NASA Challenge Frame Design Study

by

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1) Abstract

The NASA Human Exploration Rover Challenge (HERC) is a world-wide event for high school and college level students to compete in a design competition to build a “Moon Buggy” or Rover style vehicle capable of traversing a simulated other-worldly course while completing specific tasks along the way. In this competition, design teams are tasked with engineering and building a completely original design to compete in this event. Specifically, these vehicles have to be able to cross 8-inch divots, tall hills of dirt, up to a 20 degree incline, and various other treacherous terrains. Between said obstacles, there are certain tasks that each team also has to complete. This includes a spectral analysis, core soil samples, solid soil samples, and liquid samples. This adds the requirement that the Rovers must also have enough space to accommodate two riders comfortably while at the same time holding upwards of 6 different and distinct task tools.

Currently, the practice for Rover design follows two general building guidelines: 1) Rovers with independently actuating wheels on suspension, and 2) Rovers without suspension that act more as a standard road car’s suspension. The University of Alabama in Huntsville has a vast “Moon Buggy” department with many differing designs. In the past year, two different teams have engineered a more simplistic approach to a “Moon Buggy” construction that does not require the implementation of individual suspension components, reducing weight and cost. This document will investigate the major differences in weight, cost, drivability, and durability of the two different design systems in relation to the NASA HERC challenge that UAH competes in yearly. The big question answered here asks, “Is independent wheel suspension the way to win this competition or will simpler solid axle designs be better equipped?” This will include accelerometer data investigating the variety of impacts that a Rover will sustain, as well as its riders. The main intention is to focus on only the suspension components and any directly related components. Test data from three Rovers named Buzz, Falcon, and Sallie Mae is included for measuring impact forces.
2) Introduction

Many of the competition vehicles competing in the NASA HERC challenge have some design of a complex independent wheel suspension system. This leads to many schools not being able to participate due to their inability to design complicated systems that cost large amounts of money. The Falcon Rover built and finished by UAH Team 1 uses a simple solid axle that utilizes a dramatically simpler system (Appendix 1 and Appendix 2) to that of a past winning Rover named Sallie Mae (Appendix 3). Both vehicles have the ability to navigate a simulated course, but the main difference of these Rovers being their suspension systems. For reference, the Falcon Rover has been estimated to be able to achieve a speed of close to 12 miles an hour where Sallie Mae is only slightly faster at around 15 miles an hour. This speed difference is due to the integration of variable drivetrain components in Sallie Mae, unlike the Falcon Rover. Such slow speeds beg the question whether a full off road suspension system is even necessary to be successful in the competition?

The HERC challenge is open to college and high school students, so it is important that nothing should hold clubs and groups back from competing. The conclusion of this report will discuss the implications of using simpler, cheaper Rovers that are eligible for competition. Conclusions can be made from the data extrapolated from testing and further competitions. With reference to the pedigrees of some Rovers, the Falcon Rover placed 3rd highest overall in 2021 (out of the 56 competing colleges) and Sallie Mae placed 1st in the course challenge event in 2018.
3) Design Explanations of Differing Buggies

The two different frame and suspension designs relate closely to that of a streetcar and an off-road vehicle. The designs made by the University of Alabama in Huntsville design teams are not directly derived from modern day designs, but have similar elements. Plainly put, design teams do not reinvent the wheel, but rather apply similar designs to their Rovers. Both systems have their similarities while at the same time, they are indistinguishable from one another. As discussed before, modern day suspension systems from off road vehicles are extremely complicated, so for the sake of simplicity, only the main points regarding the engineering benefits will be discussed.

In the case of the full, independent wheels suspension, it is a very complex system of articulating arms pinned to a central frame suspended by the most important part of the system: a spring and shock absorber. As seen in the photo of Sallie Mae (Appendix 3), the shock absorber is designed to mount between two points: one close to the inside of the frame and one farther down the wheel support (often referred to as A-arms on most vehicles). The two subframe arms are designed to actuate along two sets of mounting brackets attached to the inside of the frame while two more sets of brackets attached to the outer subframes mount to a support plate where the wheel would be positioned. This system allows for the wheel to independently move vertically without constraint from connected components where all of the shock from the obstacles is allowed to be translated into the shock absorber. As seen in Appendix 4, this is very similar to the suspension design of a Polaris RZR off road RTV.

Since the actuating frame designs require that the wheel move vertically in relation to the frame, it also requires that the driving axle be allowed to move as well. This means that components called U-joints must be implemented at both ends of the drive axle. This allows for the drive axle, which translates the power to the wheels through rotational motion, to bend at certain points while maintaining the same amount of rotational freedom. However, some of the lower price U-joints do not transmit power in an even fashion due to the mechanical disadvantage of the two interlocked couplers. This leads to few problems in a low speed and low power application such as the HERC Rovers. The only environment that might have a problem due to this trend would be in a system that requires an exact amount of rotation at the end of an axle dependent on the precise input. A simple U-joint coupler is seen in Appendix 5 that includes a diagram of its intended use.

On the other hand, suspension designs in trucks and road cars use a version of suspension that does not require an axle that has the capability of bending at specific points. Frame designs like this belong to most on-road vehicles and can be seen in Appendix 6. This frame design has a single axle that connects to each wheel with some version of a spring and shock absorber present to allow for the axle to move up or down. Similarly, it also allows the axle to twist in a way where one wheel is able to go up and the other is able to stay in the same place. This allows the wheels to actuate up and down while still sustaining a solid axle design.
This axle design does not include the use of suspension arms or individual U-joints to actuate the axle as the independent designs do, however it includes similar spring and shock absorbers. The purpose of the shock absorbing suspension still works on the same principle, but instead when one wheel moves up or down due to the motion of the suspension in response to the terrain, the opposing wheel connected to the other side of the axle actually has a response. With a solid axle, if one wheel moves in a vertical direction while the other says put, the wheel twists around the lateral axis. It acts as if the axle itself is a Class 3 lever (Appendix 7) where the force of the road making an impact is applied to the far end of the lever (one of the two wheels) and the fulcrum is at the opposite end (the opposing wheel). This inherently means that the force applied to the “lever” in this case is the suspension soaking up some of the impact forces.

The main difference between these two designs is the fashion in which the wheels move. In an independent suspension setup, the wheels are allowed to move based on the single stimuli that is enacted on a single wheel only free to translate in the vertical direction. A solid axle suspension setup can move in a similar fashion, but when one of the wheels moves up or down relative to another, the other wheel is going to have a response enacted upon it. This is where the major differences lie. In an independent setup, each wheel can react to the terrain at any moment and always keep the total tread area of the wheel parallel to the surface. In a solid axle setup, under moments of a large surface gradient, it is possible for a wheel’s tread to be at an angle to the ground since the angle of axle twist depends on how much each wheel is moving.
4) Explain Physical Benefits of Each System

Vehicles with and without the integration of long travel suspension components are very similar systems, but both have benefits to their use in relation to the construction of a NASA challenge HERC project. They both have drastic differences in price, construction, complexity, durability, weight, and effect on vehicle drivability, all due to the assembly of specialized components.

In terms of complexity, the independent suspension is much more complex than that of a solid axle design. An independent design has to have axles that are able to actuate, two sets of suspension arms that actuate, and a wheel that actuates in a way that keeps the outer faces of the wheel always perpendicular to the ground. This makes each system have many moving parts that have to work in conjunction with each other to function correctly. Solid axles do not require U-joints or any actuating frame components to hold the wheel. The wheel is simply held to the axle and moves with it.

Complexity is a factor which influences the price and durability drastically. Since there are so many moving parts, independent suspension components tend to be much more expensive not to mention the fact that there are many more components to purchase. Conversely, solid axles require far less parts and are usually cheaper to produce (which can be seen as to why they are on most road vehicles). Also influenced by the system’s complexity, the durability of each system can be directly related to the number of moving parts. Since solid axle designs have less moving parts, it can be reasoned that there are consequently less parts to break if a critical failure were to occur. Importantly, the axles of an independent suspension setup are required to have a U-joint bend in them, they can on average have less power applied to them before a failure.

On the other hand, weight is a key factor to building a fast and effective Rover as well. In the case of the HERC challenge, most designers will only have access to aluminum, steel, and plastic components. Modern day independent suspension vehicles get around the problem of weight by using lighter aluminum alloys coupled with hollow steel components. Some very high end off road racing trophy trucks even use titanium components for high stress environments. In the case of the small pedal powered buggies however, the weight of components rack up very quickly. Since there are consequently less components in the system, solid axles can usually shave off a few pounds with the elimination of the actuating subframe components, the U-joints, and the hardware (like bearings and sleeves) that hold everything together. In the case of the UAH designed Rovers, on average the buggies that do not contain an independent wheel suspension setup are at a minimum of 50 pounds lighter.

Lastly, (and arguably the most important factor) pertains to the drivability of the vehicle itself. Off road vehicles today strive on the ability to take anything that comes at them. Most fast racing off road vehicles have a suspension that can absorb up to 40 inches of travel [1]. These vehicles can only do this because of the advanced technology that goes into the designing and production of independent
wheel suspension systems. Most vehicles purely designed for rough terrain are designed with long travel independent suspension. Now this does not mean that there are no vehicles that have solid axles competing in off road events, but the superiority of independent suspension systems shows.
5) Test Parameters and Predictions

Two major tests were conducted on three of the functioning UAH Rovers. They were two simple suspension tests that included traversing two standard three by twelve inch speed bumps and a slow speed rolling drop test over a six inch drop. These tests were designed to only test the suspension components of the Rovers rather than test any other frame aspects such as frame flexibility, wheel design, or drivability. Each test was repeated twice for each Rover to compute an average value. The three Rovers tested were Buzz (Appendix 8), Sallie Mae (Appendix 3), and Falcon (Appendix 1 and Appendix 2). Buzz is equipped with about 5 inches of suspension travel weighing close to 400 pounds without the presence of any riders. Sallie Mae is equipped with 10 inches of suspension travel weighing 250 pounds without the presence of any riders. Lastly, Falcon weighs 151 pounds without any riders and has two TPU (3d printable rubberized thermopolymer) blocks between the subframes and main frame for flexibility and slight impact relief. Each Rover is equipped with solid aluminum non-pneumatic wheels with flexible rubber sheets for grip.

In order to test the impacts to riders due to surface factors, a Wit-Motion 3-axis accelerometer (Appendix 9) was attached to the base of each Rover’s front rider seat or the consequent front seat mounting bracket. This would best approximate the g-force impacts to the riders. Data from the accelerometer was outputed into a text file, that is then read by a MATLAB code (Appendix 10) that outputs the components of angular acceleration, angle of tilt, and g-force acceleration. Since the frames of each Rover are designed differently causing the accelerometer to be oriented in different directions, the magnitude of the acceleration is displayed for examination purposes. This magnitude of g-force acceleration experienced by the accelerometer is displayed in the next section and will be the standard by which conclusions will be made in the final section. All data is taken with the same accelerometer in order to ensure consistent data readings. All testing was conducted while operating the Rovers at around 5 miles an hour, or a brisk walking pace. It is my prediction that the solid frame design will have a much larger general impact factor than that of the designs with the suspension, but it will not be enough to warrant the necessity of large suspension components if the use of flexible, non-pneumatic wheels were implemented into the system.
Test Data

**Speed Bump Test**

Figure 6.1: Rover Buzz Test 1

Figure 6.2: Rover Buzz Test 2
Figure 6.3: Sallie Mae Test 1

Figure 6.4: Sallie Mae Test 2
Figure 6.5: Falcon Test 1

Figure 6.6: Falcon Test 2
6 Inch Drop Test

**Figure 6.7:** Buzz Test 1

**Figure 6.8:** Buzz Test 2
Figure 6.9: Sallie Mae Test 1

Figure 6.10: Sallie Mae Test 2
Figure 6.11: Falcon Test 1

Figure 6.12: Falcon Test 2
6) Data Discussion

After a preliminary review of the data collected during testing, it is important to note that the hard asphalt surface used during the speed bump test caused “busy” data plots due to the tread on the solid aluminum wheels. The impact data is clearer in the six inch drop section since the hard surface used for testing was in a grassy area so dirt soaked up most of the rolling resistance due to the large wheel tread.

In the speed bump test, Rover Buzz displays clear peaks of impact when coming into contact with the obstacle maxing out at about 4.2 Gs in Test 1 and 3.6 in Test 2. Both peaks are clearly visible implying that the two rolling obstacles were felt by the rider in contrast to the standard rolling resistance. Sallie Mae and Falcon experience much busier plots. These extremely busy and varying plots not only display the impacts from the speed humps, but they also track every point where the Rovers are vibrating due to the large tread on the solid aluminum wheels coming into contact with a hard asphalt surface. That being said, Sallie Mae has two slow peaks maxing out at 3.2 Gs in Test 1 and 3.4 Gs in Test 2. Falcon reacted in a similar fashion with two slow peaks maxing out at 2.75 Gs and 3 Gs. In the drop test, there are two clear peaks in each magnitude graph that represent the impact when the front wheels of each Rover hit the ground followed by the rear. Buzz experienced 4.4 Gs force in Test 1 and 4.5 Gs in Test 2. Sallie Mae experienced 3.75 Gs in Test 1 and 3.3 Gs in Test 2. Falcon experienced 2.8 Gs in Test 1 and 5 Gs in Test 2.

An important factor however is the average rest values for each test. For the tests conducted on Buzz and Sallie Mae, the resting g-forces on the accelerometer stayed consistently around 2.4 Gs while the resting measured g-forces on the Falcon Rover were staying consistently around 1.4 Gs. This means that the change in g-force measured by the accelerometer would be the approximate maximum g-forces applied to the Rovers due to the impact forces of the terrain. This simple equation was applied to the g-force data in order to calculate the actual impact g-force measurement.

\[ F_{\text{actual}} = F_{\text{maximum}} - F_{\text{average}} \]

**Equation 1: Actual Impact Force Calculation**
After a quick recalculation, the actual Impact g-forces are displayed in Table 1 and Table 2:

### Table 1: Speed Bump Test

<table>
<thead>
<tr>
<th>Rover Name</th>
<th>First Test (Gs)</th>
<th>Second Test (Gs)</th>
<th>Average (Gs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sallie Mae</td>
<td>0.8</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Buzz</td>
<td>1.8</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Falcon</td>
<td>1.35</td>
<td>1.6</td>
<td>1.475</td>
</tr>
</tbody>
</table>

### Table 2: 6 Inch Drop Test

<table>
<thead>
<tr>
<th>Rover Name</th>
<th>First Test (Gs)</th>
<th>Second Test (Gs)</th>
<th>Average (Gs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sallie Mae</td>
<td>1.35</td>
<td>0.9</td>
<td>1.125</td>
</tr>
<tr>
<td>Buzz</td>
<td>2.0</td>
<td>2.1</td>
<td>2.05</td>
</tr>
<tr>
<td>Falcon</td>
<td>1.4</td>
<td>3.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>
7) Conclusion

Varying data during testing shows that there is room for error in the data collection. This is most likely due to the sampling rate of the accelerometer which is why more than one test was collected for each obstacle. Table 1 and Table 2 from Section 6 detail all of the data collected solely due to impacts. It is clear that accelerating up to speed (and just the application of 1 G of gravity) was also factored into the magnitude of the final data pulled from the accelerometer. This is why the data was subtracted by its average in order to determine the actual impact forces. Each Rover operated on solid aluminum wheels, so there was no impact reduction due to differing wheel designs.

From the speed bump test, it is unsurprising that the accelerometer collected very small impacts during the Sallie Mae tests. However, it is surprising to see that the average values of impact from Buzz (a heavy weight Rover with suspension) and Falcon (a lightweight Rover with no suspension) were so similar. This is most likely due to the slow speeds and weight differences in the Rovers. Buzz has a short travel suspension setup, however, the weight difference between the Rover Falcon and Buzz is drastic, so it can be inferred that weight is the largest factor (besides long travel suspension components) when a Rover is tasked with traversing over a small obstacle at slow speeds. The drop test tells a different story since this was a test of raw impact. The Sallie Mae Rover again performed the best soaking up most of the impact with the long travel suspension components. The Rover Buzz performed only slightly better averaging 0.45 Gs less than that of Falcon.

In terms of the Rover design, it comes down to a combination of suspension components and weight reduction. Specifically, different obstacles have different effects on the Rovers and in turn will require different standards for traversing these obstacles. For example, in the case of the standard speed bumps, Falcon and Buzz had nearly the same impact force. In the case of the Buzz Rover, the suspension springs/coils had to allow the wheel to raise upward due to the obstacle while at the same time lifting the heavier Rover above it. Falcon might not have had any suspension components to soak up the rapid change in terrain, but it also did not have to hoist the heavy Rover upwards so there was less overall impact on the frame. This is a different story in the case of just a vertical drop test though. When suspension components are required to soak up the impact due to a free-fall, these springs/coils are only required to catch the Rover and its frame in one direction so there is a greater difference in performance due to the quality and travel of the suspension components.

In relation to the Human Exploration Rover Challenge vehicles, it is clear that suspensionless Rovers are still able to compete. Most challenges faced on the course are mainly traversing undulating terrains and traveling up and over obstacles. If the introduction of large drops were to become factors in the competition, large distinctions will have to be made in the use of solid frame Rovers. For teams from smaller schools with less money that are eager to compete in the HERC challenges, Rovers without the presence of suspension components have the ability to compete even though at a disadvantage to the riders and important drive components. Impacts due to the course obstacles were
ramped down for testing purposes and may well be greater than previously imagined. Also, based on the decisions of the individual teams, the ability does exist to skip obstacles, so there could be the ability to design a Rover frame with only specific HERC challenge obstacles in mind. However, in the case of the three tested Rovers, the weight factor plays a huge role in the overall performance.

The Rovers Sallie Mae and Buzz both had some form of shock absorber that was used as the main component to absorb impacts from obstacles, but Buzz weighed over 100 pounds more than Sallie Mae. This means that the suspension components are having to do significantly more work in order to keep up with the rapidly changing terrain. From this, the conclusion can be drawn that if a Rover is heavier, a longer and stronger suspension system is required for longevity during use. So as previously stated, the use of suspension on HERC challenge Rovers is directly relative to the availability of components and the overall Rover weight. The lighter the Rover, the less need there will be for long travel suspension components like those that exist on high speed trophy trucks. This shows in the data collected in the relation between the Buzz and Falcon speed bump test data. There was no suspension on Falcon, but it was still able to react in the same fashion as Buzz did. However, high speed impacts and free-fall situations are much more dependent on the impact reduction abilities of the installed shock absorbers.

So in conclusion, stated in simplest terms, to answer the question “Do all HERC challenge Rovers need suspension components with actuating features to be competitive in the competition?” No, not all Rovers need these components, however they decrease the overall maintenance of the Rovers as a whole by soaking up most of the vibrations due to rolling, and mainly decrease the impacts due to free-fall conditions. If smaller teams without the engineering capabilities were to avoid certain driving conditions and further reduce the overall weight of the Rovers, there is nothing to say that these Rovers would not be just as competitive as the complicated independent suspension Rovers. That being said, it is still very important to recognize the safety and longevity of the Rovers as a whole knowing that the suspension system is just a very small (but integral) piece of a very large puzzle.
Appendix

Appendix 1: Falcon Rover Unfolded

Appendix 2: Falcon Rover Folded
Appendix 3: Rover Sallie Mae

Appendix 4: Polaris RZR Long Travel Suspension

Appendix 5: U-Joint Example
Appendix 6: Standard On-Road Suspension

Appendix 7: Class-3 Lever
Appendix 8: Buzz Rover

Appendix 9: W-t Motion 3-Axis Accelerometer
Appendix 10: Data Extrapolator in MATLAB

Data Reader

Ready Certain Data Values from .txt Files

clear
clc
close all

% Call Data From Files
filename = 'Falcon_drop2.txt';
alldata = importdata(filename);
info = alldata(:,1);

ax = info.data(:,1);
ay = info.data(:,2);
az = info.data(:,3);
wx = info.data(:,4);
wy = info.data(:,5);
wz = info.data(:,6);
Angx = info.data(:,7);
Angy = info.data(:,8);
Angz = info.data(:,9);
point = length(ax);
time = point*0.001;
t = linspace(0,time,point);

% Plot Data From Files

% GeForce Plot
figure(1)
tiledlayout(3,1)
nexttile
plot(t,ax)
title('Acceleration in X')
xlabel('time (t)')
ylabel('G-Forces (g)')
nexttile
plot(t,ay)
title('Acceleration in Y')
xlabel('time (t)')
ylabel('G-Forces (g)')
nexttile
plot(t,az)
title('Acceleration in Z')
xlabel('time (t)')
ylabel('G-Forces (g)')

figure(2)
tiledlayout(3,1)
nexttile
plot(t,wx)
title('Angular Velocity in X')
xlabel('time (t)')
ylabel('Velocity (m/s^2)')
nexttile
plot(t,wy)
title('Angular Velocity in Y')
xlabel('time (t)')
ylabel('Velocity (m/s^2)')
nexttile
plot(t,wz)
title('Angular Velocity in Z')
xlabel('time (t)')
ylabel('Velocity (m/s^2)')

figure(3)
tiledlayout(3,1)
nexttile
plot(t,Angx)
title('Angle about X')
xlabel('Time (t)')
ylabel('Angle (Degrees)')
nexttile
plot(t,Angy)
title('Angle about Y')
xlabel('Time (t)')
ylabel('Angle (Degrees)')
nexttile
plot(t,Angz)
title('Angle about Z')
xlabel('Time (t)')
ylabel('Angle (Degrees)')

% Magnitude GeForce Plot
figure(4)
G_m = sqrt((ax.^2)+(ay.^2)+(az.^2));
plot(t,G_m)
title('G-Force Magnitude')
xlabel('Time (t)')
ylabel('G-Force (G)')
References
