Characteristics and Comparisons of Roller Coaster Launching Systems: Hydraulic, Magnetic, and Friction Wheel

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Problem and Hypothesis

The four most popular categories of roller coaster launching systems are hydraulic, magnetic Linear Synchronous Motor (LSM), magnetic Linear Induction Motor (LIM), and friction wheel. I have ridden many of the world's fastest launching coasters, and my hypothesis is that the hydraulic launching system is the most powerful because of the higher velocity and hill height the trains are able to reach compared to the magnetic and friction wheel systems. Is there a unique way that the hydraulic launch system components work to generate the most power, and is there a way to calculate the forces required to achieve a new record-breaking coaster?

Abstract

Over the past decade, launching roller coasters are extremely popular over traditional chain-hill coasters as ride engineers push the boundaries of physics and engineering to satisfy the always-demanding coaster enthusiasts' appetite for bigger, faster, and taller thrills. With this project, I have thoroughly researched important aspects of the physics and engineering forces that underline the four popular launching systems, with the goal of determining how they work, why they work, and how future coaster layouts can be designed for even faster speeds and towering heights. I have calculated and correlated 13 physics metrics for 24 coasters, including power, work, force, acceleration, top velocity, launch track distance, time to top speed, and track hill height, and I proved which launching system is most powerful. I then reveal an algorithm that I created to calculate a record-breaking hill height for a newly-imagined launch coaster.

Research

How the Hydraulic System Works

Even though the Intamin company's patented hydraulic launch system (*Figure 1*) is extremely powerful, the operating principle is fairly simple for the Formula Rossa, Top Thrill Dragster, and Kingda Ka coasters, all designed by Intamin. Hydraulic oil pumps from a reservoir into storage cylinders filled with nitrogen. "The nitrogen compresses and acts like a spring, and the hydraulic oil acts like potential energy," explains Cedar Point's Monty Jasper, vice president of maintenance and new construction. The ride operator gets a signal when pressure has built up and the train is ready to launch. Pushing the start button opens high-speed valves at the storage cylinders and sends the oil flowing to 32 hydraulic motors. Gears on each end of the motors turn a large gearbox. Gearboxes sit on either side of a cable-winding drum that turns at 500 rpm. "The drum works like a big fishing reel, taking up cable as it turns." Jasper explains. The launch cable attaches to a locking device called a catch car that, in turn, attaches to the coaster train. The catch car runs in the track and propels the train forward. Reaching the target speed of 120 mph disengages the cable from the train, closes the hydraulic valves, and restarts the process.

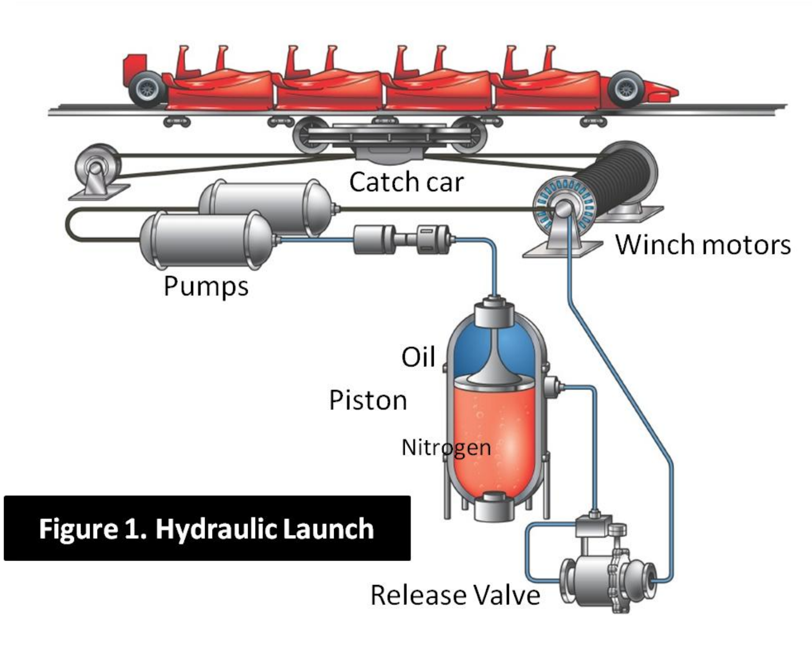

Figure 1. Hydraulic Launch

The volume of the cylinders is divided into two parts by a movable piston in the uppermost cylinder. One part contains the nitrogen, the hydraulic oil is pumped into the other one between the launches. The oil is hardly compressible, so it moves the piston and compresses the nitrogen on the other side at the same time. So there a pressure of up to 300 bar is generated, which is 300 times the air pressure in the atmosphere - an enormous energy. For the launch, the hose to the pump is closed and the valves to the motors are opened. Now the oil is pressed through the hydraulic motors because of the pressure inside the nitrogen. Two seconds later the entire oil is back in the pressureless tank.

The motors are arranged circularly around a huge toothed wheel that is connected to a winch. Through a hole in the ceiling they are hardly visible. On the winch, which has a diameter of about one meter, the ends of the steel cables that actuate the so-called catch car are wound up and off. This longish sliding carriage moves shortly underneath the launch track. To transfer the power of the hydraulic system to the train a pusher under the vehicle engages the catch car. At the end of the launch track the Catch Car is decelerated by magnetic brakes in the track, the train automatically disengages from the pusher and rushes towards the coaster pleasure at full speed.

Figure 2. Kingda Ka

Equally amazing is the low power consumption of the drive system, because the immense power of the catapult launch lets one to assume differently. Only the hydraulic pump stresses the power supply system, which has a power consumption of only 150 kilowatts, but this is enough to increase the pressure inside the nitrogen to 300 bar within about one minute. The energy stored that way is transformed in just two seconds during the catapult launch - the hydraulic motors provide about 3 megawatts (3 million watts) during this period - enough to accelerate the seven-ton train from stand to 120mph. It is amazing that only 150 kW of input power is converted to over 3,000 kW of output launching power. Source: machinedesign.com

It is interesting to note that the launch systems are built to generate a peak power and speed of up to twice that they produce at launch, so that the system components last a long time and do not wear down quickly, and thus designers rarely design a system to operate at peak power. This is similar to cars that have a peak speed of 150 mph but we rarely drive faster than 80 mph. With this, the Kingda Ka (*Figure 2*) engineering designers do not want the ride to launch faster than a prescribed speed of 128 mph because the 456 feet tall hill has a curved top hat crest design, and if the peak operating speed is used the train will produce G-forces at the top that would injure or kill riders.

Figure 3. LSM Track: Cheetah Hunt

How the LSM System Works

The use of LSMs in roller coasters is used to launch and accelerate roller coaster car along a straight section of track. An LSM roller coaster (Figure 3 and Figure 4) has a set of permanent magnets embedded launch track, with the north and south electromagnets

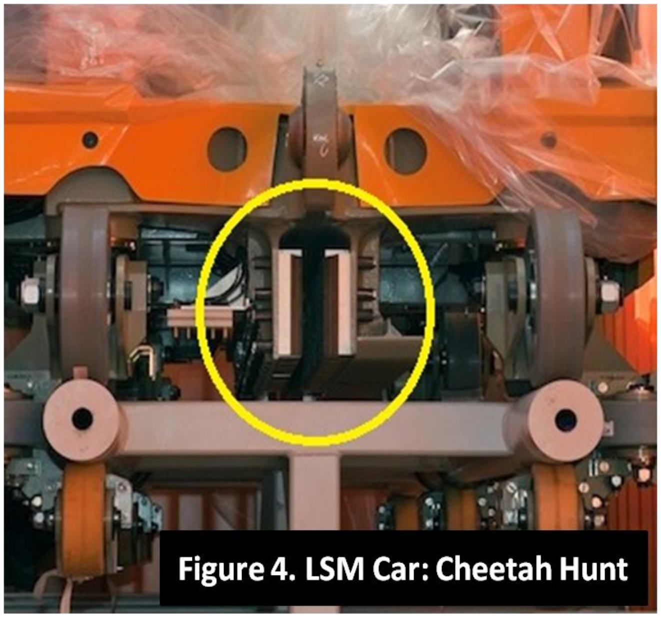

Figure 4. LSM Car: Cheetah Hunt

alternating. There is also a set of electromagnets (a north and a south) called armatures placed inside the car of the roller coaster at specific intervals. The north electromagnet in the armature would be placed intentionally in between a north magnet on the right and a south magnet on the left on the roller coaster track. Thus, the two north magnets would repel each other, while the armature north magnet would be pulled toward the south magnet to the front. This would cause an overall forward motion. When the armature magnets attract toward the permanent magnets on the track, polarization of the armature magnets is needed to allow the roller coaster car to continually move forward. Here, a "synchronized" pulse turns electromagnets on and off in sequence to accelerate the roller coaster car to its full speed. It is this force between the armature magnets and the permanent magnets on the coaster track that propels the roller coaster forward. The longer the track of magnets is used, the coaster will generate faster speeds.

How the LIM System Works

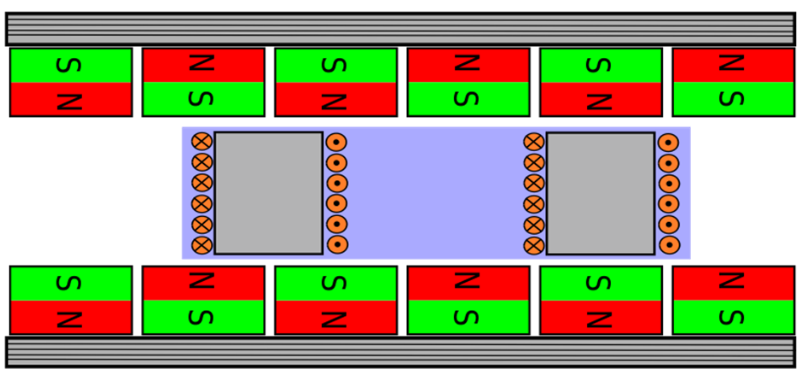

Figure 5. LIM Track

When a piece of metal passes through a magnetic field, a current is induced. When the alternating current power supplied to the magnets in the transformer turns on and off quickly then the metal coil in between the two batteries spins. Now if you take that and lay it out flat, you get a linear induction motor. Two magnets are placed on top of each other on the side of the track, leaving a space in between. When a metal fin attached to the train passes through the magnetic field created, it "rides" the magnetic field. AC current is applied which creates a wave for the fin to ride. LIM powered coasters (*Figure 5* and *Figure 6*) use multiple sets

of magnets on both sides to power their rides. Flight of Fear at Kings Island and Kings Dominion were the first coasters to use LIM technology in 1996.
Source: www.ThrillNetwork.com

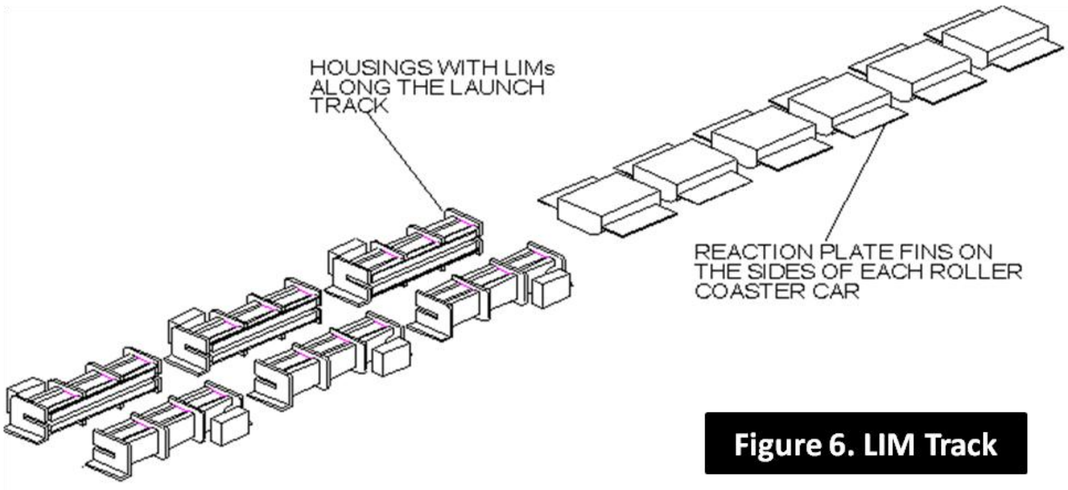

Figure 6. LIM Track

Data Analysis

Through my research and data analysis, I learned that the hydraulic launching system is the most powerful system to propel the train because it generates the highest average launching power of over 2500 Kilowatts, compared to an average of 750 Kilowatts generated for the magnetic systems. The hydraulic system also has a maximum launching power of 3800 Kilowatts (Formula Rossa coaster), and all seven of the hydraulic coasters generate double or greater output than any of the magnetic LIM/LSM coasters. These results correlate to the top speed of the coasters, where the hydraulic coasters launch between 72 - 149 mph top speed, compared to the magnetic systems that propel the train to a top speed of 53 - 100 mph. The speed and power are correlated into the hill height that he trains can attain, where a hydraulic coaster (Kingda Ka coaster) climbs to a world record 456 feet tall. The LIM and LSM coasters climb between 70 - 180 feet tall, but the Superman LSM ride climbs to 370 feet high, due to using a unique double-magnet system. The horsepower and force of launch that a hydraulic launching system generates is over three times that the LSM and LIM launch system produces. This correlates to a faster initial acceleration between 15.6 - 19.1 meters per second for the hydraulic launch coasters in contrast to the LSM and LIM systems having an initial acceleration of 6.1 - 12.6 meters per second. The power that a hydraulic launch system produces is substantively greater than an LSM and LIM launching system because of the greater amount of watts generated to launch the train down the track.

I calculated the mass of each train using an average car mass of 1,100kg plus 75kg per person, multiplying by the number of cars and riders for each train type. I increased the mass for a few of the trains that use a heavier shoulder harness design. The mass of the train, the length of the launch track, and height the train has to crest after the launch are substantial factors that cause a variety of the work of the launch depending on the type of launching system used.


Figure 7. Formula Rossa

To calculate the amount of pumps for all seven hydraulic coasters, I took the already-known power (Watts) and number of pumps from three coasters of Formula Rossa (*Figure 7*), Kingda Ka (*Figure 2*), and Top Thrill. I then calculated total power divided by number of pumps to find a new number called 'power per pump', which at 79,200 to 80,500 Watts per pump was extremely close for the three coasters. I used an average of 80,000 Watts per pump, then for each of the remaining four hydraulic coasters, I divided its total power by 80,000 Watts to arrive at the number of pumps that each coaster uses. For example, *Xcelerator* coaster generates 2,057,587 Watts divided by 80,000 Watts/pump = 25 pumps.

To calculate the magnetic surface area for the LIM and LSM coasters, I took the already-calculated total power (Watts) of each coaster. I learned that launching systems using neodymium magnets generate power at a force density of 7.5 feet pounds per square inch. I found that Watts x 0.736 = 1 foot pound force per second. There are 144 inches in a square foot. Therefore, to convert the coaster power to find the launch runway magnetic surface area, I created the formula, Magnetic Area=Watts(.736)/7.5ftlb/sec/144in, to arrive at the total magnetic area for each LSM and LIM coaster. For example, Cheetah Hunt (*Figure 8*) generates 675,662 Watts at launch, so 675,662 Watts x (.736)/7.5ftlb/sec/144in = 460ft^2 of total magnetic area (*Figure 3 and Figure 6*).

The Physics Behind the Thrills

The math and physics results that I calculated for each of the 24 coasters follows, using Kingda Ka (*Figure 2*) in this example: the train accelerates to 128 mph in 3.5 seconds. A train loaded with 18 riders weighs 6,650 kg. Velocity = 57 meters per second, therefore the launch distance traveled by the train in these first 3.5 seconds is .5(velocity X time) = .5(57m/s X 3.5s), which equals 100 meters. Acceleration = velocity/time, a=v/t, 57m/s/3.5s, which equals 16.3 meters per second. Force=mass X acceleration, where F=ma, so F=6650kg X 57m/s = 108,395 Newtons. The kinetic energy and work to create this force is W = Force X distance, therefore kinetic energy and Work = 108,395 Newtons X 100 meters = 10,888,108 Joules. Power in Watts = Work/time, W/t, or Joules/second, therefore Power = 10,888,108J / 3.5s = 3,110,888 Watts. One horsepower = 1340 Watts, therefore HP=Power/1340, or 3,110,888/1340 which generates 2,322 horsepower at launch. Those are enormous physics forces generated!

To calculate the effects of friction, I calculated how much energy is required for the train at the end of the launch runway to climb the hill, as mass X gravity X height, or mgh. Then I solved to compare the energy that the train would require with a frictionless hill climb versus its actual power generated. For example, if there was no friction, Kingda Ka with mass of 6650kg and climbing 456 feet, would only require mgh = 6650kg x 9.8m/s^2 x 456ft = 9,058,000 Joules of work. But the coaster actually generates 10,888,108 Joules to climb 456 feet, meaning the energy lost to friction up the hill climb is 10,888,108 – 9,058,000 = 1,830,108 Joules or 17%. So the system needs to generate 17% more power than expected to make the hill climb with friction present.

System Engineering Differences

I identified that the main driver behind why the hydraulic system packs so much more power than the magnetic systems is that the hydraulic system can be scaled up by adding more pumps, valves, and motors that are all contained together in the winch launch room (*Figure 9*). Expanding the room, which is easy to do, allows for more equipment to generate more power and speed. Conversely, the magnetic LIM and LSM systems generate power and speed from the magnetic surface area (*Figure 3*) on the length of track. Therefore to generate more speed, the magnetic coasters require longer launch runways, which are mostly impractical, due to the way that theme parks cluster their rides together. There is not room in most theme parks to build a 200 meter horizontal launch runway, which is why the magnetic rides are designed with runways mostly in the range of 30-60 meters.

Figure 9. Hydraulic Winch Room: Kingda Ka

A New Record Breaking Coaster

While researching hydraulic coasters, I identified that Formula Rossa (*Figure 7*) is the fastest velocity (149 mph) of any launching coaster, yet Kingda Ka (*Figure 2*) is the tallest (456 feet). I was curious as to how tall a record-breaking hill Formula Rossa's train could climb if it had a similar vertical track layout as Kingda Ka. The reason Formula Rossa's tallest hill is only 170 feet is because it needs extra power to run a much longer track layout consisting of many hills, whereas Kingda Ka uses all its power to climb the one tall hill. I kept Formula Rossa's velocity, launch time, and launch distance constant, so that I would be using the same force, work, and power for this new record-breaking coaster hill. To calculate how much greater Formula Rossa's launch power is, I divided Formula Rossa's power by Kingda Ka's power to arrive at 3,826,626Watts/3,110,888Watts = 1.23, where Formula Rossa's power is 23 percent greater than that of Kingda Ka. Finally, I multiplied Kingda Ka's existing 456 feet high hill by 23 percent to discover a new record breaking hill height of 456 X 1.23 = **561 feet high** in which Formula Rossa's train would be able to reach with its current launch system power.

Additional / Future Research

Because these 24 coasters are dispersed around the nation and world, it was time and cost prohibitive to conduct research at the theme parks. For that reason I conducted interviews with subject matter experts, such as design engineers, and gathered research from leading engineering journals and theme park publications. I have advanced this project as far as I can from my current understanding of physics. To continue this research, I will need to learn electricity, magnetism, thermodynamics, fluids, and gas pressure. To achieve this, I will study mechanical engineering in college, where I can also conduct experiments and tests on engineering lab equipment as it relates to hydraulic and magnetic launching systems.

Conclusion

Based on analyzing 13 physics metrics that I calculated, including acceleration, launch distance, friction, work, force, and power to describe the physics contributing to the 24 launch coasters, I can conclude that my hypothesis was correct in that the hydraulic launching system is the most powerful system to launch a train along the coaster track. The average force generated from the hydraulic launch is 113% higher than the average LSM magnetic system force. The average amount of work and power is 96% higher than is generated from the magnetic systems. I concluded that all of the hydraulic coasters accelerate faster than any of the other coasters, allowing for higher maximum hill heights. I identified that the main driver behind why the hydraulic system packs much more power than the other systems is that it is easier to increase power generation by adding more pumps, valves, and motors in the winch launch room, as opposed to the magnetic systems which require longer launch runways. I successfully calculated a record breaking hill height of 561 feet tall for a new rollercoaster that utilizes Formula Rossa's hydraulic launching system while using a track layout based on Kingda Ka. Within the magnetic systems, I calculated that the LSM and LIM systems generate similar physics forces even though their engineering designs are different. I learned about the basics of engineering design about how hydraulic and magnetic launch systems work, including basics of fluids, gas pressure, thermodynamics, electricity, and magnetism.

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