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ESG Report
FALL 2011

Engineering Dreams: ANALYTICS VS. TESTING CASE STUDY

It all started with something of a dream. A year or so ago, a few stunt aficionados discovered a record that needed to be broken: The longest jump to-date made by a gas-powered four-wheel vehicle was 298 ft. The challenge? Jump farther. The hook? Replicate a life-size version of a popular child's toy race track to pull it off. Books, boxes, doorways, chairs, pillows and sofas – anything goes when you're dreaming up a stunt. This one was not much different except the doorway was 100 ft tall! In concept it seemed easy, but once the pencils hit paper it got complex, even a little problematic, very quickly. In this edition of the ESG Report we'll share a little bit of how this project/stunt evolved and then discuss how actual load testing became a critical requirement to help validate — even trump — mathematical calculations. Here's how it all started...

The Project:
Hot Wheels™ Fearless at the 500

The Client:
Murphy Productions

The Scope:
Engineer a tower, drop-in ramp, run-in, and launch and landing structure to withstand code-required wind loads and the dynamic loads induced by the truck's acceleration, take-off and landing on the custom-built structure.

The Problem:
A 4,100-lb truck traveling 100 mph, launched at a 15-degree angle.

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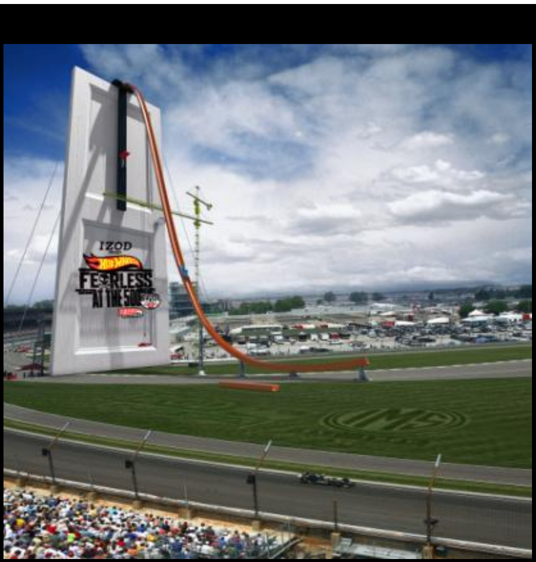
Engineering for the Entertainment Industry



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As with any engineering project, the first question is usually "what are the loads?" In this case, several variables made this a complex challenge where the calculated results were potentially so high, they required actual mock-up testing to validate.

Let's examine the problem in more detail and break it into its critical components. This challenge has but a singular goal: successfully launch the truck across a distance greater than 298 ft (the previous record distance).

The logical starting point was to use simple motion and trajectory formulas to determine basic working design criteria. The distance had to be greater than 298 ft. From past experience with stunt jumps, the anticipated takeoff angle would be between 13 and 15 degrees.

Step 1:
Determine the takeoff speed. Using Range R=300 ft and angle θ = 15 degrees in the formula $R = (Vo^2 sin2\theta)/g$ minimum launch velocity is calculated at 139 ft/sec, or a minimum of 94.7 mph. After considering the effects of wind resistance, this launch velocity was increased to 98 mph.

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Step 2:
Determine the acceleration and deceleration distance. Intuitively we need to break this down into two components: Part A takeoff and Part B landing. Each of these two parts must consider elements of both dynamic force and distance. Calculating the stopping distance is the easiest of those elements. The vehicle tires used a heavy off-road terrain tread pattern having a conservative value of 0.6 for μ. Presuming a velocity of 98 mph – and knowing that the velocity will be lower at landing than at launch – we use the formula $d = Vo^2/(2\mu g)$ to calculate a stopping distance of approximately 535 ft.

Part A is quite a bit more challenging because the final takeoff speed of 98 mph had to be achieved in a reasonable distance but also had to be constant when the truck left the takeoff ramp. Any acceleration would cause the truck's center of gravity to pitch backward, any deceleration would cause it to pitch forward and nose-dive.

Let's get an idea of what it takes in terms of distance and acceleration to get a vehicle up to that speed. A stock-class drag racing vehicle can turn a quarter-mile (1,320 ft) at top speeds ranging easily upwards from 98 mph, depending upon its factored weight-to-horsepower rating. However, the Indianapolis venue's total available space for the stunt structure was around 2,000 ft, which meant that the truck had to start, accelerate, jump, land and stop in less than that distance to maintain a reasonable margin of safety. Think about that for a moment while we consider other factors.

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At 100 ft tall, the tower is possibly the tallest aluminum truss tower system of its kind ever constructed and serves as the starting point for the truck. Given 100 ft as the height, 45-degrees as the drop-in ramp incline, and a truck starting velocity of 1 mph we could approximate the truck's velocity at the bottom of the ramp, again using basic velocity formulas.

Calculations revealed that with gravity acceleration only, considering friction, the truck will reach a maximum velocity of approximately 57 mph when it reaches the bottom of the incline. At that point, the vehicle must continue acceleration to the target launch velocity, which is where we left off previously: how much space would be required to do so?

In horizontal distance, enough space is required for the truck to park at the top of the ramp (20 ft). A 45-degree incline from a 100 ft tall tower also translates to 100 ft of horizontal distance, but the radius transition required at both the top and the bottom of the ramp pushes that to 130 ft. We know that the target jump distance to clear is 300 ft and the anticipated stopping distance is 535 ft. Add those values together for a cumulative distance of 985 ft. Given the available on-site space, an absolute not-to-exceed site distance of 2000 ft, this leaves just over 1000 ft to accomplish the acceleration.

Knowing that Trophy Class vehicles like the one used for the stunt are easily capable of higher-than-normal acceleration in a shorter than average time frame, and given a calculated starting velocity of 57 mph, the designers agreed to start with a distance of 400 ft as the initial run-in distance to achieve target launch velocity of 98 mph. Now it's time to run a few tests.

So far, this has been an academic exercise to provide an overview of the design process and to demonstrate how analysis helped establish design criteria for the basis of the structural analysis, because we haven't yet considered the structural design loads. All of this preplanning is for naught if the structure can't withstand the dynamic forces generated by the truck.

At the test facility, the team ran the truck through several tests to determine how much distance would be required to accelerate from 57 mph to 98 mph. The results proved that 400 ft was unrealistic – the truck simply could not accelerate quickly enough. During these tests, 400 ft was also proven to be dangerously short because it didn't give the driver enough time to estimate sufficient speed, and then safely abort if something went wrong. There had to be enough time and space to make calculated decisions for success, and for safety. Additional tests were run to determine that 800 ft was a comfortable run-in distance. Sounds easy, doesn't it?

Now the structural engineering begins in earnest with a few major design considerations. The aluminum truss tower system would be one of the tallest of its kind ever constructed, but an even greater challenge was the load case: a 4,100-lb truck, the forces imparted by the winch that hauled the truck up the ramp to the top, along with essential technical staff required at the top of the tower. These loads must be safely supported on a structure that must also withstand code-required design wind loads.

The next challenge was to calculate the dynamic loads of the truck at three critical locations on its path: first at the bottom of the drop-in ramp at the transition between the ramp and the run-in. Second at the transition of the run-in to the launch ramp and third at the actual landing zone point of impact. Using centripetal force calculations the forces at the first two critical points were easily determined, but the calculation results were a little disturbing because they revealed that the launch forces could be as high as three times the force of gravity. Using basic force and acceleration formulas, the landing zone forces were estimated at an extremely high value of almost 7g. To say the least, designing a temporary structure with enough capacity to withstand this magnitude of force is not practical.

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Another key factor that quickly became a very complex, yet critically important variable to resolve was how the truck's suspension would behave. This is where real-life testing became most important to validate the dynamic impact forces the structure would need to withstand. The production team went back to the test facility and ran additional tests, this time using sensors installed on the truck, permitting real-time capture of dynamic data during the runs. The results revealed that the actual forces were considerably lower than the calculated forces. Because those results were consistently repeated, they were critical in justifying a reduction in design load, thus permitting a valuable reduction in the size of structural framing members.

Finally, after considerable analysis, testing, and verification the ramp system design was complete, verified and built. The net result was an exciting event and a successful jump of well over 300 feet – a new world record!

We'd be remiss if we didn't acknowledge the design team members who helped make this project a huge success – from design, engineering and fabrication, to installation, testing and execution. A lot of people, too many to name them all, worked collaboratively to make this project a success.

Our circle of appreciation includes the folks at Murphy Productions (Jack, Jon, Pete) and their highly specialized install team led by Jerry and including Shane, James, Jimmy, and many others. Thanks also to the rock stars at Staging Dimensions, Light Action, and Applied Trussing (Scott, Mike, Mikey C, Andrew and Andy), with a special nod to Bill G. and his team at McLaren for their watchful eyes, too.

These types of events aren't the only time actual testing is used to validate results. Engineers use this type of data validation for various things, such as staging platforms and railing connections, when the code required load cases are difficult to prove analytically.

Finally, there are also real-life situations where you don't want to rely solely on live-load testing to validate results. When the wind is blowing on a temporary outdoor structure during an actual event, this isn't the time to wonder if your engineering is accurate or your management plans sufficient. In light of the recent roof system collapses we've seen in our industry, we're closing with a recap from the Operations Management Plan article we wrote back in our winter 2009 issue of the ESG Report. You can download it here.

We won't mince words about the importance of safety or of planning ahead. The entertainment industry has worked diligently for many years to develop safety standards, one of which (ANSI E1.21) pertains to outdoor temporary roof truss systems. Parts of this standard address engineering and operations management plans for the explicit purpose of ensuring that these systems are both appropriately designed and safely used – even when weather conditions may create a need for heightened levels of awareness. Unfortunately, one cannot always predict unforeseen weather conditions, but one can prepare in advance to mitigate the effects of such unpredictable weather so that events, systems and people remain safe. The existing standards are a valuable resource for users and code officials alike. If you are not using these resources you should be.

Thoughts or comments? Send them to us c/o
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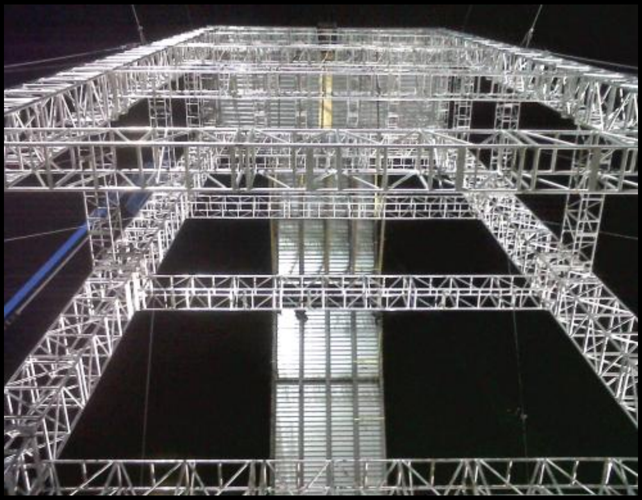
We're listening.



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Disclaimer: This article is not intended to be a thorough treatment of the topic of structural evaluation. Local, state and national building codes should be consulted. The author cannot be responsible for any evaluation based solely upon this article.

About the author: Richard Nix is ESG's division project coordinator. His diverse range of expertise includes that of stagehand and staff rigging supervisor in addition to rigging system design and installation. He is the author of many published technical articles relating to entertainment technology and has participated in PLASA-NA's standards development effort for over 16 years.