# Driver Controls Analysis and Redesign

Physics 492R Capstone Project Report, April 2019


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**Abstract**: During the SAE International Collegiate Series Baja Competition Oregon 2018, various failures in driver control systems occurred resulting in poor performance in dynamic events. These failures were analyzed, and weaknesses were identified in the 2018 BYU Baja vehicle, including the design of the pedals, steering shaft, and suspension components. An improved design was developed by iteration, analyzed for strength using computational and finite element analysis, and field tested for validation. Results of field testing indicated increased capability of redesigned components, which were integrated into the 2019 BYU Baja vehicle. During the SAE Baja California 2019 Competition, no failures were observed in the redesigned components.

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**INTRODUCTION**

The International Society of Automotive Engineers describes the Baja collegiate series competition on their website as follows:

> Baja SAE challenges engineering students to design and build an off-road vehicle that will survive the severe punishment of rough terrain and in some competitions, water. As in real work situations, these future engineers work together as a team to discover and resolve technical challenges in design, test, and manufacturing, as well as business issues. The most rugged of all the competitions, Baja SAE also gives students the first-hand challenge of pursuing their passion while managing real-life demands and priorities. Each team's goal is to design and build a prototype of an all-weather, rugged, single-seat, off-road recreational vehicle intended for sale to the nonprofessional weekend off-road enthusiast.

The competition consists of the following events: Sales Presentation, Technical Inspection, Design Review, Acceleration, Hill Climb, Maneuverability, Terrain, and Endurance. Each team is scored in these areas and awarded a composite score at the end of the competition. Due to the intensely analytical nature of the scoring criteria as well as a staggeringly thick rulebook of specifications, the competition is much more than a road race. Comprehensive understanding of the physics involved with the vehicle is essential to performing well in all events.

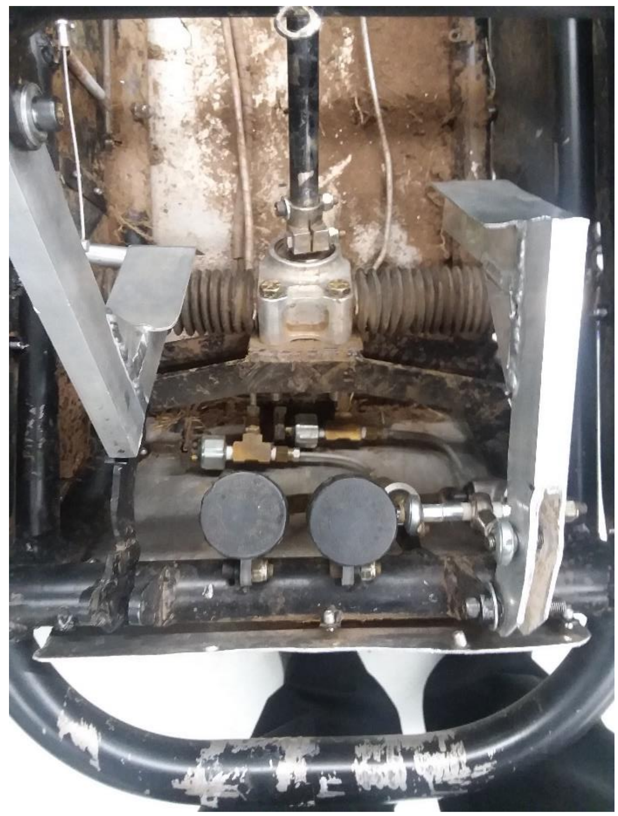


*Figure: 2018 Vehicle Pedal assembly, Aluminum*

At the beginning of every academic year, the BYU Baja Racing team designates an improvement plan in preparation for the SAE International Collegiate Baja Series Competition. For the 2019 Competition, our Project Objective Statement read: "The objective of the 2019 BYU Baja Team is to improve on the 2018 Baja vehicle through an enhanced instrumentation package, E-CVT, and more robust driver controls. The improved vehicle and capstone design package will be completed by April 1, 2019 with a budget of $10,000 and 4,500 man hours," We set out to accomplish this with a team of 15 Students with backgrounds in Mechanical Engineering, Manufacturing Engineering, Electical Engineering, and Physics. This paper focuses on work done primarily (though not exclusively) by the driver controls sub-team, Brady Hales, Cameron Crawford, Joshua Tunick, Nick Lawrence, and Bryan Andrews. The objective of the driver controls sub-team was to **design, build, and test a robust driver control system that is also lightweight and ergonomic by April 1, 2019 under a budget of $2000 dollars and utilizing 1800 man-hours.**

Efforts from previous BYU Baja teams were focused on making lightweight components, due to the 10 horse-power restriction on vehicles. Because of this and other prioritizations in previous years, the 2018 pedals were made of rectangular aluminum tubing, welded in angular joints with thru holes and bolts for pivot points. We used the smallest possible suspension hardware, and the steering shaft was made from a hollow steel tube with a thru hole and a bolt at the bottom. During the 2018 competition, the following failures to driver control mechanisms occurred:

- Pivot point of the throttle pedal became loose by deformation
- The brake pedal buckled several times, requiring pit stops and ultimately the manufacture of a steel reinforcement piece
- The steering shaft began to shear at the attachment to the steering rack
- The heim joints connecting the tie rod to the steering rack deformed

While efforts in mass optimization could improve the vehicle's power to weight ratio making it faster, the pit stops required to address failures made those improvements obsolete. Our strategy for the 2019 competition was to prioritize durability over weight reduction and provide a foundation of usable knowledge for future teams to better understand the forces involved.

## METHODS

To ensure proper direction throughout the project, the following requirements matrix was referred to frequently. We determined potential performance measures for the driver controls system and then placed them in the matrix to ensure they were connected to our market requirements. We also made estimates on the desired values located in the bottom of the matrix, with corresponding units in the top row.

| # | Market Requirements | Importance | Subsystem meets SAE rules and regulations | Subsystem Weight | Minimum continuous run time without failure | Static Steering Effort on asphalt | Pedal force required to lock all tires on asphalt | Static Turning Radius | Driver comfort survey score | Maximum time to change any steering component |
|---|---|---|---|---|---|---|---|---|---|---|
| | Units | | N/A | lbs | hrs | lbs | lbs | ft | N/A | min |
| 1 | Subsystem is lightweight. | 3 | | x | | | | | | |
| 2 | Subsystem provides for a maneuverable vehicle | 5 | x | | | x | | x | | |
| 3 | Subsystem is serviceable. | 7 | x | | | | | | | x |
| 4 | Subsystem is ergonomic. | 6 | x | | | x | x | | x | |
| 5 | Vehicle brakes well. | 4 | x | x | | | x | | | |
| 6 | Subsystem is safe. | 2 | x | | x | | | | | |
| 7 | Subsystem is durable. | 1 | x | | x | | | | | |
| Ideal Values | Lower Acceptable Limit | | Yes | 17 | 4 | N/A | 80 | N/A | 8 | N/A |
| Ideal Values | Ideal | | Yes | 21 | 8 | 85 | 90 | 7 | 9 | 10 |
| Ideal Values | Upper Acceptable Limit | | Yes | 30 | N/A | 95 | 100 | 9 | 10 | 15 |

### Justification of Market Requirements

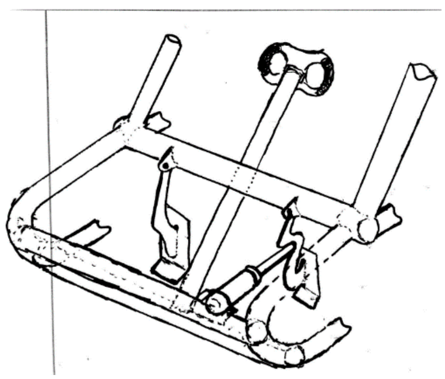
- Market requirements 1 – 3 were justified using market surveys conducted by the 2017-2018 capstone team. These surveys were conducted at various power sports dealerships throughout Utah Valley.
- Market requirements 4 – 7 were justified by the 2019 SAE Baja Rules book. This book lays out the governing standards and rules for the Baja vehicle.

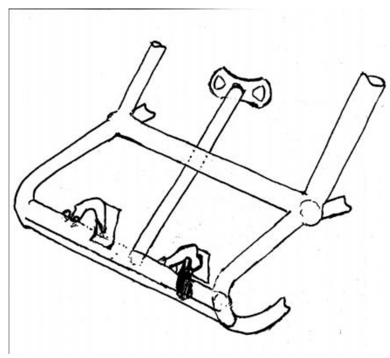
### Justification of Performance Values

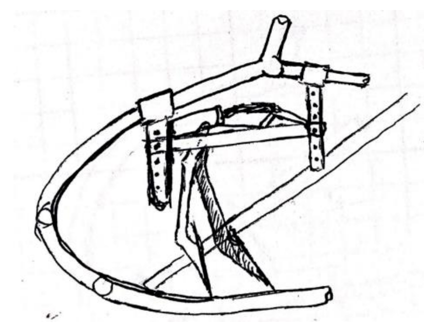
- Subsystem meets SAE rules and regulations. The values are indicated as pass/fail criterion.

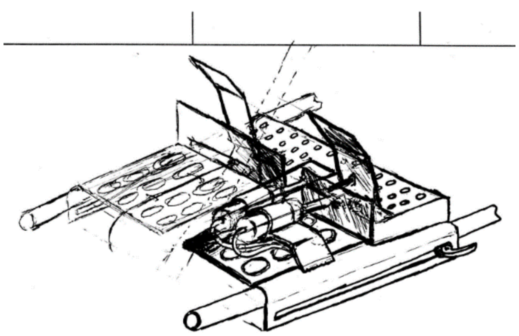
- Subsystem weights based on 2017 Baja controls subsystem weight budget (p.42 Capstone Report). Many of the respective components of the controls subsystem did not change in the 2018 car v. the 2017 car. As such, we desire to work off of the same budget because we will be creating more durable components while utilizing mass optimization techniques.
- Static Turning Radius based on 2017, Static Turn Radius test (2017 Capstone Team 32 Report p.34)
- Minimum run time without failure determined by total run time in SAE Baja competition.
- Static Steering Effort on asphalt (Liu, Nagai, & Raksincharoensak, 2008).
- Braking force on pedal due to foot (McMulkin & Woldstad, 1994).
- The Driver Comfort survey is tentatively planned to take both of the Baja cars out to Brigham Square and ask students to rank comfort and ergonomics on a scale of 1 – 10, 1 being the worst and 10 being the best. They will have the old design and the new design to make comparisons.
- Minimum time to change a steering component based from practical tear down experience.

We then moved on to concept generation by brainstorming ideas from every team member and then screening those ideas on a whiteboard. The five most reasonable solutions were sketched and placed in a scoring matrix for evaluation.









| Rating: | |
|---|---|
| 1 | Much worse than reference |
| 2 | Worse than reference |
| 3 | Same as reference |
| 4 | Better than reference |
| 5 | Much better than reference |

Reference is 2018 Baja car pedals.

| Requirements | Weighted Score | Fixed top mount, components | Fixed bottom mount, components | Adjustable bottom mount, assembly | Adjustable top mount, assembly | Joystick throttle & brake |
|---|---|---|---|---|---|---|
| Weight | 0.2 | 3 | 3 | 2 | 2 | 4 |
| Cost | 0.15 | 3 | 3 | 1 | 2 | 1 |
| Ergonomics | 0.1 | 3 | 3 | 5 | 5 | 4 |
| Strength | 0.35 | 3 | 3 | 5 | 4 | 1 |
| Adjustability | 0.15 | 3 | 3 | 5 | 4 | 3 |
| Modularity | 0.05 | 3 | 3 | 5 | 5 | 3 |
| Weighted Score | | 3 | 3 | 3.8 | 3.45 | 2.3 |
| Decision | | Discard | Discard | Accept | Research | Discard |

**Matrix Conclusions:** We considered various concepts of adjustability, modularity, and ergonomics. We believe that adjustable bottom-mount assembly will outperform all others. However, we also decieded to research adjustable top-mount, assembly due to the fact a driver might not be able to apply enough braking force with bottom mount assembly.

**Scoring Conclusions:**

The most important requirement for pedal concepts is strength, because the team experienced failures last year that required pit crew repairs. These repairs cost the team more time during competition than light weighting could reasonable make up for. As a result, concepts that did not meet or improve upon the 2019 vehicle's strength were discarded due to the weighted scoring.

The weight requirement was considered to be the next most significant due to the impact on vehicle performance. Heavier pedal systems will have an adverse effect on the car's quickness and acceleration which are critical for competition.

The remaining requirements were considerable factors that affect driver performance and the vehicle's competitive advantage in terms of the marketing strategy considered for the sales aspect of competition. However, these factors (i.e. ergonomics, cost, adjustability and modularity) when considered individually are not as critical as strength, simply because if the pedals break, then the vehicle can't perform.

**Fixed top mount, components:**

This and the bottom mounted component based systems were the previous 2 year models.

**Fixed bottom mount, components:**

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**Adjustable bottom mount, assembly:**

Strength is much better due to the design capabilities of a modular bottom system. Bottom pedals that are adjustable allow for optimized location for the forces that the driver places on the pedals. However, this assembly would require more components and fabrication thus increasing the cost and weight.

**Adjustable top mount, assembly:**

Similar to the adjustable bottom assembly, the top mounted assembly would be conducive to driver comfort and optimize the forces placed on the pedals. This would improve the strength of the system. However, this assembly would increase the cost and weight similar to the bottom mounted version.

**Joystick throttle & brake:**

This system improves the ergonomics of the vehicle and lowers the weight since the physical pedals would be removed from the vehicle. Adversely, implementing this system would require many new parts and man hours for redesign which would sharply increase cost. Also, creating a joystick would put the entire weight of the driver on the system and would induce fatigue and sheer failure similar to previous model steering columns.

## Testing Procedures

### Strength

1. Using ANSYS and CAD design of the prototype, create predictive model of failure points in compression and bending assuming maximum driver force of approximately 400 pounds (combined driver weight and arm strength)
2. Attach strain gauge to prototype and complete 10 laps on the track, recording strain
3. Compare strain gauge results to predictive model
4. Measure prototype for bending and other deformation

**Weight**

1. Perform mass optimization in ANSYS
2. Weigh prototype of assembly and record mass

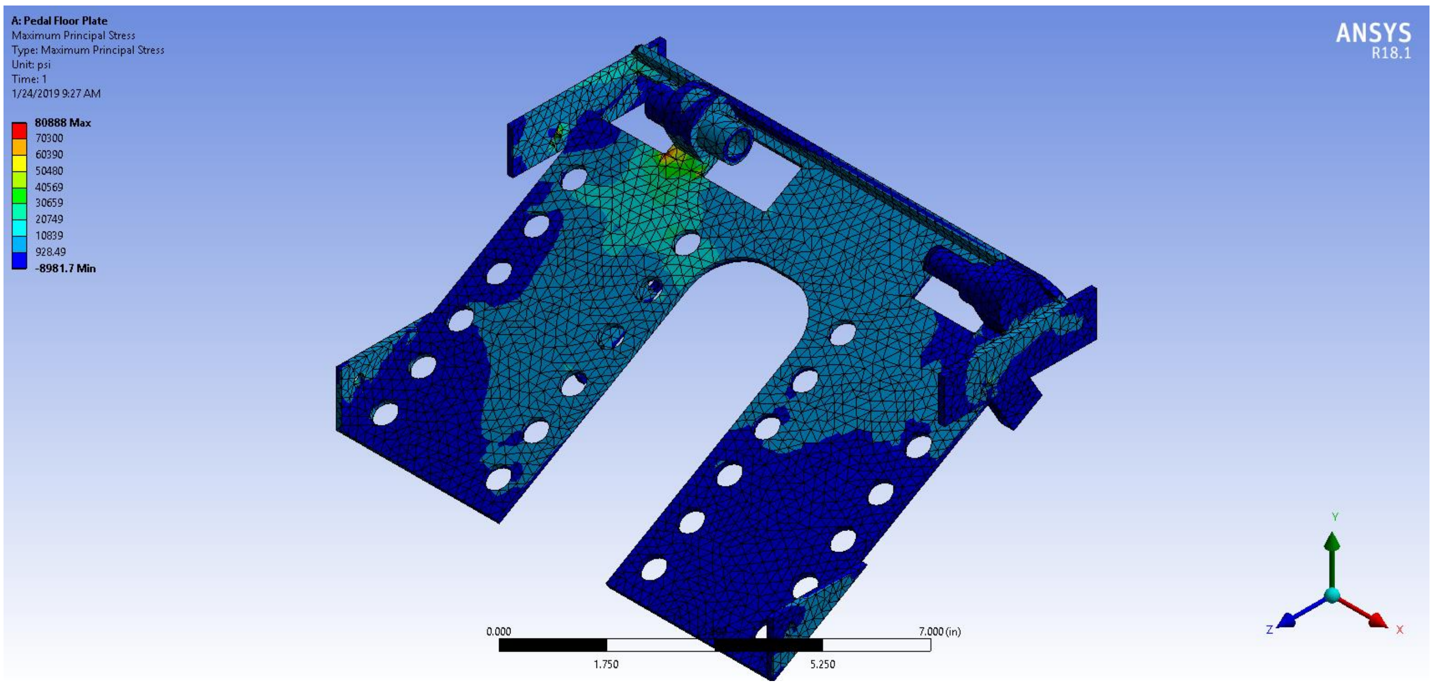
**Ergonomics**

1. Allow 10 drivers to drive 10 laps each around the track
2. After each driver completes the test of 10 laps, drivers complete the following survey without discussion with other test participants
    a. On a scale of 1 to 10, rate your comfort (1: painful – 10: I could do this all day)
    b. On a scale of 1 to 10, rate your control of the vehicle (1: I had no control of the vehicle – 10, I had complete control of the vehicle down to the inch)
    c. Describe any pain/soreness experienced as a result of the vehicle controls (pedals, steering)
    d. Given an extended driving time, predict the first part of your physique as the driver to experience fatigue

**RESULTS / DISCUSSION**

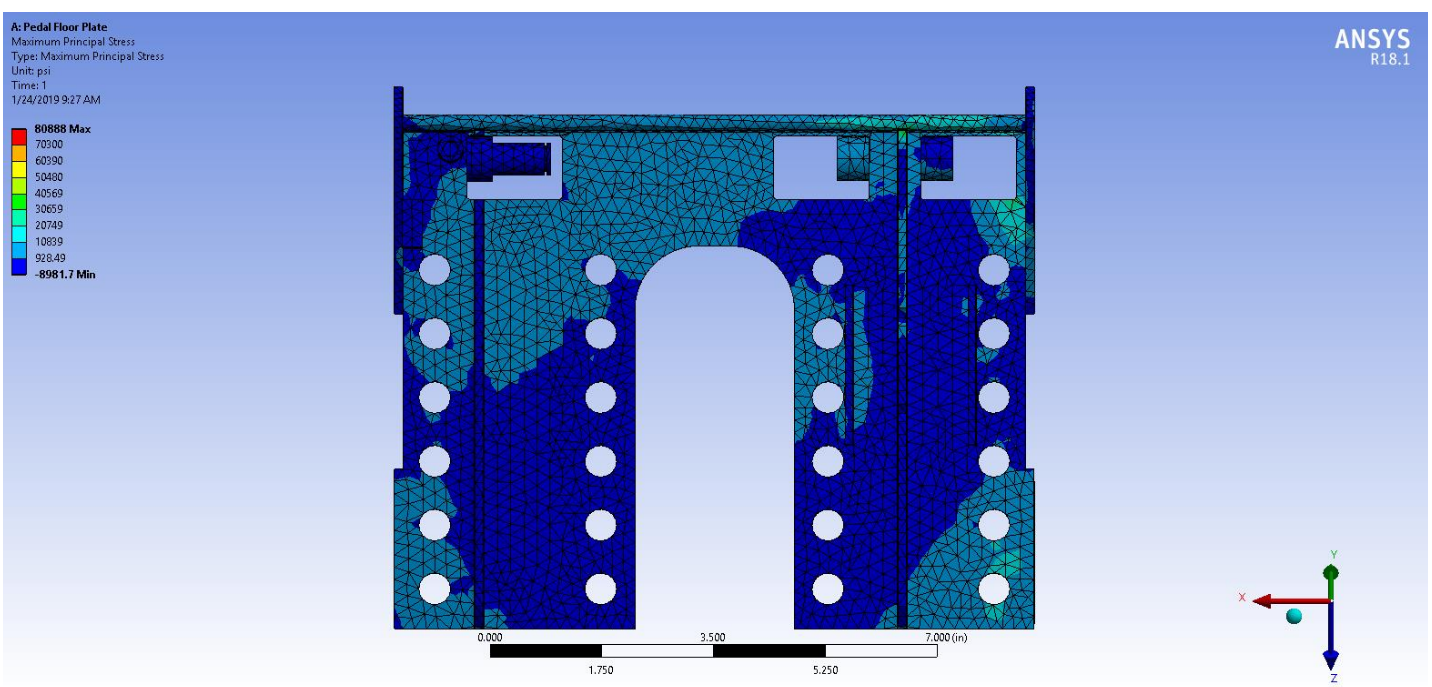
After several iterations of finite element analysis using ANSYS Workbench 18.1 the following results were compiled for the 2019 pedal assembly concept. Results were compiled with safety factors from 1 to 4, including stresses and deformation. With a desired safety factor of 4, the maximum applied load on a pedal will be 440 lbs. The final analysis of the current geometry of the pedal housing shows major stress concentrations that will result in failure due exceeding the yield strength of the material (shown in red on the Figures below regarding Von-Mises stresses).

**Steel 1060 (SF=1, max load = 110 lbf)**



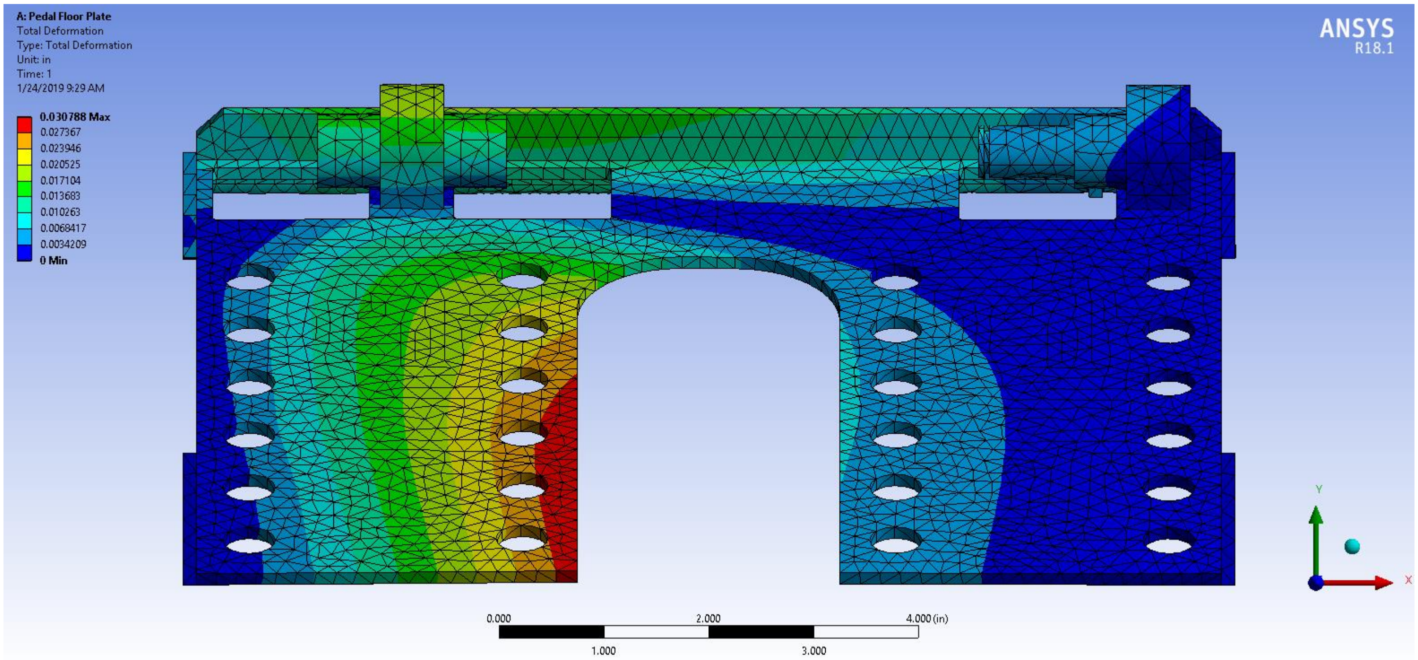

Equivalent (Von-Mises) Stresses

*Isometric view*




*Back view*

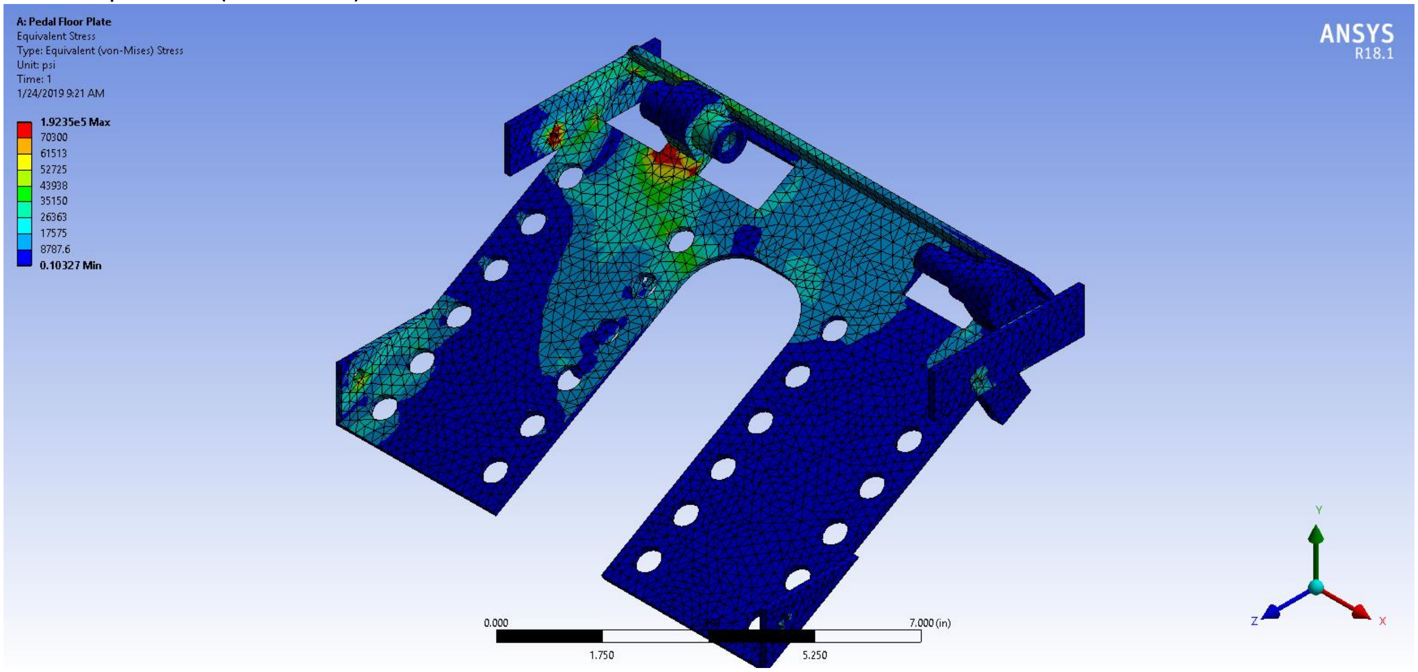
Total Deformation



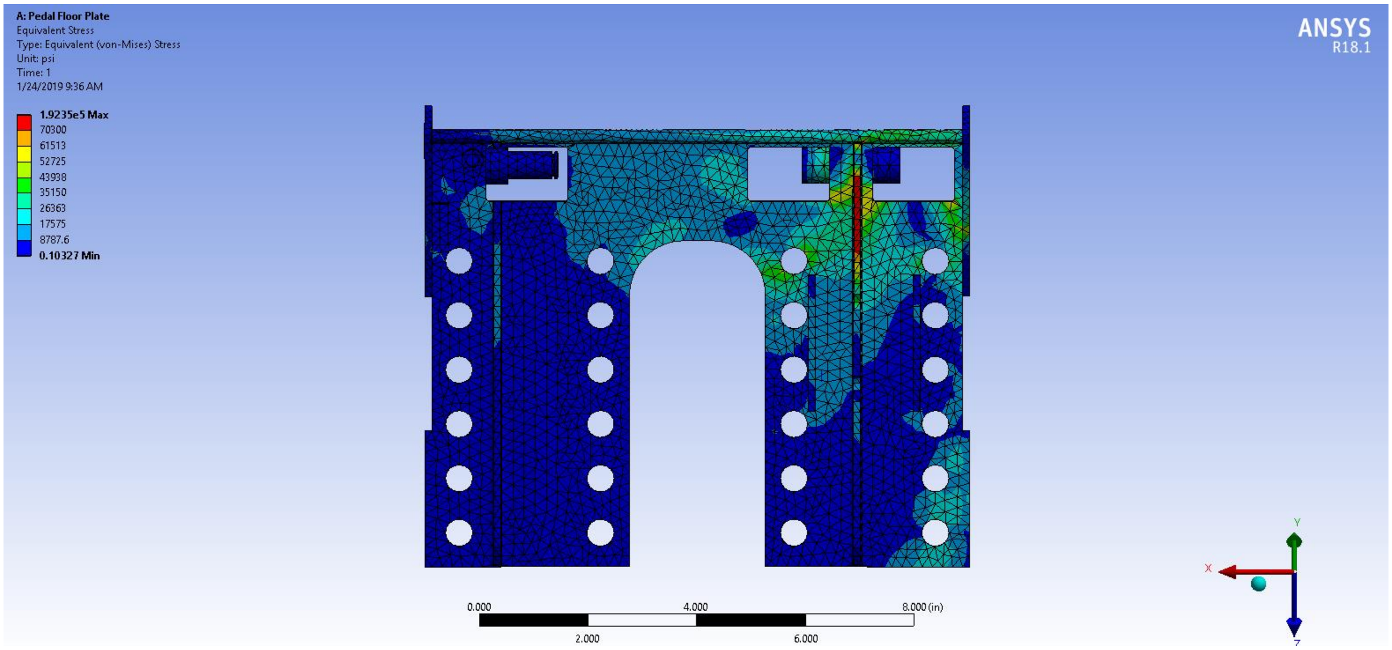

*Front view (deformation)*

**<u>Steel 1060 (SF=2, Max Load = 220 lbf)</u>**

Equivalent (Von-Mises) Stress

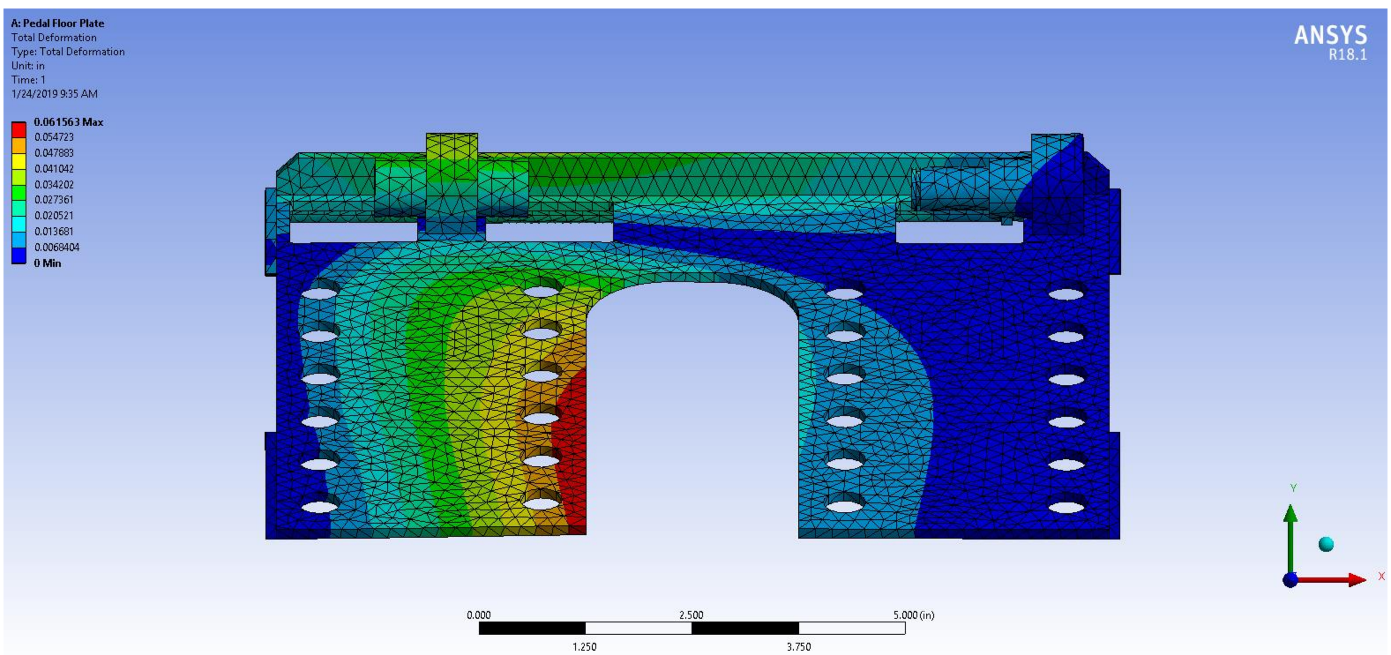



*Isometric view*




*Back view*

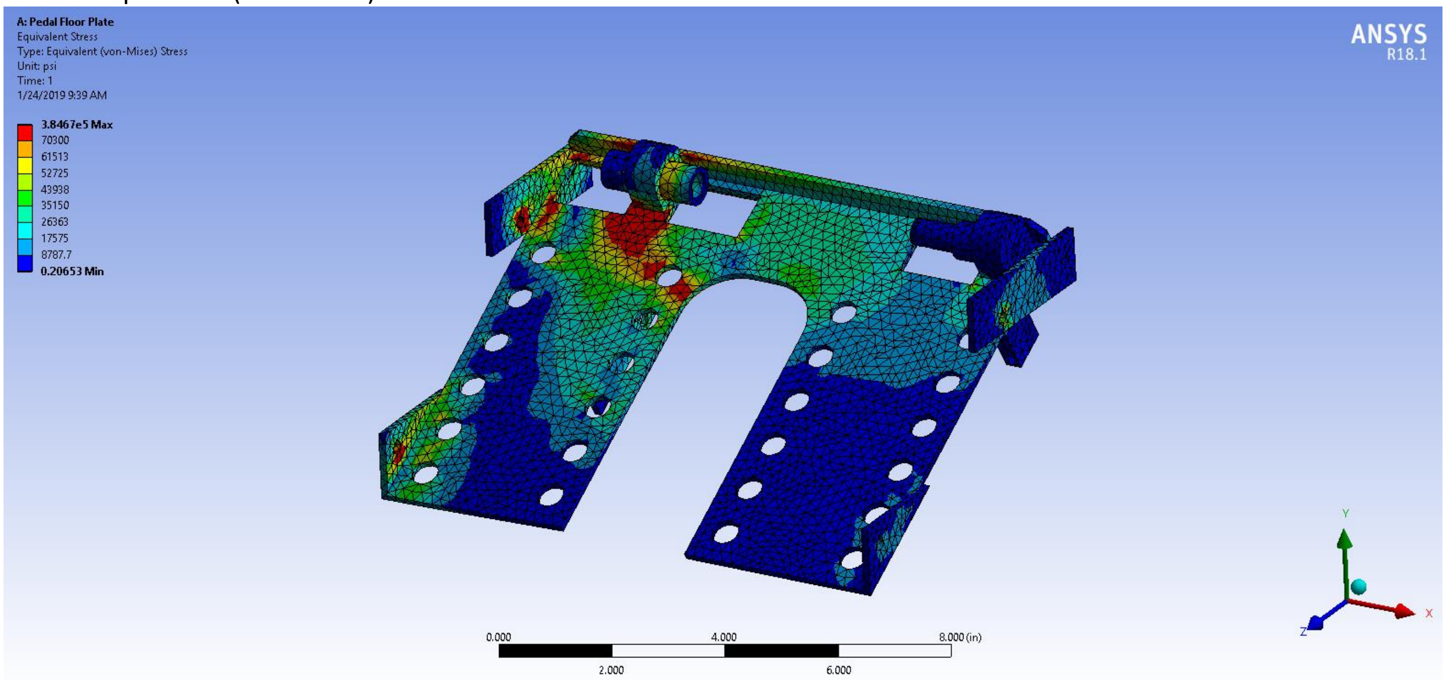
Total Deformation



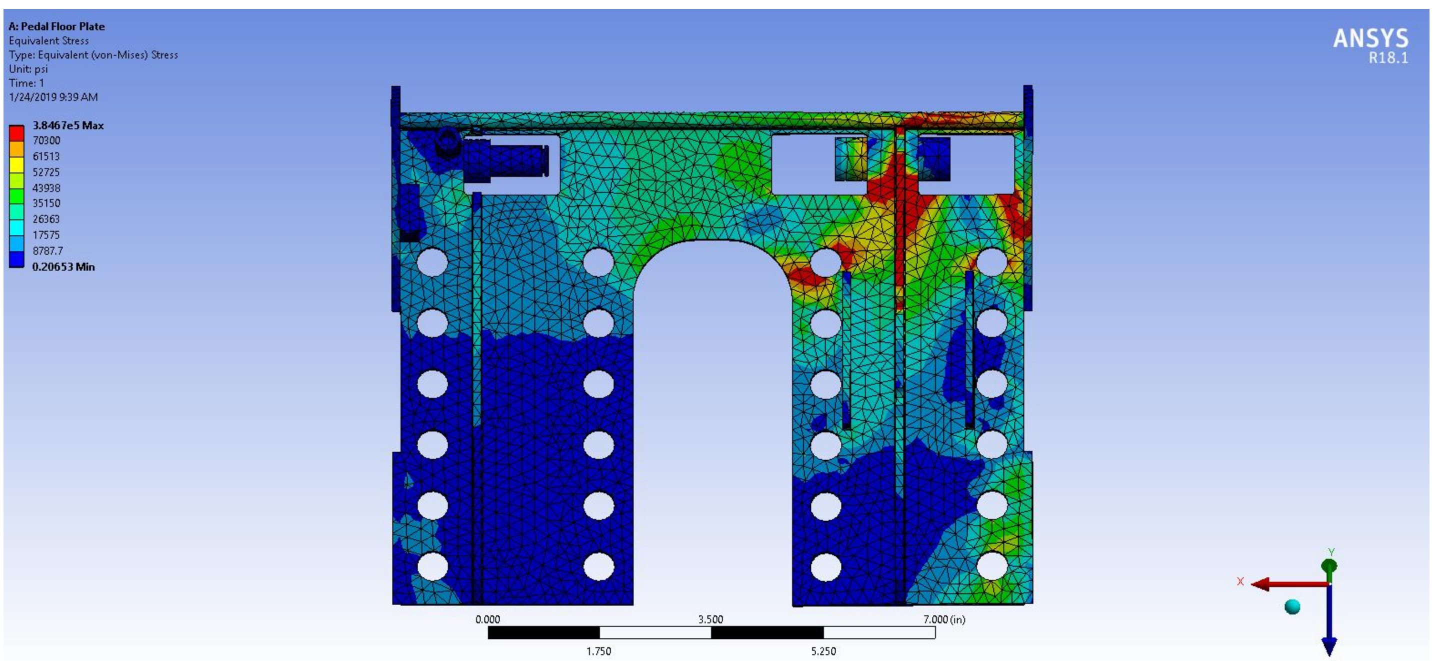

*Front view (deformation)*

**Steel 1060 (SF=4, Max Load = 440 lbf)**

Equivalent (Von-Mises) Stresses

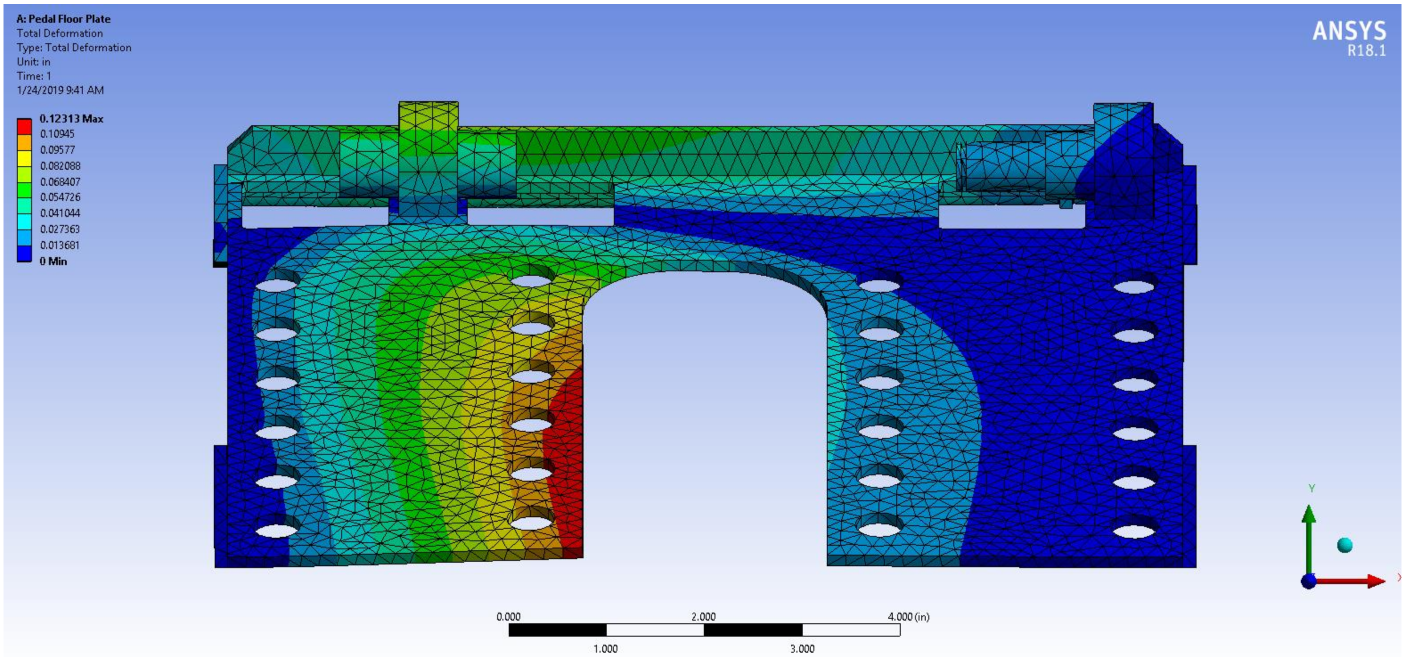



*Isometric view*




*Back view*

Total Deformation (due to material failure mentioned above, this configuration would break before deforming)

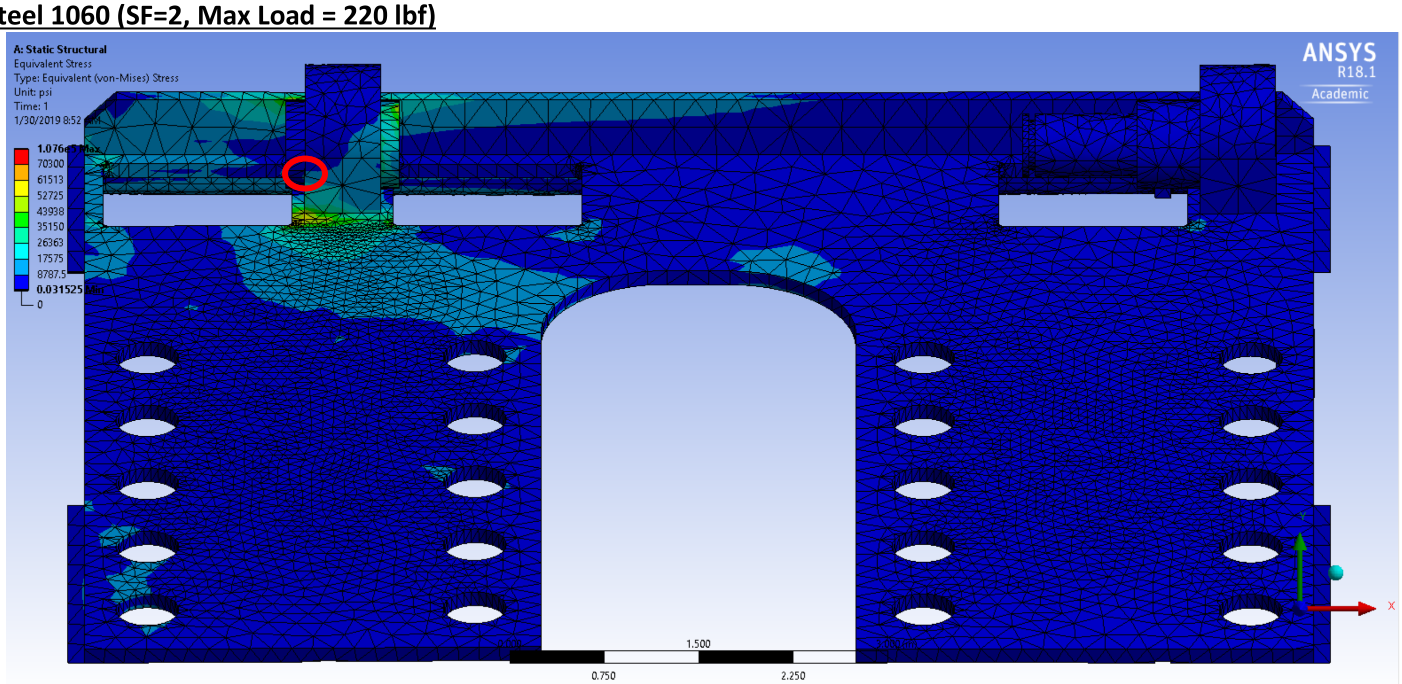



*Front view (deformation)*

At this point it was clear that redesign of the housing is required to eliminate stress concentrations at the points near the brake pedal location.

REDESIGN RESULTS: Added material around the base of the brake pedals allows for greater reduction in stresses and adds rigidity to the system. Further increasing the radii of the inside edges of the slots where the pedals pass through will also reduce stress concentrations.

**Steel 1060 (SF=2, Max Load = 220 lbf)**




*Front view*

As can be seen, compared to the original 220lbf design, the stress through the plate is reduced due to added material on the back side near the brake pedals. A high stress concentration can be noticed at the notch highlighted by the red circle above. Rounding the corners to a greater radius will reduce the effect of the stress concentration. This can be implemented easily within the CAD model.

The above models were then validated by the following strength test data.

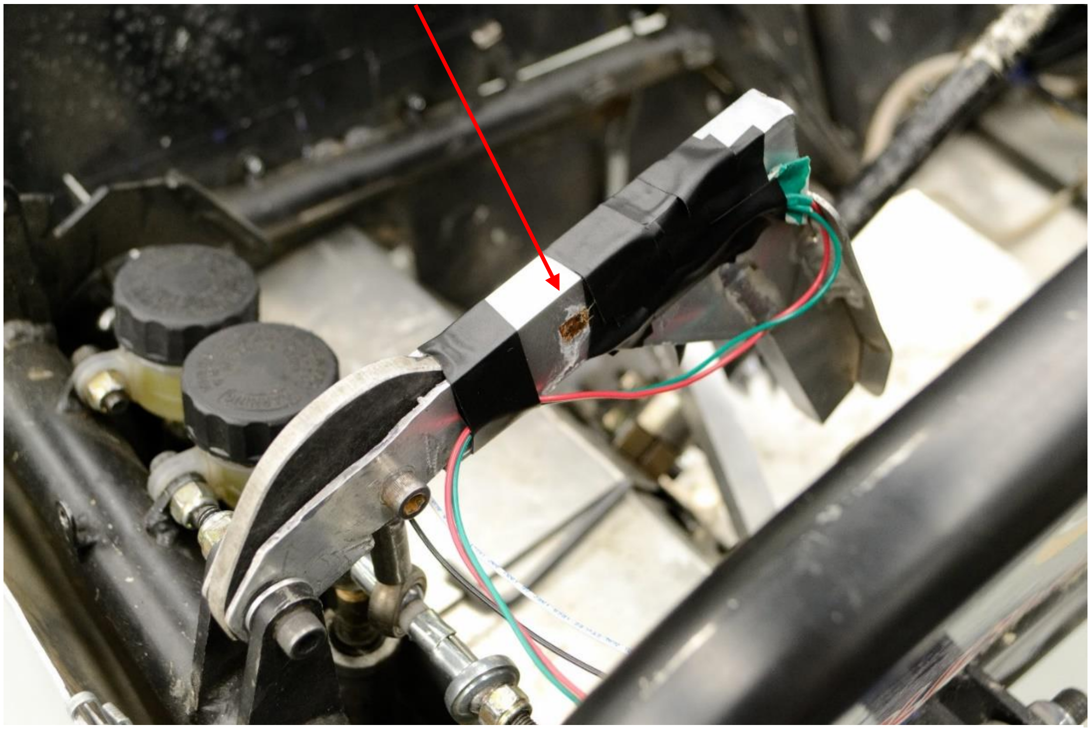


**Figure 1 (above)** shows the placement of the strain gages on the brake pedal. These were oriented such that they could gather data on the compressive forces in the brake pedal.

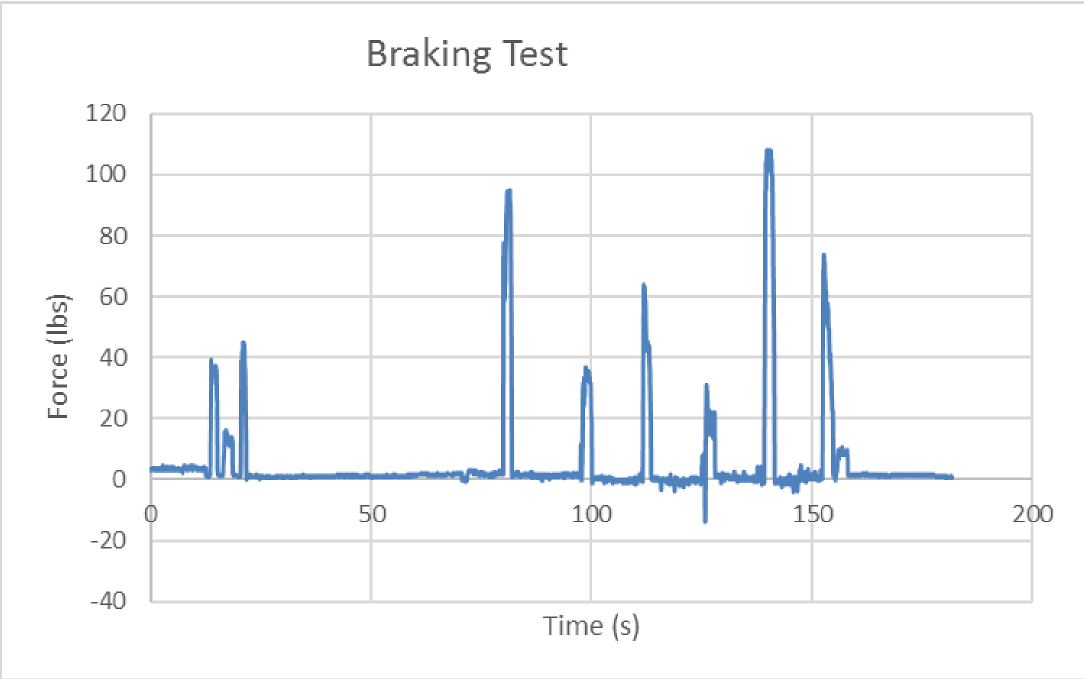



**Figure 2** shows the max compressive forces in the brake pedal where the driver achieved maximum speed and then braked as hard as possible.

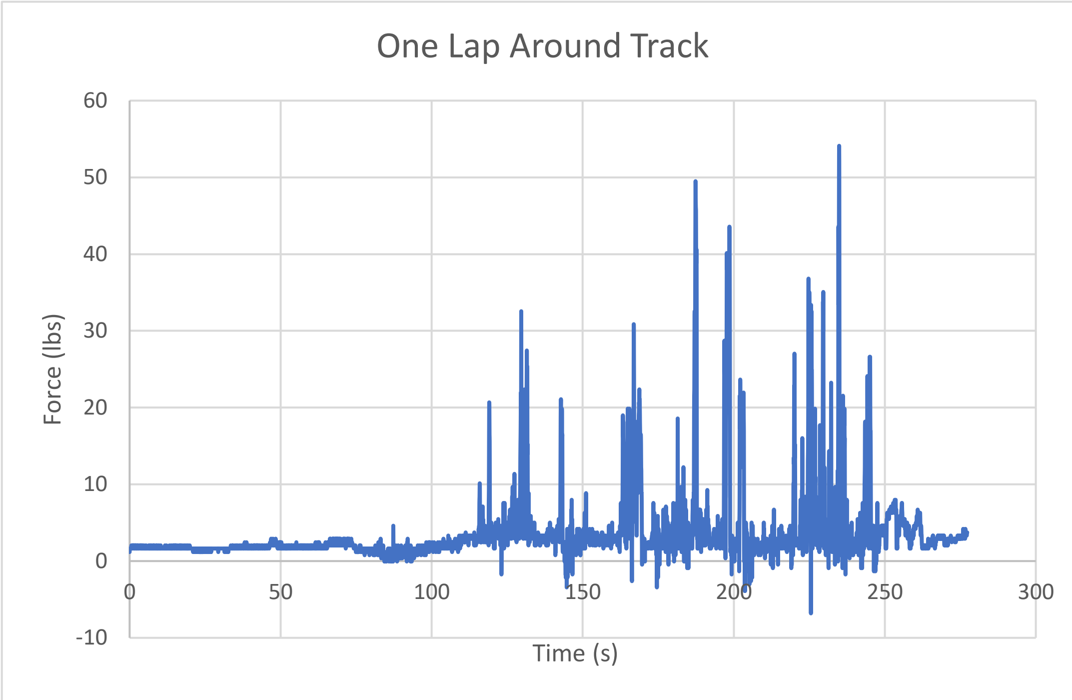


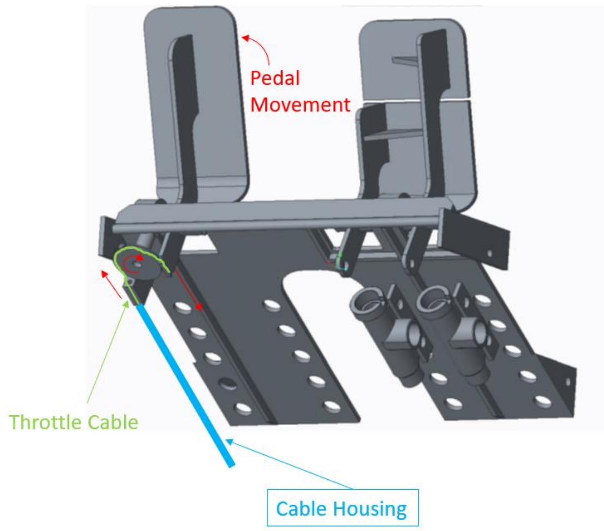

**Figure 3** shows the compressive forces in the brake pedal during 1 lap around the gravel track with the driver attempting to complete the lap as fast as possible.

Though we expected it could be higher the max force experienced was approximately 110 lbs. According to preliminary calculations this confirms the 2018 pedal system failure and satisfied our confidence that the improved design for 2019 would not fail, accomplishing our goal of durability. It also predicts the reliability of the new design and it's ability to make the car safer overall as it is important to have fully working pedals all the time.

**Above:** Prototype of redesigned pedal assembly for 2019

**CONCLUSION**

Other design considerations with the 2019 pedal assembly included the use of a torsion return spring, a guarded pulley, and a double brake pedal. These considerations were made based on calculations that did not merit testing for validation. The pedal-on-axle design aligned the applied force from the driver with the pivot of the pedal, reducing the off-axis moment caused by the 2018 design. A guarded pulley on the underside of the throttle pedal housing aligned the return force caused by the throttle cable, reducing an additional off-axis moment in the 2018 design. The double brake pedal was implemented allowing the driver to allocate front-rear braking force as needed, which showed increased maneuverability at high speeds.




It may be of interest to note that the failure in tie rod heim joints mentioned in the introduction were resolved simply by using higher grade units, and that the steering shaft was remanufactured with a slug in the end that sheared. Redesigning the steering and suspension completely was considered, but the team determined that it was beyond the scope of the 2019 improvement project.

Proper due diligence regarding the design of driver controls systems is an aspect of Baja Racing that should not be overlooked. With the right analysis failures can be addressed and prevented, with effects as far reaching as improved performance in all dynamic events, especially endurance. The collective knowledge of the BYU Baja team has been expanded by this research and engineering and will drive further improvements in the coming years. Now that this work has set a team standard for strength on pedals, one area of improvement that could follow this work is mass optimization and light-weighting. It would be a step forward If the team could determine how to make the 2019 design lighter without compromising it’s structural capability.

**REFERENCES / AKNOWLEDGEMENTS**

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Liu, L., Nagai, M., & Raksincharoensak, P. (2008). On Torque Control of Vehicle Handling and Steering Feel for Avoidance Maneuver with Electric Power Steering. *IFAC Proceedings*. doi:10.3182/20080706-K-KR-1001.02044

BYU Baja 2019 Team Roster:

| Name | Position |
|---|---|
| **Yuri Hovanski** | Project Coach |
| **Sage Stubbs** | Team Lead |
| **Tom Naylor** | Team Manager |
| **Benjamin Ralph** | ECVT |
| **Bradford Clark** | Instrumentation |
| **Brady Hales** | Pedals/Steering |
| **Bryan Andrews** | Pedals/Steering |
| **Cameron Crawford** | Pedals/Steering |
| **Christian Peper** | ECVT |
| **Clark Green** | Instrumentation |
| **Dallin Colgrove** | ECVT |
| **Dustin Doty** | ECVT |
| **Ezra Clark** | Instrumentation |
| **Joshua Lee** | ECVT |
| **Joshua Tunick** | Pedals/Steering |
| **Nick Lawrence** | Pedals/Steering |