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Feel the Vibration! Measuring the Ground Motion Caused by Racecars at the zMAX Dragway

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Abstract

Dragsters raced down a straight 1,000 ft track at the zMAX Dragway and the resulting ground motion was recorded, analyzed, and displayed live to fans. At the NGK Spark Plugs NHRA Four-Wide Nationals on April 26 – 28, 2019 and the NTK NHRA Carolina Nationals on October 11-13, 2019 the ground motion was recorded with novel devices anchored on the track walls. The devices were fit with Raspberry Pis, precise clocks, and accelerometers recording at 400 samples per second. Connection to the track's fiber optic network allowed for high speed instrument communication and data streaming to the public website. In April, the geometry of the devices was located near the start line and in October, devices were anchored to the outside wall at positions distributed to 1,000 ft. Each race generated high frequency seismic waves and our devices recorded this signal, calculated, and published the peak ground acceleration in *g* every 0.25 seconds to a public website in real time for the race fans.

Post processing focuses on two categories of racecars: Top Fuel and Funny Car. These vehicles race with the greatest velocities and created the largest ground motion signal. Post processing answers quantifiable questions including, what race and category produces the most ground motion, the maximum distance of noticeable motion, frequency of prominent motion, the characteristics of the seismic wave, and the speed of the seismic wave compared to the speed of the racer.

In October, two vehicles raced, resulting in peak ground acceleration values at 1.20 *g*. In April, four dragsters simultaneously propelled themselves down the track, producing peak ground acceleration values at 2.87 *g*.

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Acknowledgements

This experiment was possible because of the curiosity of the staff of the Charlotte Motor Speedway/zMax Dragway. The staff provided us with every tool and comfort we needed to not only conduct an effective experiment, but also to enjoy the thrilling atmosphere of the drag races. Thank you to Candace Corrigan, Jonathan Coleman, Susan Russo, Jim Guess, and Greg Walter, but also to every staff member who showed us the ropes of the world of drag racing. We were treated to the highest standards and provided with a fine drag racing experience. The team is now full of drag race fans.

The original project began with the 2018 Environmental Geophysics Class at the University of South Carolina. Each student in the course put forth the initial effort and brainstorming needed to get this experiment to the races.

A smaller group of students continued the experiment into 2019 to collect the data processed in this paper. Carolina Alumni, Jacob Burstein, Josh Burstein, and Emma Woodford spent hours writing novel software to get our ideas into reality. Graduate students Kevin Hurler provided technical support and Jacob Vincent helped us understand drag racing from campus. Returning for the Carolina Nationals, Jackson Saftner and Lottie Crotwell helped get the new stations prepared. Thank you especially to Allen Frye with the A&S Mechanical Prototype Facility for providing our experiment with vital equipment.

Wonderful leadership came from School of Earth Ocean and Environment professors Dr. Thomas Owens and Dr. Philip Crotwell. They provided guidance and instruction to all members of the project along every step since 2018. The insight given by both of these brilliant professors was crucial to creating a meaningful experiment.

Background

A drag race is a contest of speed over an exact distance. Most often a two-vehicle event, drivers compete in elimination rounds until one winner remains. First, racers perform a burnout to warm the tires. They then begin the race by inching forward towards the start line. The driver has their eye on the ‘Christmas Tree’ – the staging signal with six lights on each side. Connected to a laser, the Christmas tree pre-stages when the front of the vehicle is 7 inches from the start line. The next signal alerts the driver the race has begun. The vehicle races up to 1,000 ft and may exceed speeds of 330 mph. Meanwhile, the crew monitors the environmental conditions such as weather, elevation, track temperature, and humidity (NHRA, 2019).

The NGK Spark Plugs NHRA Four-Wide Nationals sent sparks flying as four hot rods flew well over 300 mph down the track. The event lasted late into the night and the hot rods shot flames into the darkness in front of a cheering crowd. The Four-Wide Nationals took place in April of 2019. The weather was hot and sunny, however there was an intense windy period that caused some delays in racing. Along with the wind came rain and small hail.

The NTK NHRA Carolina Nationals raced two vehicles in the lanes closest to the fans seated in the John Force Grandstands (Figure 7). The excitement of the races was cut short due to poor weather. On October 13th, the races were cancelled due to rain and were rescheduled to the next Monday, October 14th. The zMax Dragway graciously provided our team with a suite overlooking the track. This room came to be known as the ‘Seismic Suite’ and those monitoring the data recording were given the title ‘Duty Seismologist’. As the product of this experiment was intended for the drag race audience, metric units were not always the appropriate choice. Metric units are included in this paper, but English units are used more often to relate to the language of drag racing.

The origin of this project was an inquiry by Candice Carrigan of the Charlotte Motor Speedway, who saw publications at other drag strips claiming equivalent Richter earthquake magnitudes at drag races in the western US (Daley, 2012, 2slow, 2007). Ms. Carrigan's hypothesis was that the upcoming 4-Wide races at the Charlotte Motor Speedway should generate much larger magnitudes than two car races. She was correct in that the 4-wide races generated much larger ground acceleration than traditional races with only two dragsters. However, as we shall see, the conversion of these ground accelerations to earthquake magnitude is not appropriate. Earthquake magnitudes exist to estimate the amount of energy released into the ground. What we measured at the zMax Dragway and what previous experiments measured was peak ground acceleration, not energy. Ground acceleration depends on many factors including distance from the source and site conditions, including soil conditions at the observing stations. While the sensation of the sound and ground shaking of drag races from a few feet to tens of feet away from the starting line is a unique and stunning experience, the phenomenon involved releases only a miniscule amount of energy into the ground compared to even the smallest of felt earthquakes.

Top Fuel

Figure 1: Leah Pritchett racing in her Top Fuel Dragster at the 2019 NGK Spark Plugs NHRA Four-Wide Nationals. Photo by Emma Woodford

Top Fuel dragsters are propelled by a 10,000-horsepower engine accelerating them down the track in less than 3.7 seconds (NHRA, 2019). Top Fuel dragsters win the title “kings of the sport” as they reach speeds over 330 mph (531 kph) (NHRA, 2019). These dragsters are fueled by nitromethane and may use up to 15 gallons in one run (NHRA, 2019). The Top Fuel vehicles are 25 feet (7.6 m) long and weigh 2,330 lbs (1057 kg) (NHRA, 2019). This class of dragster is a crowd favorite (Figure 1).

Funny Car

Funny Cars are similar in speed to the Top Fuel class (Figure 2). Funny Cars have a slightly shorter wheelbase and are capped with a liftable body shaped like a common automobile. Funny Cars also race at speeds over 330 mph (531 kph) and complete the track in the neighborhood of 3.8 seconds (NHRA, 2019).

Figure 2: Funny Cars lined up at the NGK Spark Plugs NHRA Four-Wide Nationals. Photo by Emma Woodford.

Ground Motion

The release of energy on the track of zMax produces vibrations and a thunderous sound. Energy travels through the earth as a waveform and may be recorded in units of acceleration.

Acceleration is the measure of the change in velocity over time and is recorded in units of distance and time. A *gal* (Galileo) is one unit of acceleration and is equivalent to 10^{-2} m s^{-2} (Fowler, 1990). Values of acceleration are commonly compared to gravity. The acceleration of gravity on earth is roughly 981 *gal* (Fowler, 1990). Scientists compare measurements of accelerations to earth gravity with the term *g*, where 1 *g* equates to 981 *gal.* A racer may be familiar with this term. To travel at speeds over 300 mph in 4 seconds, dragsters accelerate more than 4 *g* (Davis, 2004).

Seismology is a field of science using elastic waves traveling in the earth surface to learn about the subsurface. The source of energy produced by the dragsters sends motion into the ground, similar to how an earthquake releases energy. An earthquake, however, produces energy on a scale difficult to recreate by humans. Only large nuclear explosions generate comparable surface waves (Fowler, 1990).

The question often arises how the motion produced by a dragster compares to an earthquake. If four Top Fuel dragsters simultaneously produced the 7,400 ft-lbs of torque, they would produce 4.0×10^4 Joules of energy (SIP Trunking Report, 2004). While an earthquake registering on the Richter magnitude scale with a Magnitude of zero (M0) creates 6.3×10^4 Joules of energy (USGS). M0 earthquakes are never felt. This comparison assumes that the energy produced by the dragster is directed entirely into the ground instead of its true intention of propelling the car. Therefore, motion at the drag race cannot be quantified on an earthquake magnitude scale; the energy released into the ground by even 4 dragsters starting simultaneously is thousands, perhaps tens of thousands, times less than the smallest of felt earthquakes. The ground motion, however, is large and quantifiable at the zMax Dragway.

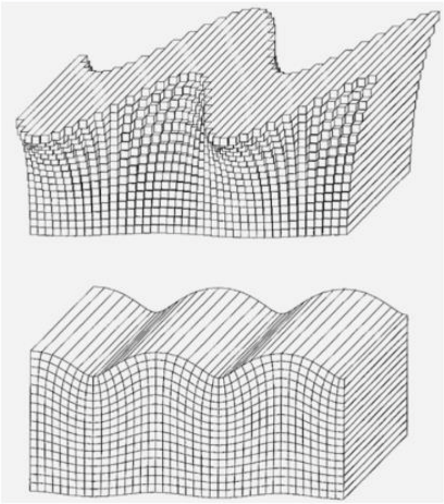


Figure 3: Love (top) and Rayleigh (bottom) particle displacements. (from Bormann et. al 2012)

This experiment measured magnitudes of ground acceleration that traveled as surface waves. Surface waves are a type of seismic wave that propagates along a free surface. A surface wave is characterized by two types of particle motion, Rayleigh waves and Love waves. Rayleigh wave particle motion is elliptical and counterclockwise while the particle motion of a Love wave is purely horizontal (Bormann et al., 2012). For Rayleigh and Love waves, the amplitude of the wave decays exponentially with depth (Figure 3, from Bormann et al. 2012).

Experiment

Device Design

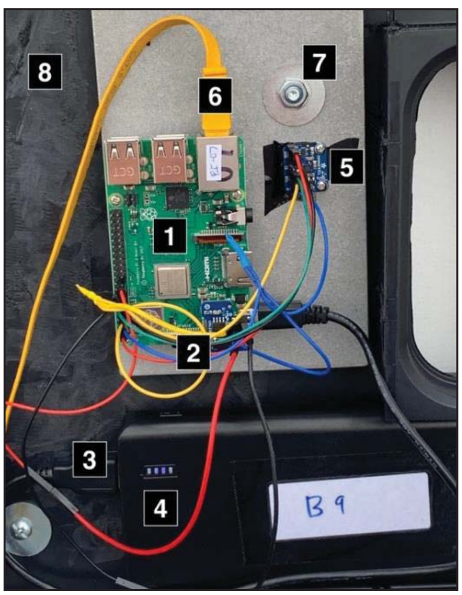


Figure 4: The devices were identical in the April and October races besides a software update. Photo by G. Herrin

#	Part List
1	Raspberry Pi 3 Model B
2	Adafruit PiRTC PCF8523 Real Time Clock
3	Battery Power Cable – USB to micro USB
4	Monoprice 20,000 mAh Battery
5	Adafruit MMA8451 Accelerometer +/- 2g
6	Cat 5 Ethernet Cable
7	Aluminum Plate and Fastener
8	Stanly Adjustable Compartment Box (17”x3”)

A Raspberry Pi, an accelerometer, and a clock were essential to the simplistic device design (Figure 4, #1, #5, #2). The other parts that constituted each device served functional purposes such as power and network connectivity (Figure 4, #3, #4, #6).

The devices were firmly secured to the concrete boundary of the track. It was important to have a secure connection to limit unnecessary motion. Each device was mounted on an aluminum plate inside a plastic waterproof case (Figure 4, #7, #8). Once or twice a day, the power supply was exchanged and recharged (Figure 4, #4).

Connectivity was established with each device through access to the track's fiber optic network. Fiber optic cable ran from a telecommunication box into a converter (Figure 5, #2, #1). The converter converted fiber optic into Cat 5 ethernet cable. The ethernet cable was ran along the outside base of the border wall into the plastic case

Figure 5: Within the teleconnection box on the track the fiber optic network connection to the network was made. Ports used here had sister ports in the communication shed. Photo by G. Herrin

#	Part Name
1	OS2 SC SC In/Outdoor Duplex Fiber Patch Cable 9/125 Singlemode
2	Planet FT-802S15 10/100TX-100Base-FX Fiber Media Converter

hosting the Raspberry Pi to establish high speed internet connection (Figure 4, #6). The cable was secured with tape.

At the communication shed, located away from the track, ports of connection were secured for the experiment. At this location, members of news and television channels could connect to their respective stations. We used the same techniques to connect our devices from the track, to the internet. Our devices at the track were connected to the nearest track-side telecommunication box that had permanent connection to the communication shed. At the communication shed, a few rows of fiber optic sockets were designated for our experiment and provided connection with the track devices.   From the sockets, fiber optic cables were converted to Cat 5 cables and provided our connection to the internet. For each device, an additional media converter and Cat 5 ethernet cable was required at the communication shed (Figure 5, #2, Figure 4, #6).

Geometry

To describe the acceleration vector completely, different device layouts were used at the Spring and Fall races. Although locations differed, the devices were

Figure 6: Example of the device mount on the outside border walls. This image is from the NTK Carolina Nationals at station FL. Pictured: Gabrielle Herrin and Emma Woodford. Photo by Dr. Thomas Owens.

mounted in similar ways. Devices were mounted 1 ft (31 cm) above the ground on border walls adjacent to the racing vehicles (Figure 6). The orientation of the three component accelerometers were corrected to a global coordinate system with the *y* axis pointing towards the finish line (Figure 7). To compensate for the slant of the border walls, the angle of the wall and direction of the device was recorded for each station location. The strike and dip correction were applied after recording. The raw data recorded onto the device memory did not include gravity, position, or coordinate system corrections.

Recording Data

Table 1: Stations

Station Code	Description
FL	Far Left
NL	Near Left
NR	Near Right
FR	Far Right

Data was recorded and saved onto an 8 Gb microSD card in each Raspberry Pi. The accelerometer recorded data at 400 samples per second and was outfitted to record data between +/- 2 *g* on each component of motion. A Finite Impulse Response (FIR) filter was applied to the live streaming data to allow decimation of the incoming data by a factor of 2. This was required to lower the streaming data volume. The decimation dropped the Nyquist frequency to 100 Hz. The ground acceleration was recorded as mini seed (MSEED), a data type commonly used by seismologists.

NGK Spark Plugs NHRA Four-Wide Nationals

In April, the Four-Wide provided the potential for large ground acceleration. The four devices at this competition were arranged near the start line. FL and FR were mounted on the outer walls of the outside lanes (Table 1, Figure 7). The devices were within 7 ft from the start line. NL and NR were secured to the inside walls of the safety triangles bordering the inside lanes (Table 1, Figure 7).

NTK NHRA Carolina Nationals

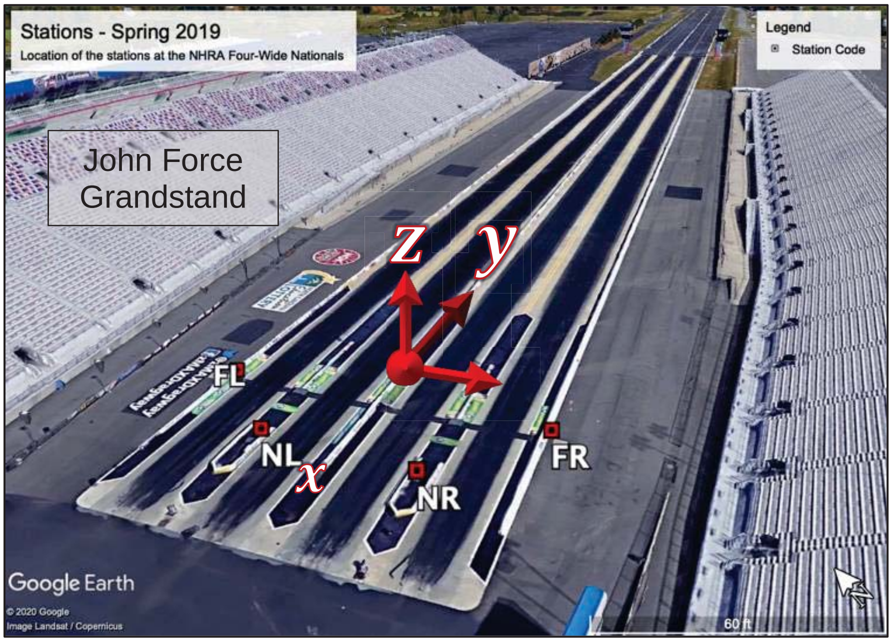
Upon our return in October, we mounted devices along the FL outside border wall and created a new station positioned near the rear wheel of the dragsters. Station FL0 was fastened 24 ft behind the start line and served as the record for the beginning of a race (Figure 7).

A total of seven devices were mounted. FL and NL from the April experiment remained in their previous location. FL0 was located 24 ft from FL. Then at 60 ft, 330 ft, 660 ft, and 1,000 ft (measured from the start line), four more devices were deployed (Figure 7). The limiting factor for the number of devices was the distance to the telecommunication stations. These telecommunication stations are positioned near our devices.

Troubleshooting

In April there were some instances that the vibrations of the cars would cause the cables to be disconnected. To prevent this, we would tape the cable securely. In the Fall, a larger problem occurred. A server at the University of South Carolina hosted the websites and data tools. On the second day of races (October 12), the internet at South Carolina went down, breaking our connection with the devices completely. To resolve this issue, we recreated the server as a virtual cloud hosted system (Linode), however, we were unable to properly record the data in the morning of October 12.

Device Geometry



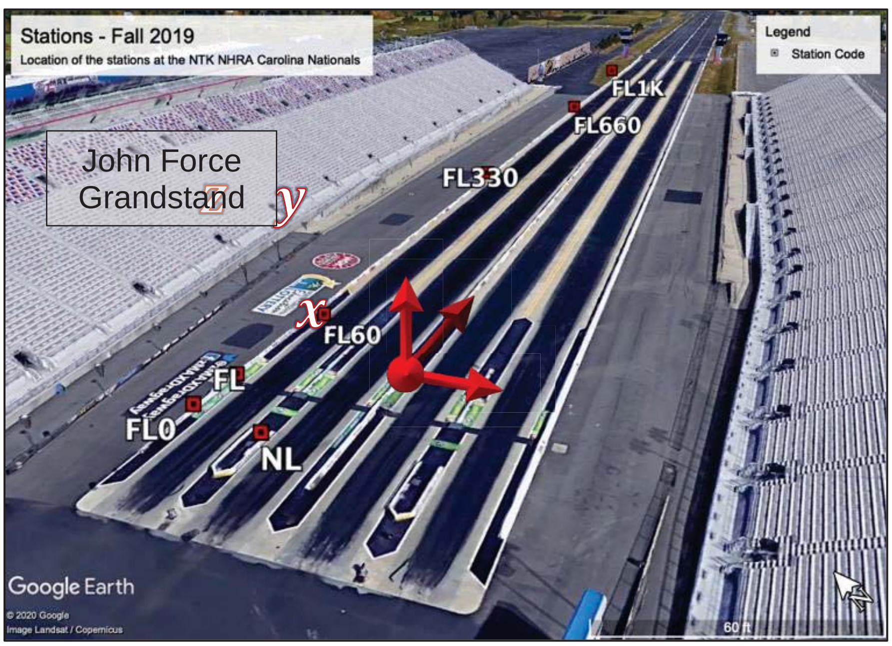


Figure 7: Device Layout for April (spring) and October (fall) races. The station placement with the respective station code shows the location on the zMax Dragway lanes. Each device recorded data in a local coordinate system. Before analysis were made, all records were transformed into the global coordinate system shown.

Calculations

On board the Raspberry Pis, a script calculated information essential to the experiment. The processes applied to the data were called 'Seismogram Tasks' (written in Python, see Appendix). These tasks in order included:

1. Coordinate transform
2. Gravity correction
3. Calculation of vector magnitude

Coordinate Transform

To transform the data into the global coordinate system (Figure 7) a pseudo 3-dimensional coordinate transform was applied. To simplify calculations, the three components were transformed in 2-dimensional space and then combined. First *x* and *z* were sent through the calculation (Eq. 2.0, 2.1). To accomplish this, the angle of the device from horizontal was converted to radians.

$$x' = x * cos(\theta) + z * sin(\theta) \tag{2.0}$$

$$z' = x * -sin(\theta) + z * cos(\theta) \tag{2.1}$$

After *x'* and *z'* were calculated, *y* and z' were corrected. Local *y* was either aligned with global *y* or pointed 180° away and equation 2.1 had the same effect on *z'*. The angle of *y* was the angle away from the global system and was used to orient all components globally (Eq. 2.2, 2.3).

$$y' = y * cos(\alpha) + z' * sin(\alpha) \tag{2.2}$$

$$z'' = y * -sin(\alpha) + z' * cos(\alpha) \tag{2.3}$$

Gravity Correction

The correction of gravity was applied to the global *z* axis (*z''*). The accelerometer's value of 1 *g* was equivalent to 4096 *counts* (Eq. 3.0). *Counts* are a data unit of a device before earthly meaning is given through a conversion factor.

$$1\ g = 4096\ counts \tag{3.0}$$

The acceleration of gravity on the *z* axis. To remove the acceleration of gravity from *z''*, 4096 *counts* were subtracted from *z''.*

Vector Magnitude

After the data was oriented into the global coordinate system and gravity was removed, the vector magnitude was calculated (Eq. 4.0). The vector magnitude *(m*) was converted from counts into *g* and every quarter second *m* was sent to the public and private websites (Eq. 4.0).

$$\boldsymbol{m} = \sqrt{\boldsymbol{x^2 + y^2 + z^2}} \tag{4.0}$$

Websites

In the 'Seismic Suite' a 'Duty Seismologist' had a task to monitor the start of every heat on the 'Duty webpage' - a private website designed to monitor the stations. This page plotted seismic traces of every active device. A device status bar was a key feature on the 'Duty Seismologist' webpage. The status bar showed all the station codes next to a colored circle icon. This icon would change from green to yellow if data latency began to increase, and from yellow to red if data was not being sent at all. When one hovered the mouse over this icon, a tooltip appeared with the Raspberry Pi's code (ex. 'PI01'), and the IP address of the device. This was vital to monitoring the network and performance of each device.

When cars started to stage, the ‘Duty Seismologist’ selected the appropriate race information including category, round, and heat on the Duty webpage. Then he or she clicked a trigger to capture a time window of data records. To err on the side of caution, the trigger captured the data 20 seconds before and after it was clicked. The time window is identified with the input race information (Figure 8a).

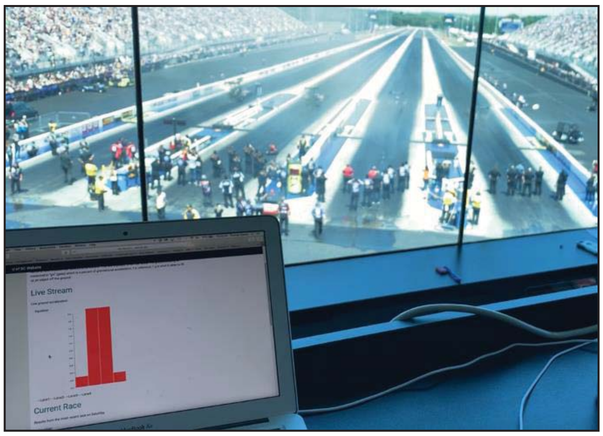


Figure 8a: Experiment set up in the ‘Seismic Suite’ with clear view of all four lanes. The ‘Duty Seismologist’ clicked the trigger and monitored the live streaming website. Photo by G. Herrin.

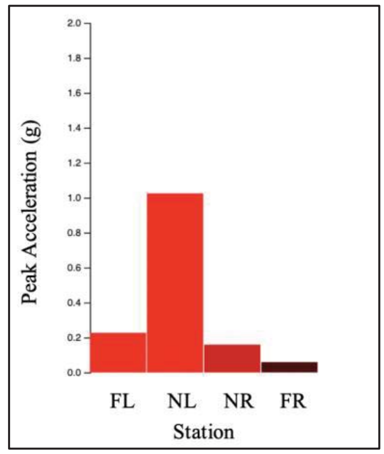


Figure 8b: Example of the ‘Equalizer’ from the live streaming website in spring. In the spring and fall, the equalizer showed all stations.

Rather than displaying seismograms on the public ‘Live Stream’ webpage, we created an equalizer (Figure 8b). This equalizer was a simple bar graph with amplitude corresponding to the vector magnitude of the ground motion (Eq. 4.0). Each bar represented a station. The live data streaming through the fiber optic network allowed us to update the magnitude of ground acceleration at high speeds (Figure 8b). This made the equalizer react to the magnitudes of ground acceleration recorded by each station in time. Beneath the responsive equalizer, the peak accelerations from the most recent trigger were displayed as a static equalizer. Information about the race input by the 'Duty Seismologist' identified the static equalizer with category, round, and heat.

The 'Live Stream' webpage included links where the user could navigate to all past races recorded. This navigation brought the user to nested links sorted by date, category, then heat. The equalizer, seismograms, and identifying information was displayed on the Live Stream webpage.

Ring Server

The Ring Server was an essential tool to the experiment's function. The Ring Server stored information temporarily until it was requested for use. The server allowed for the devices to post information from the track. Then the websites would automatically request this information. The information on the websites was automatically updated given stable internet connection. The Ring Server was essential to monitor the stations because all information published onto the webpages was distributed by the Ring Server.

Coding Languages

The websites were written in coding languages HTML, CSS, and JavaScript. The equalizer was created using a tool in JavaScript called D3. D3 included tools to create an animated appearance when the flowing data was displayed.

Python was the coding language that handled the all the tasks on the field instrumentation on the track, including communications with and data collection from the accelerometers, filtering and decimation of the data streams, coordinate rotation, gravity correction, and peak acceleration calculation. Information was exchanged between components of the software system by posting JSON objects on the ring server. (See Appendix).

Results

NGK Spark Plugs NHRA Four-Wide Nationals

Largest Ground Motion

Race: Top Fuel E2 Heat 2

Peak Ground Acceleration: 2.87 *g* at station NL

Table 2:

Lane	Driver	Place	MPH	Reaction Time (s)
1	Steve Torrence	Win	324.05	0.055
2	Terry McMillen	RU	316.75	0.087
3	Scott Palmer	3rd	217.53	0.076
4	Dom Lagana	4th	81.51	0.067

NHRA. *2019 NGK Spark Plugs NHRA Four-Wide Nationals.*

Top Fuel remains 'king of the sport" as they produced the top three highest ground motion at the NGK Spark Plugs NHRA Four-Wide Nationals. The runner up was in Top Fuel Q2 Heat 3 with 2.54 *g* (NL) and third place went to Top Fuel E1 Heat 1 (NL) with 2.53 *g.* The recording limit of the accelerometers was reached by these races in the *y* or *z* component. The value above the accelerometer's +/- 2 *g* limit is a cause for concern. It is uncertain if the recorded value is an artifact of the device. Devices capable of recorded at least +/- 4 *g* are required to properly record the data at future Four-Wide competitions.

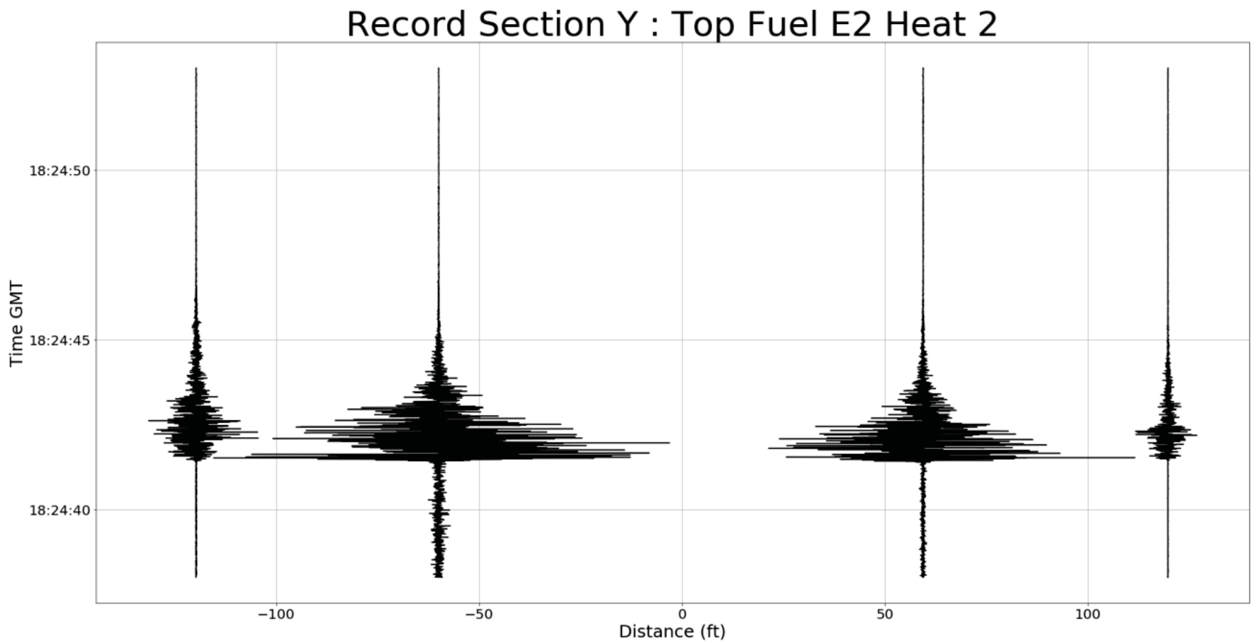


Figure 9: The four stations at the NGK NHRA Four-Wide Nationals arranged with relative distances a part. 0 ft distance aligns with the center of the track. The peak ground motion in April was recorded by station NL shown here at -60 ft. The position of the racers with respect to the amplitude of ground motion is visible. Station NL recorded the constructive motion of Torrence and McMillen that was much greater than the motion recorded at NR where Palmer and Lagana underperformed in comparison (Table 2).

The position of the station affected the amplitude of ground motion. The N stations recorded the greatest ground acceleration. These stations recorded motion 3.31 times greater than the F stations. The N stations recorded an average of 1.16 *g* while the F stations recorded an average ground acceleration of 0.35 *g.* The N stations were directly bordered by two vehicles while the F stations were adjacent to one vehicle. The N stations recorded the constructive motion from the two racers. The source of the ground motion recorded at the F stations is dominantly from the adjacent vehicle. The surface wave did not travel more than 30 ft with sustained amplitude in the *x* direction (Global System, Figure 7).

NTK NHRA Carolina Nationals

Largest Ground Motion

Race: Top Fuel Q3 Heat 5

Peak Ground Acceleration: 1.20 *g* at station NL

Table 3:

Lane	Driver	MPH	Reaction Time (s)
1	Clay McMillican	315.06	0.084
2	Doug Kalitta	323.35	0.077

NHRA. *2019 NTK NHRA Carolina Nationals.*

Doug Kalitta was the Runner up at the NTK Carolina Nationals, losing to Steve Torrence but here, Kalitta and McMillican are winners for our purposes. In their race they produce 1.20 g of ground motion (Table 3).

The seismographs in the fall had a distinct pattern where the background noise was broken by a small amplitude wave that preceded a signal with large amplitude. The largest amplitude was assumed to occur at the time the vehicle was closest to the device. Motion with small amplitude recorded shortly before the vehicle reached the station is identified as the surface wave (Figure 10). It is presumed that the surface wave was produced from the energy released at the start of the race.

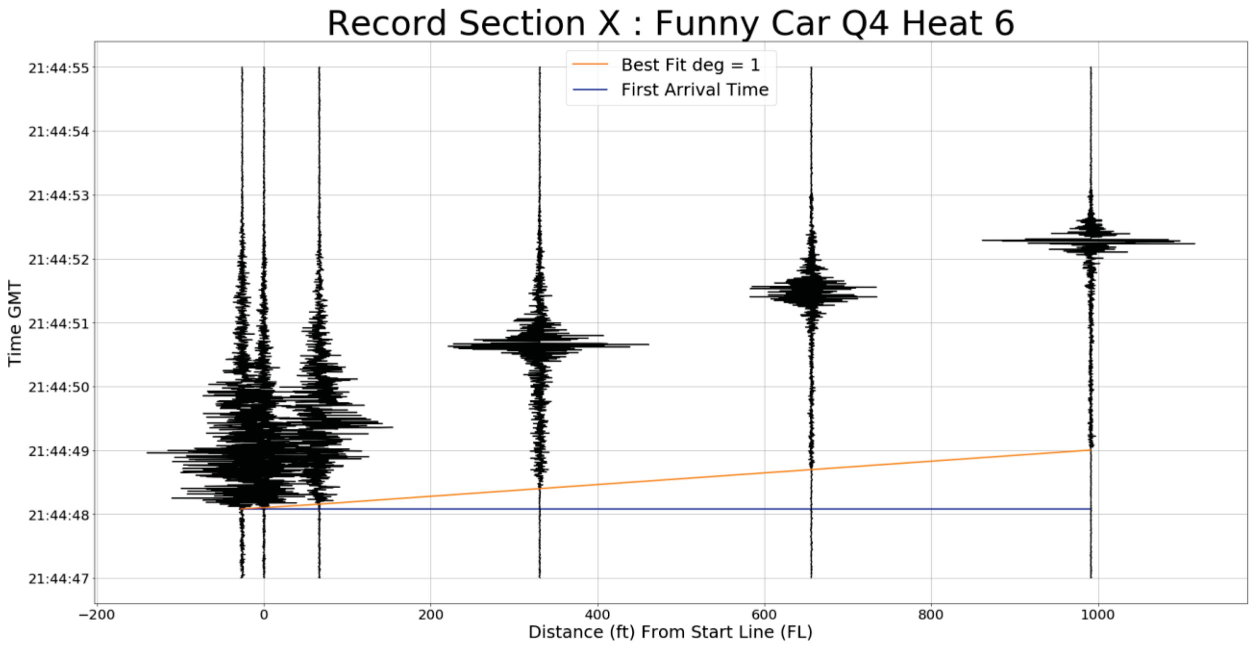


Figure 10: Record Section of FL stations at NTK Carolina Nationals. The blue line shows the first arrival taken from station FL0. With increasing time and distance, the first motion is clearly visible in all the records. This first motion has a linear behavior with a best fit line of degree 1. Therefore, the velocity of the wave remains constant.

Layout at the fall races allowed the average speed of the surface wave to be calculated. First, the time of the surface wave arrival was selected at each station. A start time was chosen from station FL0 as this station is located near the back wheels of the vehicles. Time elapsed from the FL0 start time was divided by the distance of the station from FL0 to calculate the surface wave's average speed. The calculation resulted in a wave traveling at an average speed of 835.59 mph (1,344.8 kph = 373.54 m/s).

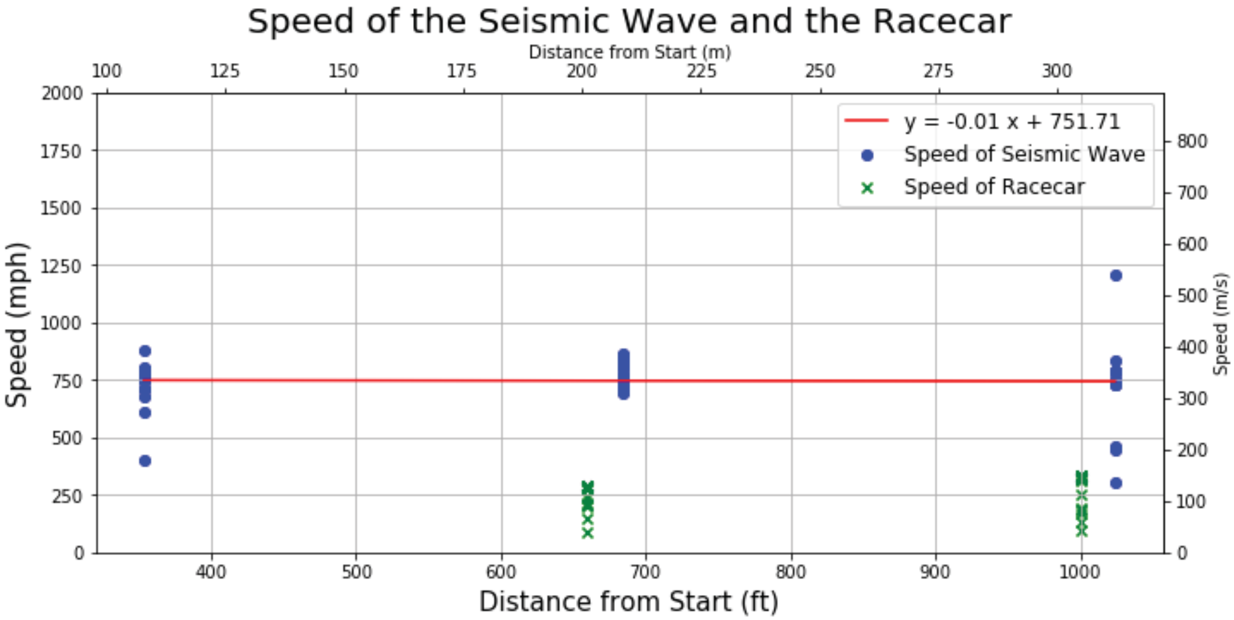


Figure 11: Speeds calculated at stations FL330, FL660, and FL1K. These stations are plotted because the low error in first motion selection. The slope of the best fit line supports the conclusion that the wave is not accelerating. The speed of the wave over all stations averages to be 835.59 mph. In green the racer's reported speed at 660 and 1,000 ft is shown to allow for the comparison of the average wave speed at a station with the racecar speed. At 660 ft the Top Fuel or Funny Car racer is traveling an average of 265.32 mph. While at 1,000 ft, the racer is traveling 295.02 mph on average. Near 660 ft, the average wave speed is 3.12 times the speed of the racer and near 1,000 ft, the average wave speed is 2.83 times the speed of the racer. The seismic wave is not increasing in speed, like the racer is. The average speed of the racer completing 1,000 ft track in ~3.7 seconds is 184 mph. The wave is traveling 4.5 times faster on average than the racer over the entire track distance. The offset of the seismic wave speed positions is 24 ft due to the wave's *start line* being at station FL0.

The speed of the seismic wave does not significantly change with distance from the source (Figure 11). Due to the amplitude of motion when the vehicle is nearby and crowd noise, the surface wave is difficult to distinguish at stations before 330 ft. The noise produced by the first motion could produce a sound wave that complicates the signal recorded at the stations. Further noise could be from human sources such as the grandstands that extend ~800 ft from the start line. The crew and race fans are clustered in the first ~150 ft of track, where three of the six devices are located on the

FL wall. The close proximity of the high amplitude ground motion and added background noise created difficulty in detecting the first motion at stations before 330 ft.

The clear arrival of the seismic waves at station FL660 was used to conduct a frequency analysis. The first motion of the surface wave was evaluated for its frequency content. The spectrogram shows a window of 2 seconds from the first detection of the surface wave (Figure 12). The frequencies prominent in the spectrogram are near 85 Hz but are complex and unevenly spread in time. For both Funny Car and Top Fuel seismic traces, frequencies near 85 Hz were prominent within the first arrival motion. To properly capture the frequency band, a window of 75-90 Hz was chosen for the bandpass filter shown in Figure 12. The 75-90 Hz frequency is also present near the peak amplitude (Figure 12).

Funny Car Q4 Heat 6-FL660: component X
Seismogram and Inset Spectrogram of the Surface Wave

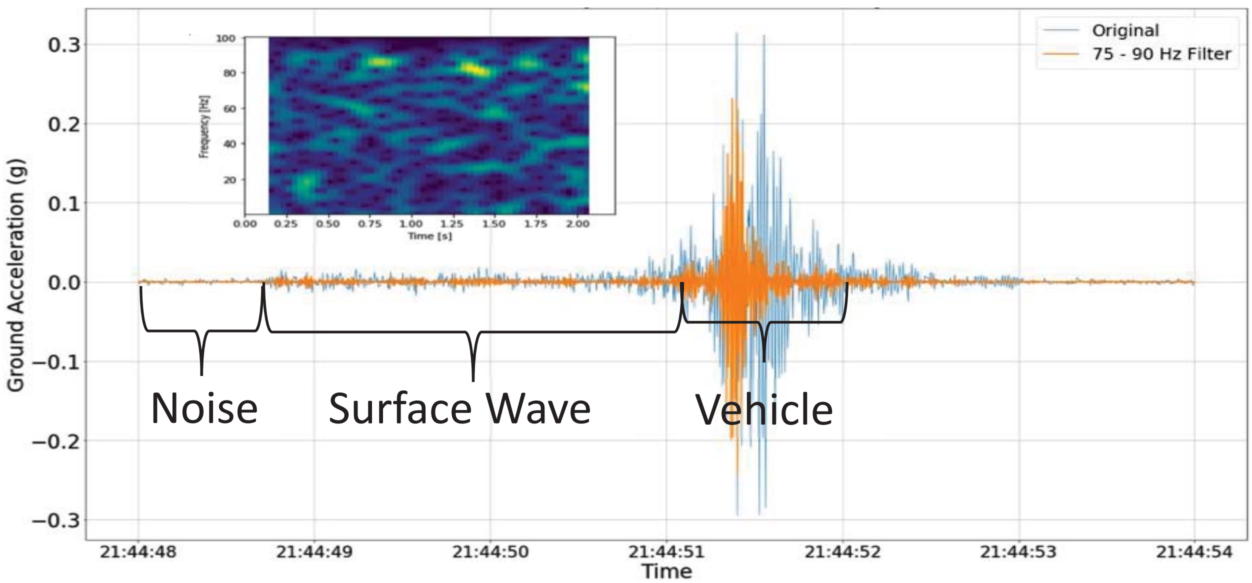


Figure 12: FL660 *x* component seismogram with Butterworth double pass IIR bandpass filter (orange). The first arrival of the wave at 21:44.48.642 is composed of the same frequencies as the racecar arrival near 21:44:51.5. The background noise is steeply filtered with the IIR. Since the vehicle had not yet passed the station, the source of the early motion is from the start line impulse earlier in time. The spectrogram shows the frequency amplitudes occurring in the first 2 seconds of the surface wave. The prominent frequencies (75 – 90 Hz) occur near 0.8 s and 1.3 seconds after the first motion.

The frequency (f) of the earliest arriving surface wave ranged between 75 - 90 Hz. Using the average wave velocity (v) as 835.59 mph (373.54 m/s), Eq. 5.0 calculates the wavelength (λ) to lie within a range of 4.15 - 4.98 m (13.6 – 16.3 ft) (Figure 12). A surface wave travels to a depth of the wavelength divided by three (Fowler, 1990). The wave produced by the racers travels to a depth within a range of 1.38 – 1.66 m (4.53 – 5.44 ft)

$$\lambda = \frac{v}{f} \qquad (5.0)$$

The velocity of a surface wave in a homogeneous material is constant. If paved like other drag strips, the concrete at zMax most likely extends a maximum of 12 in

(30.5 cm) and gradually decreases to a thickness of 4 in (10.2 cm) (Heydorn, 2004). The material beneath the concrete is most likely clay loam (Stephens, 1988). The deepest surface waves are therefore, traveling in the clay loam beneath.

Albers recorded S-wave velocities in clay to be 390 m/s at frequencies between $10^{-2} – 10^{-6}$ Hz (2011). Rayleigh waves travel at 92% of the S-wave velocity and when present, Love waves travel at velocities greater than Rayleigh waves (Fowler, 1990). The surface wave produced by the dragsters operated near 85 Hz and produced motion at 374.54 m/s (Table 4). The Rayleigh wave traveling in clay, loam clay, or pure clay is expected to be 358.8 m/s.

Table 4: Surface wave velocities calculated from the S-Wave velocity β.

Medium	Surface Wave Velocity (m/s) $v_s = 0.92\beta$
Clay, Loam clays, Pure clay (Albers, 2011)	358.8
zMax Dragway, Concord, NC	373.54

Discussion

For an unconventional source measured with novel devices, the measured seismic surface wave speed is consistent with expected values in the likely surface soils at the ZMax Dragway (Table 4). This speed is characterized by a source complicated with background noise and high frequency motion. To produce a better estimate of the wave, there are some improvements possible in the experiment. Most importantly, a precise measurement of the device location from FL0 would increase the precision of the surface wave velocity. The devices themselves should be outfitted with an accelerometer capable of recording +/- 4 g because in the spring, uncertainty arose when the devices recorded values above their prescribed +/- 2 g limit. This uncertainty led us to doubt the accuracy of the devices, but the dragsters pushing the limits of the equipment was a pleasant surprise. Furthermore, as with any experiment, a higher sampling rate would increase the range of frequencies available to record. The correlation of the drag racer's speed to the magnitude of the ground motion could be investigated further. At a Four-Wide race, placing devices on each side of the track (FL and FR) at 660 ft and 1,000 ft would record the amplitude of motion dominated by the nearest driver. The speeds of the drivers are recorded at these positions are accessible after the race. Identifying and quantifying the relationship to racer speed and ground amplitude could give insight into the racer's individual input to the ground motion.

Summary

The surface waves produced at the zMax Dragway travel with sustained amplitude over 660 ft. They travel at average speeds of 835.59 mph and propagate dominantly parallel to the track. Top Fuel and Funny Car dragsters at the 2019 Four-Wide Races produced ground motion an average of 1.28 g and at the 2019 NTK Carolina Nationals they produced an average of 0.48 g. The surface wave is traveling the fastest at frequencies between 75-90 Hz and to a depth of 4.53 – 5.44 ft.

Appendix

Experiment files may be found at:

https://github.com/crotwell/dragrace.git

Processing and data files may be found at:

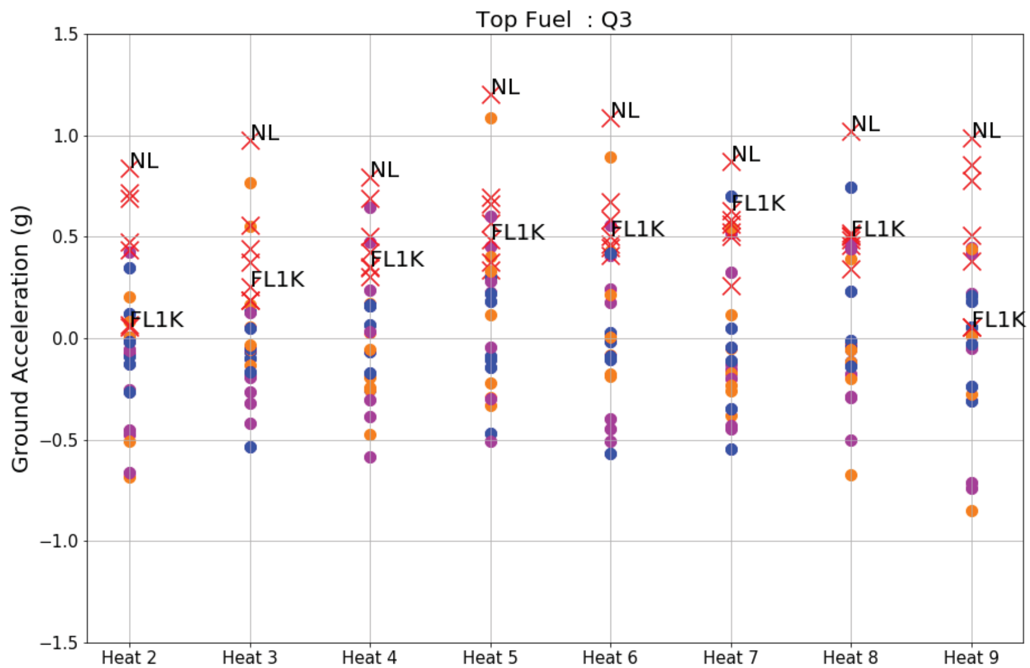
https://github.com/herringabrielle/dragraceAnalysis.git

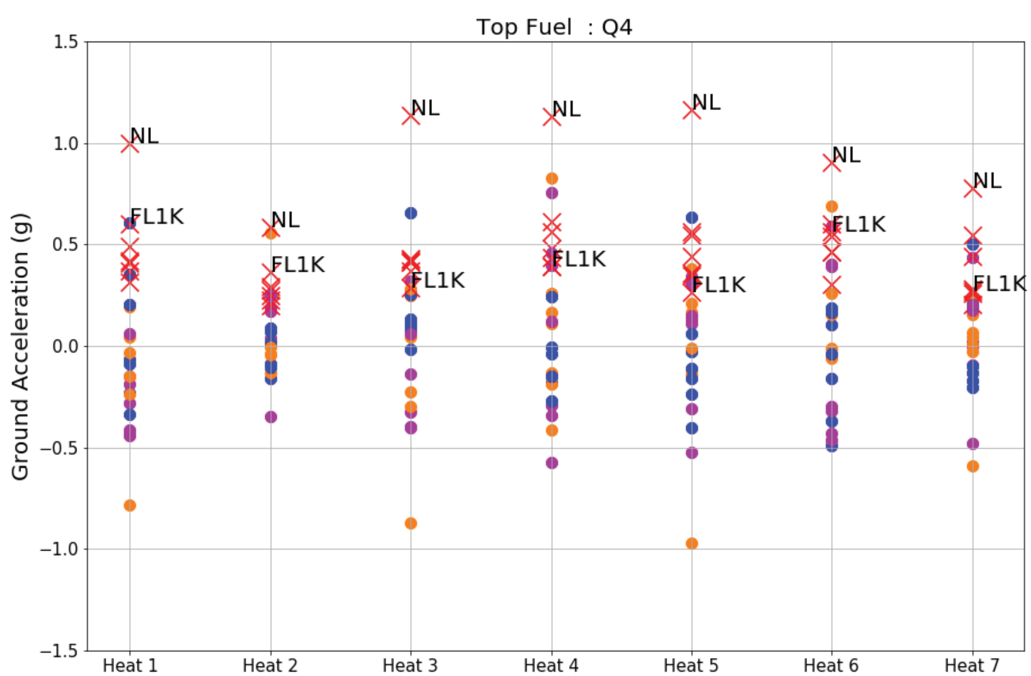
First visit the README.md for detailed instructions to recreate figures seen in this paper.

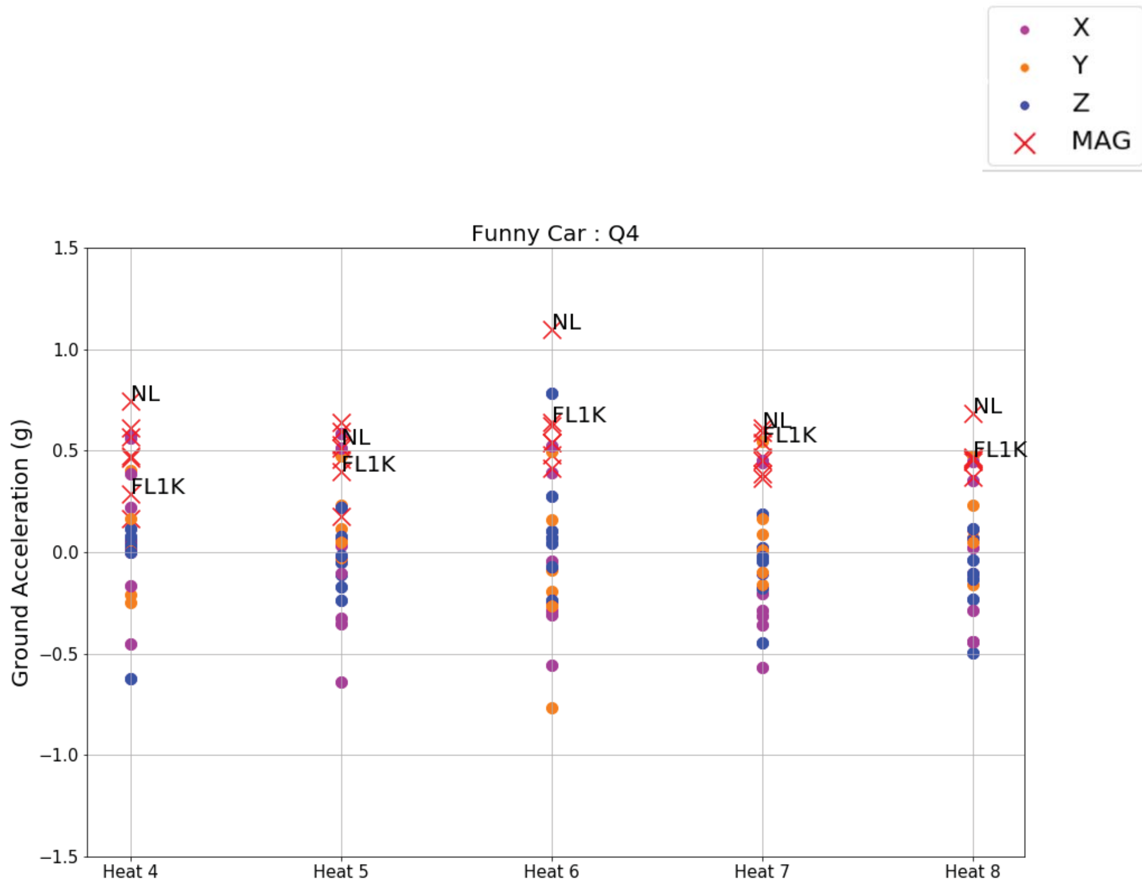
Additional Figures

NTK Carolina Nationals

Peak magnitude recorded at each station by category

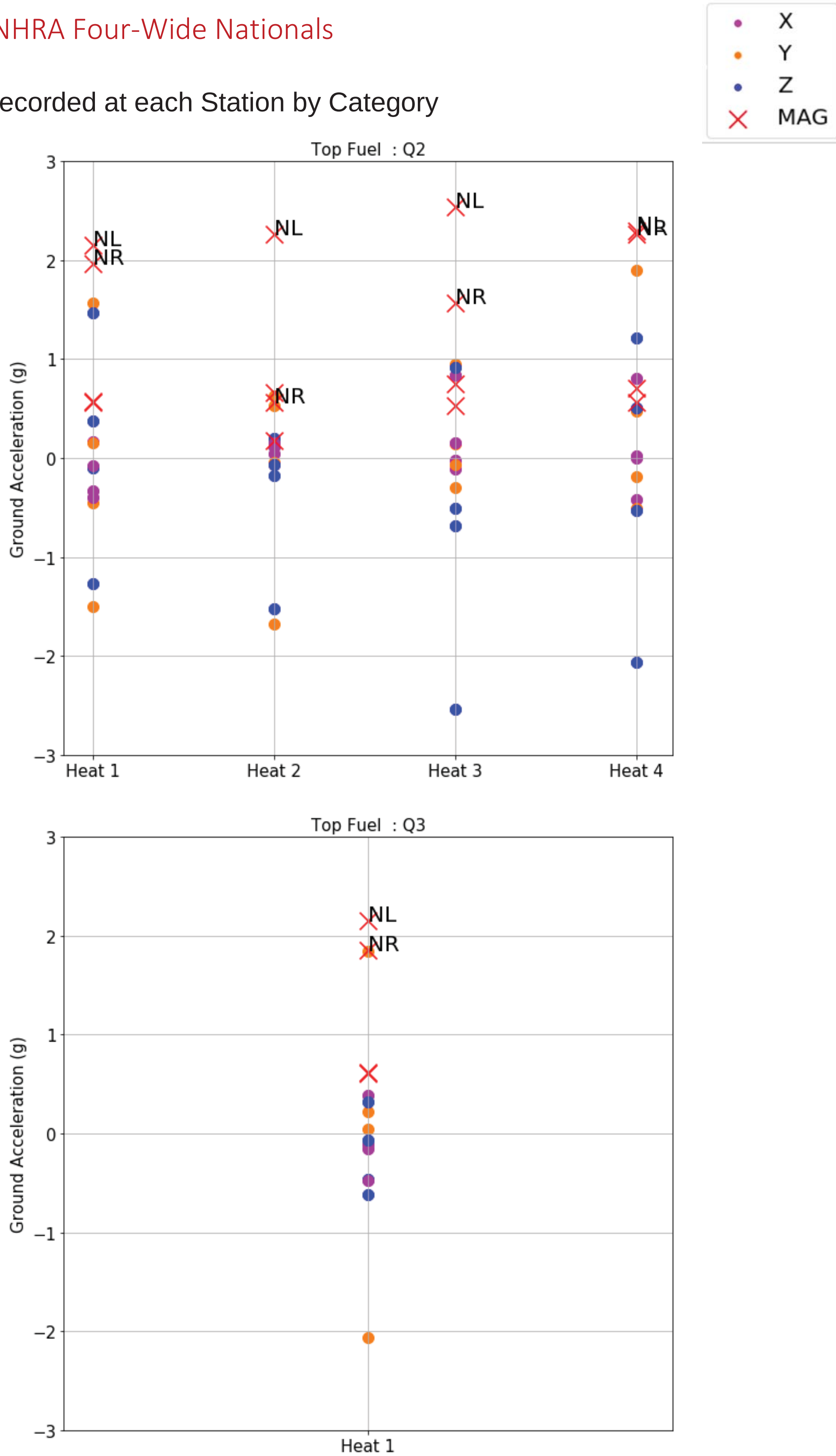


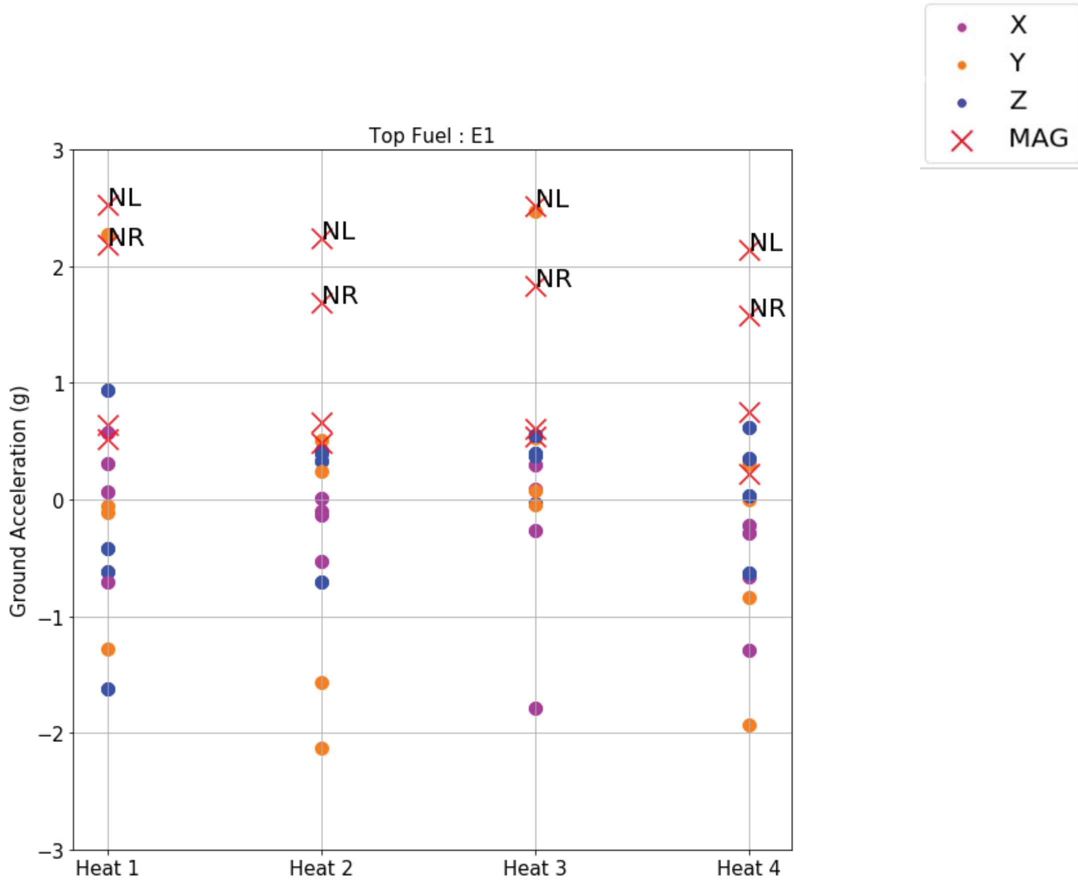


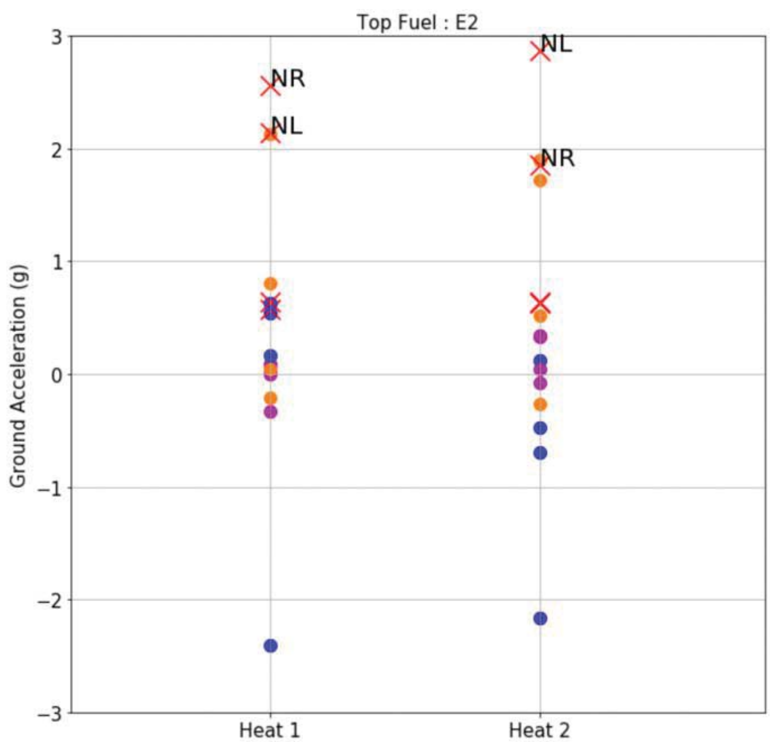

X
Y
Z
MAG
Funny Car : Q4
Ground Acceleration (g)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
Heat 4
Heat 5
Heat 6
Heat 7
Heat 8
NL
FL1K

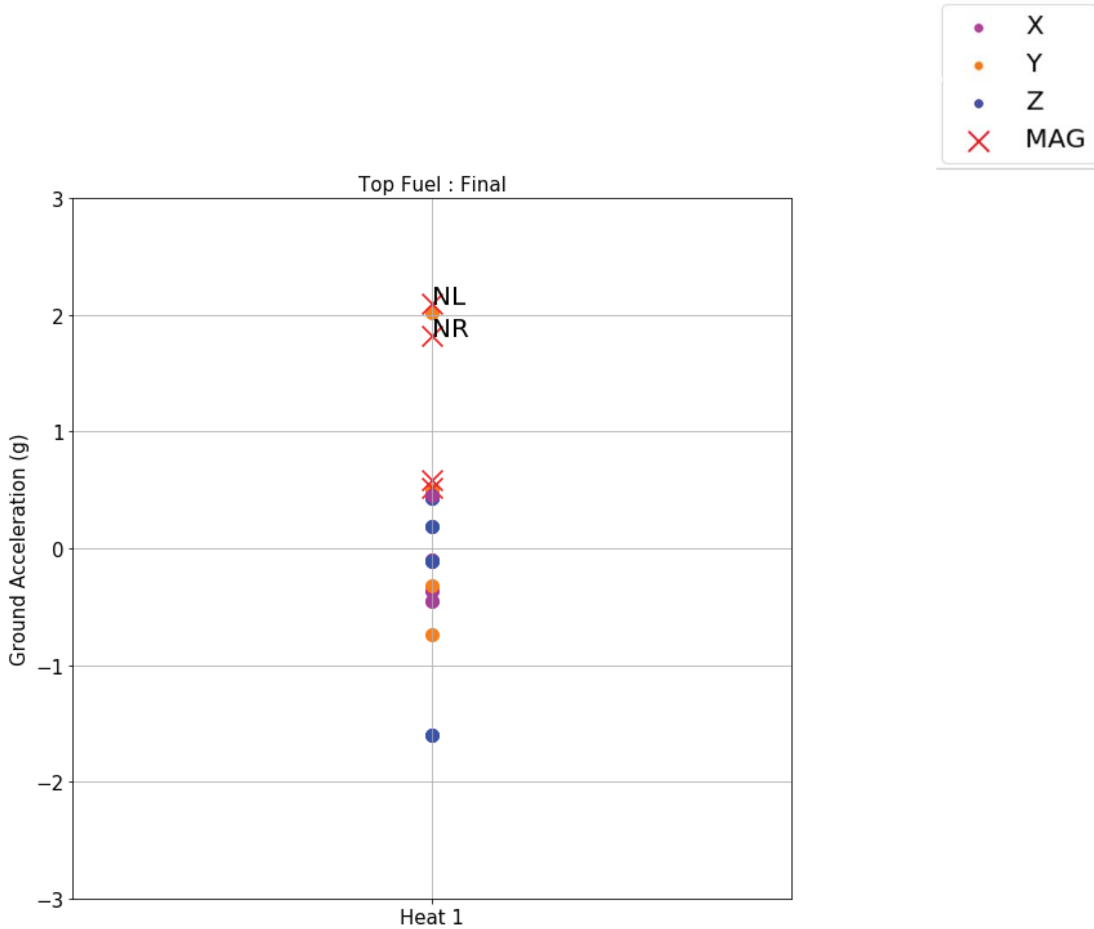
NGK Spark Plugs NHRA Four-Wide Nationals

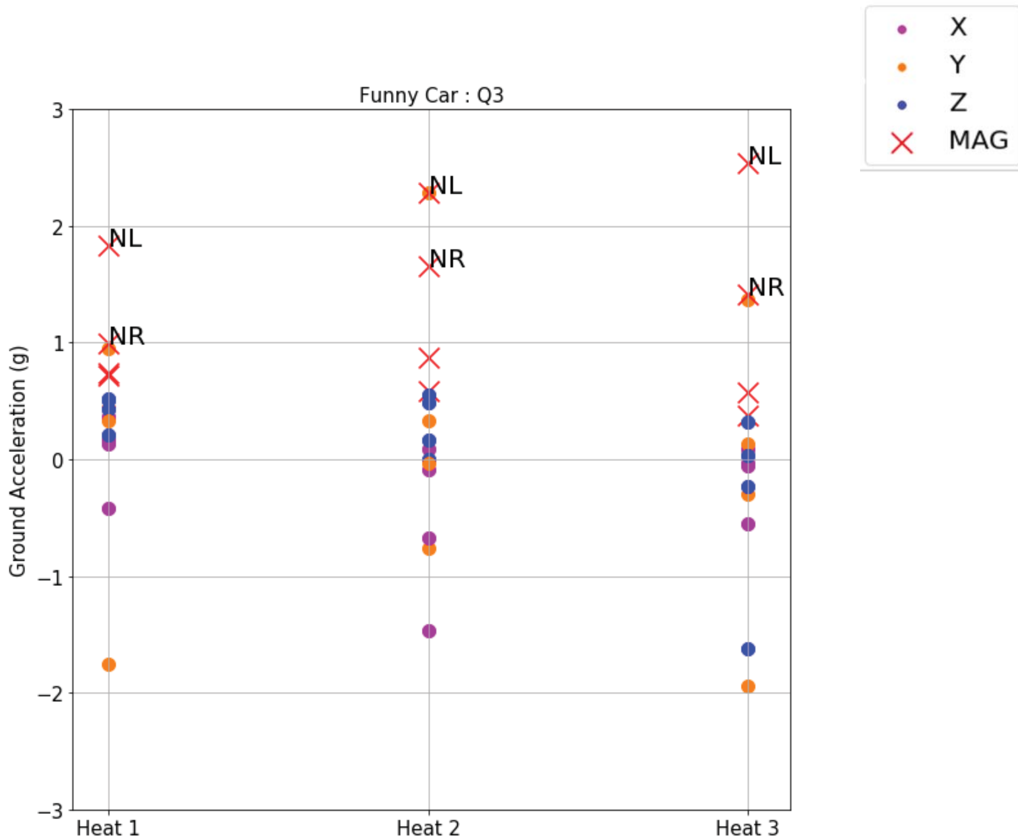
Peak Magnitude Recorded at each Station by Category

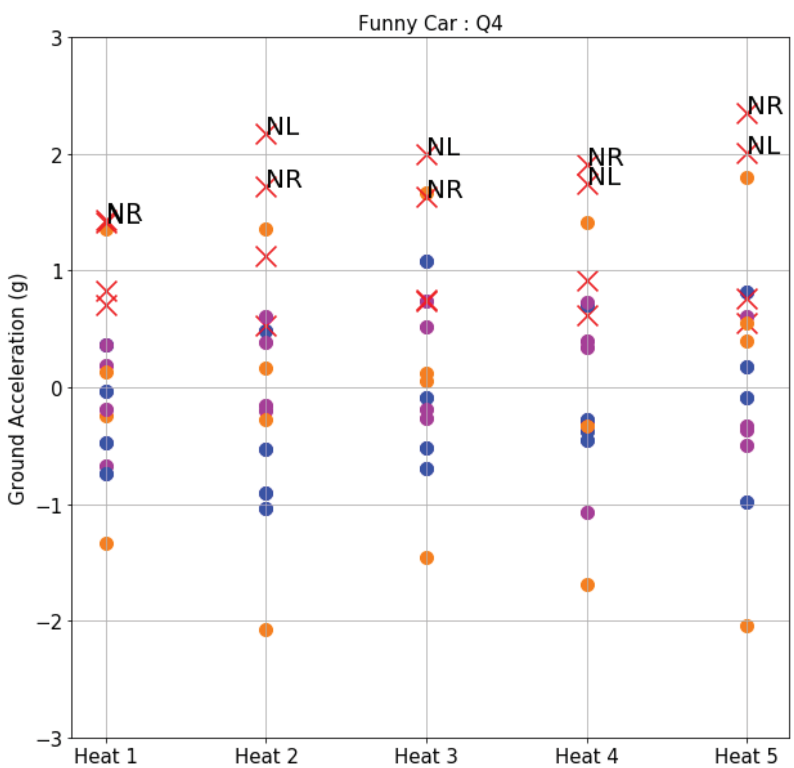


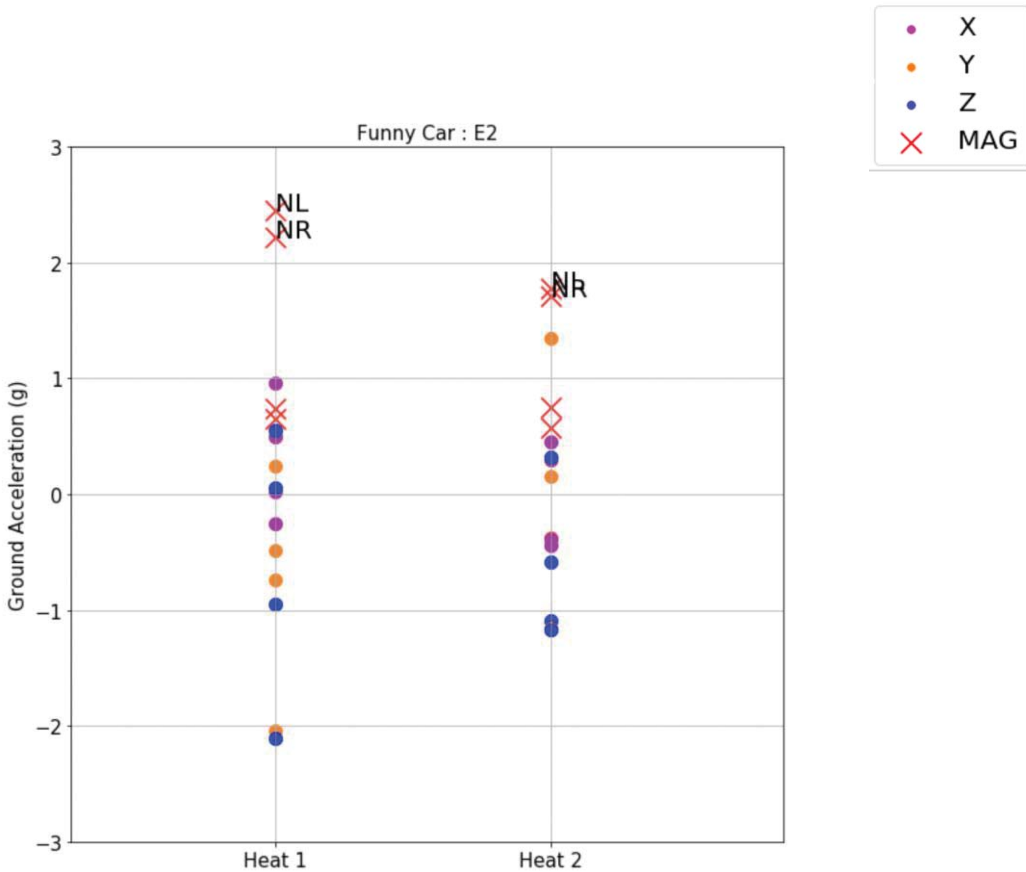

X
Y
Z
MAG
Top Fuel : E1
Ground Acceleration (g)
Heat 1
Heat 2
Heat 3
Heat 4
NL
NR

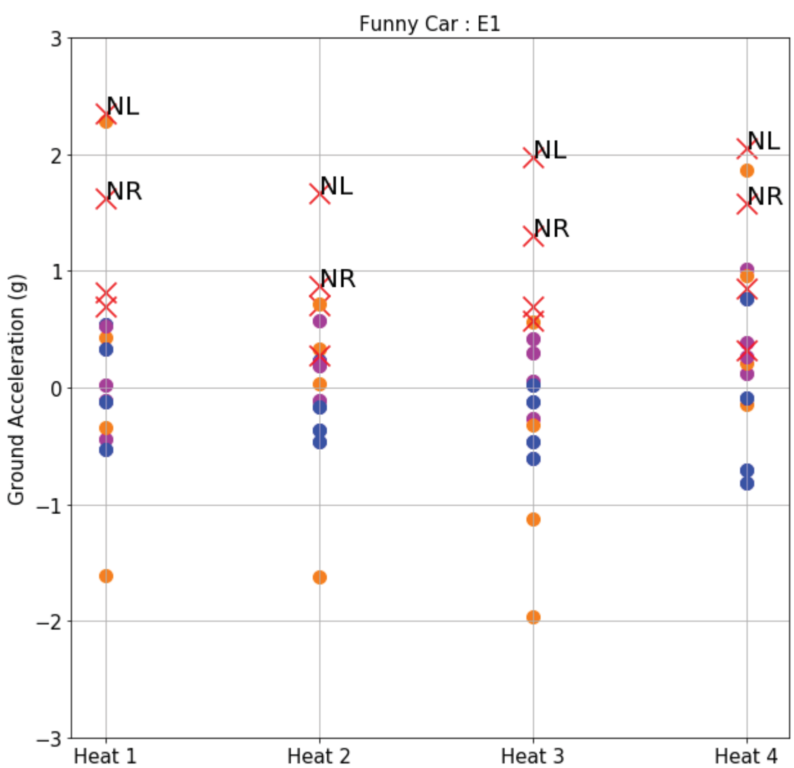

Top Fuel : E2
Ground Acceleration (g)
Heat 1
Heat 2
NL
NR

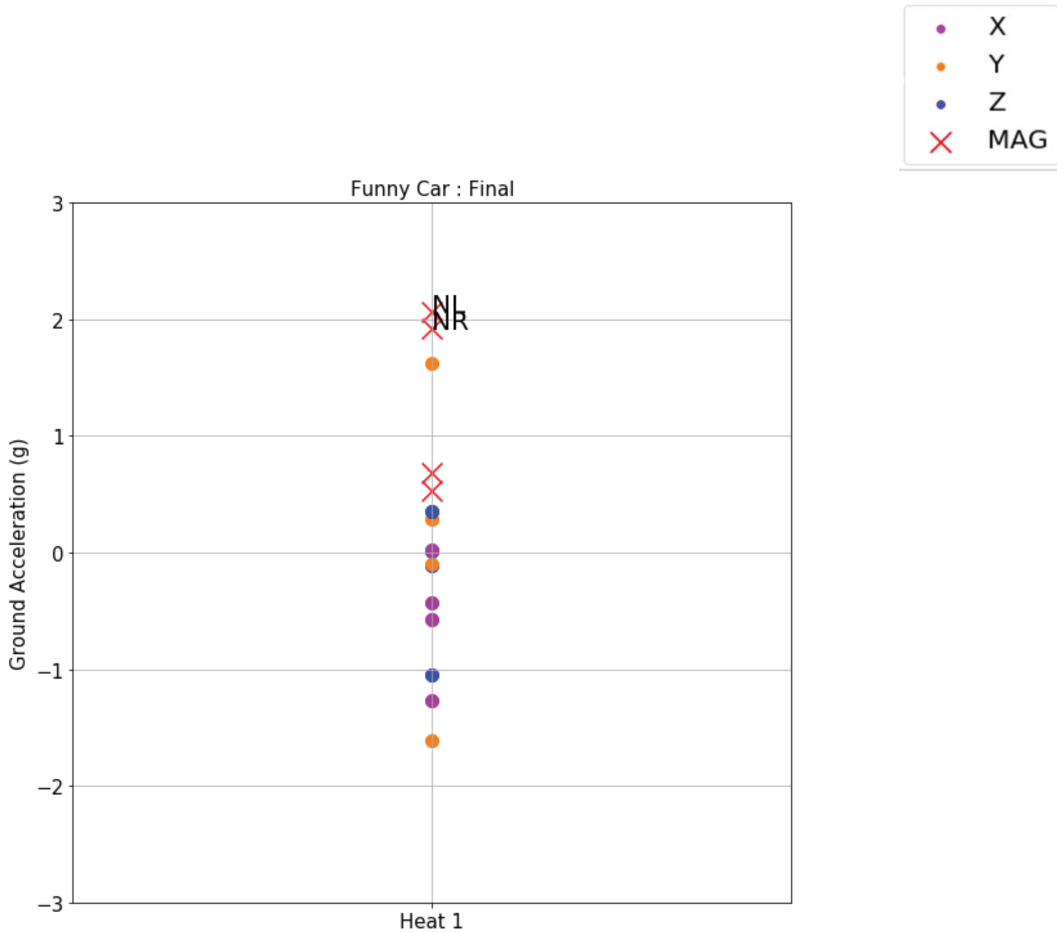

X
Y
Z
MAG
Top Fuel : Final
NL
NR
Ground Acceleration (g)
Heat 1
3
2
1
0
−1
−2
−3


X
Y
Z
MAG
Funny Car : Q3
Ground Acceleration (g)
3
2
1
0
−1
−2
−3
Heat 1
Heat 2
Heat 3
NL
NR


Funny Car : Q4
Ground Acceleration (g)
3
2
1
0
−1
−2
−3
Heat 1
Heat 2
Heat 3
Heat 4
Heat 5
NL
NR


X
Y
Z
MAG
Funny Car : E2
Ground Acceleration (g)
3
2
1
0
−1
−2
−3
NL
NR
NL
NR
Heat 1
Heat 2


Funny Car : E1
Ground Acceleration (g)
3
2
1
0
−1
−2
−3
NL
NR
NL
NR
NL
NR
NL
NR
Heat 1
Heat 2
Heat 3
Heat 4


X
Y
Z
MAG
Funny Car : Final
3
2
1
0
−1
−2
−3
Ground Acceleration (g)
NL
NR
Heat 1

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