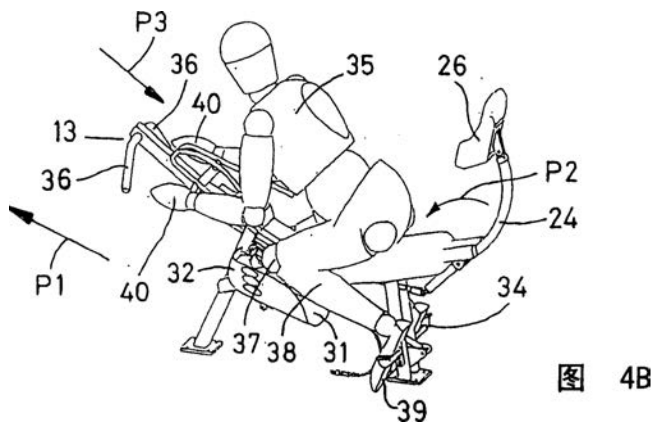


Figure 4: Ulysses following the car of Nausicaa. From "Stories From Homer" by the Rev. Alfred J. Church, M.A.; illustrations from designs by John Flaxman. Published by Seeley, Jackson & Halliday, London, 1878

Appendix D: Other Related Patents

Name	Patent #, Company	Related Image
Vehicle transportation room system and method	US9526997B2, Universal City Studios, LLC	
Device for changing the direction of travel of a rail-bound vehicle, rail-bound ride having such a device, and method for operating such a device	AU2014381043B2, Mack Rides Gmbh & Co. Kg	

Rollercoaster	EP3628384A1, Mack Rides Ip Gmbh & Co. Kg, De	FIG 1 
Loading turntable systems and methods	US20200269888A1, Universal City Studios, LLC	 FIG. 1
Track system for an amusement ride, in particular for a roller coaster or suspension rail	EP3052210B1, Mack Rides Ip Gmbh & Co. Kg, De	 Fig. 3  Fig. 4

[Rail system for a fairground ride, in particular for a rollercoaster or suspended ride](#)	EP3574968A2, Mack Rides Ip Gmbh & Co. Kg, De	
[Entertainment Equipment.](#)	NL1022745C2, Vekoma Rides Engineering B.v.	
[Ride attraction anti-roll back system](#)	US5715756A, Universal City Studios, LLC