Malibu Gone Wild: Suspended Edition, Spring 2013

Suspension System

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Abstract

In support of NC State University's EcoCAR2 team, a modified suspension system that offered a solution to the altered loading conditions caused by the addition of a 550 pound battery pack to the rear of the vehicle was designed. Static, harmonic, and transient analyses were conducted to analyze the safety and performance implications under these new loading conditions. A solution was designed which involved replacing the stock rear suspension springs with stiffer springs while simultaneously removing the rear sway bar. Testing was performed to validate component parameters. A supplemental project was also completed which consisted of performing transient finite element analysis (FEA) on a trailer hitch design.

Introduction

As part of converting the Chevrolet Malibu Eco to a PHEV powertrain, roughly 550 pounds of additional batteries were added to the rear of the car. Thus, the suspension had to be evaluated to determine if compensating modifications were required. The vehicle's suspension must adequately support and balance the vehicle while providing safe handling and steering characteristics. The installation of a towing hitch is required for competition participation, as the vehicle must be able to tow an instrumentation trailer. The height of the trailer hitch must be within a certain range to allow for proper alignment, which was accounted for during the design and analysis of the suspension system.

Design Considerations

This project consisted of two parts. The first was the modification of the suspension of the 2013 Malibu to compensate for the additional weight of the battery pack. To correct for this added weight, stiffer rear springs need to be added. However, the addition of the battery pack and the stiffening of the rear suspension springs would decrease the understeer tendencies of the vehicle. Therefore, analysis was performed to maintain the vehicle's stock understeer tendencies. NC State University's EcoCAR2 team designed a trailer hitch for use in the competition. In order to receive approval for use of the trailer hitch, transient FEA simulations needed to be run for the design.

ECOCAR 2 CONSTRAINTS:

These are summarized from the Year 2 and Non-Year Specific Rules.

- Minimize suspension modifications
- Appropriate modification evaluations
    - Ensure suspension safety for normal driving with "dynamic modeling of roll center, understeer/oversteer, critical speed, etc."
    - "[A] different trailer hitch [requires a waiver] proving the design meets Class II towing requirements."
- Respect the rules' geometry and load limits, particularly for the hitch's height:
    - "receiver and tow ball […] measures 18" (+/- 0.5") from the ground to the top of the ball."
- Pursue production-level performance:

- “Vehicle ride and handling would ideally be at production levels in regards to vehicle systems such as the steering, brakes, and suspension.”

MAE 416 COURSE CONSTRAINTS:

- $800 maximum budget
- Built in the senior design lab if possible
- Team members may only use the equipment that they were trained to use
- Complete and present by April 25, 2013

Modeling and Simulation

A static balancing analysis was conducted using the free body diagram (FBD) shown in Figure 1. This model was used to compare the CG height (z) and the pitch angle (θ) for the various configurations of the Chevy Malibu.

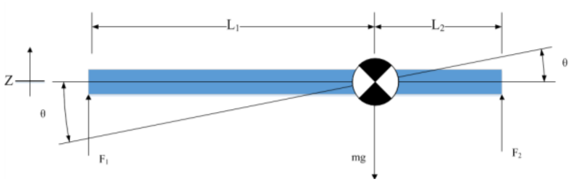

Figure 1: FBD for Static Balancing

The equilibrium equations for this model can be expressed in matrix form, as shown below.

$$\begin{bmatrix} -k_1 & k_1 L_1 \\ -k_2 & -k_2 L_2 \end{bmatrix} \begin{Bmatrix} z \\ \theta \end{Bmatrix} = \begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix}$$

The results of the static balancing analysis are shown in Table 1. This data verifies that the addition of the stiffer springs would correct any sag resulting from the addition of the batteries and ensure the clearance necessary to attach the trailer hitch to the vehicle.

Table 1: Static Equilibrium Positions

Vehicle Configuration	z (mm)	θ (deg)
Stock	589	2.06
Stock + Battery	579	1.31
Revised	600	2.17

The roll response and steering characteristics of a car can be determined from a steady state cornering analysis. The FBD used to perform the steady state cornering analysis is shown in Figure 2.

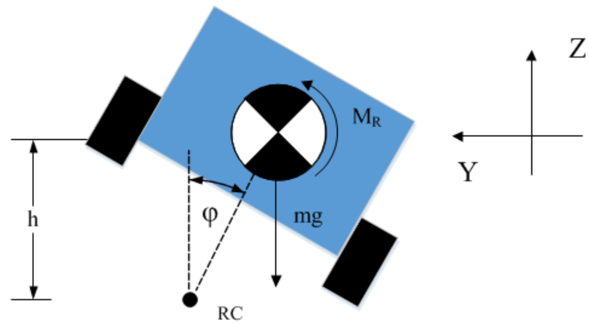

Figure 2: FBD of Roll during Cornering

The roll angle and the lateral load transfer that occurs during steady state cornering can be calculated using the equations below. Lateral load transfer is one of the primary indicators of steering performance. Vehicles with more lateral load transfer at the front tend to have understeer characteristics, while vehicles with more lateral load transfer at the rear tend to have oversteer characteristics.

$$\varphi = \frac{m\ddot{y}h}{(K_\varphi - mgh)}$$

$$\Delta F_1 = \left(\frac{m\ddot{y}h}{t_1}\right)\left(\frac{K_{\varphi 1}}{K_\varphi}\right) + m\ddot{y}\left(\frac{L_2}{L_1 + L_2}\right)\left(\frac{h_1}{t_1}\right)$$

$$\Delta F_2 = \left(\frac{m\ddot{y}h}{t_2}\right)\left(\frac{K_{\varphi 2}}{K_\varphi}\right) + m\ddot{y}\left(\frac{L_1}{L_1 + L_2}\right)\left(\frac{h_2}{t_2}\right)$$

A steady state cornering analysis was conducted to compare the roll response and steering characteristics for the various configurations of the Chevy Malibu, as shown in Figure 3.

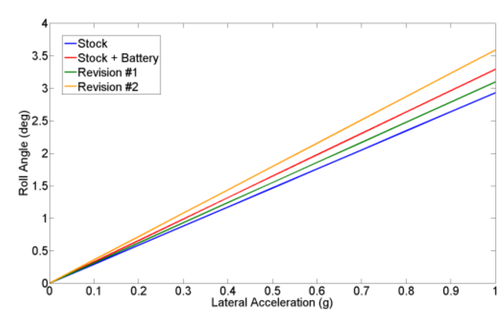

Figure 3: Roll in Steady State Cornering

The roll rates for the different configurations are shown in Table 2. Adding a battery pack increases the roll rate; increasing the rear spring stiffness (Revision #1) decreases the roll rate; additionally taking away the rear anti-roll bar (Revision #2) increased the roll rate slightly.

Table 2: Roll Rate Comparison

Vehicle Configuration	Roll Rate (deg/g)
Stock	2.93
Stock + Battery	3.29
Revision #1	3.10
Revision #2	3.59

In addition to roll rates, lateral load transfer was considered.

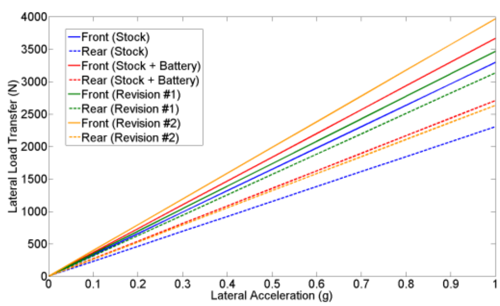

Figure 4: Lateral Load Transfer

While in its stock configuration, the Chevy Malibu exhibits strong understeer tendencies. The addition of the battery pack decreases these tendencies, and the further addition of stiffer rear suspension springs brings the vehicle dangerously close to neutral steer tendencies. However, the removal of the rear sway bar would restore strong understeer tendencies to the vehicle.

Table 3: Front/Rear Lateral Load

Vehicle Configuration	Front/Rear Lateral Load Transfer Ratio
Stock	1.43
Stock + Battery	1.35
Revision #1	1.11
Revision #2	1.51

In order to determine the harmonic response of the car, a system model with four degrees of freedom (DOF) was created, as seen in Figure 5.

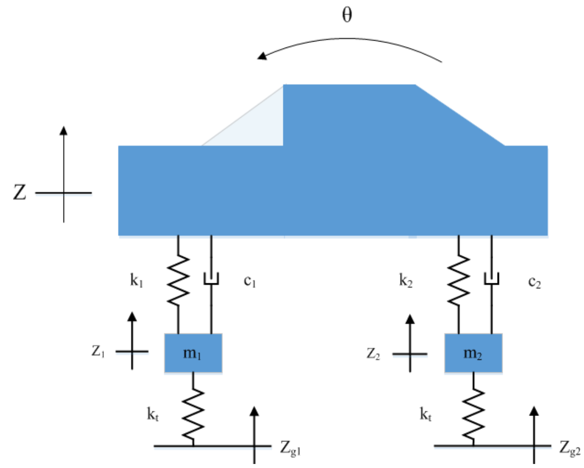

Figure 5: Model for Harmonic Analysis

The matrices that represent this system are shown below.

$$[M] = \begin{bmatrix} m & 0 & 0 & 0 \\ 0 & J_\theta & 0 & 0 \\ 0 & 0 & m_1 & 0 \\ 0 & 0 & 0 & m_2 \end{bmatrix}$$

$$[C] = \begin{bmatrix} c_1 + c_2 & c_2L_2 - c_1L_1 & -c_1 & -c_2 \\ c_2L_2 - c_1L_1 & c_1{L_1}^2 + c_2{L_2}^2 & c_1L_1 & -c_2L_2 \\ -c_1 & c_1L_1 & c_1 & 0 \\ -c_2 & -c_2L_2 & 0 & c_2 \end{bmatrix}$$

$$[K] = \begin{bmatrix} k_1 + k_2 & k_2L_2 - k_1L_1 & -k_1 & -k_2 \\ k_2L_2 - k_1L_1 & k_1{L_1}^2 + k_2{L_2}^2 & k_1L_1 & -k_2L_2 \\ -k_1 & k_1L_1 & k_1 + k_t & 0 \\ -k_2 & -k_2L_2 & 0 & k_2 + k_t \end{bmatrix}$$

The results of the harmonic analysis can be seen in Table 4. There were no significant differences between the natural frequencies of the different vehicle configurations.

Table 4: Natural Frequencies

Vehicle Configuration	ω_1 (Hz)	ω_2 (Hz)	ω_3 (Hz)	ω_4 (Hz)
Stock	1.04	1.45	7.51	8.50
Stock + Battery	1.03	1.21	7.51	8.48
Revised	1.03	1.39	7.51	9.00

The harmonic analysis vehicle model was expanded to consider the transient response of the vehicle by incorporating the longitudinal coordinate system, as shown in Figure 6.

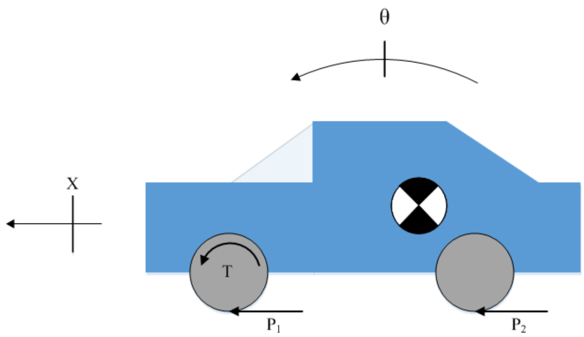

Figure 6: FBD for Transient Analysis

As can be seen from the plots, the simulated responses of the various configurations are comparable when experiencing acceleration (Figure 7), braking (Figure 8), and speed bumps (Figure 9).

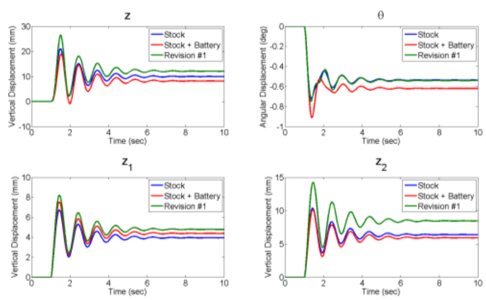

Figure 7: Acceleration Transient

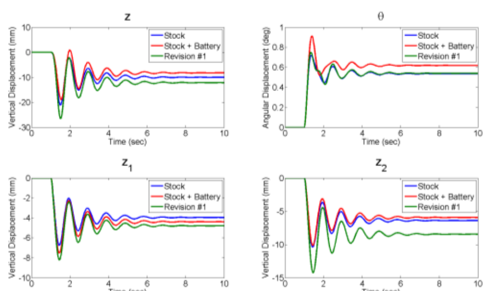

Figure 8: Braking Transient

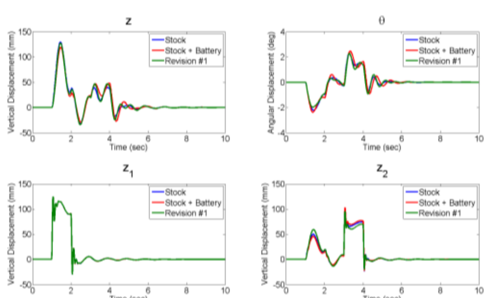

Figure 9: Speed Bump Transient

Standard suspension systems utilize helical compression springs, as shown in Figure 10.

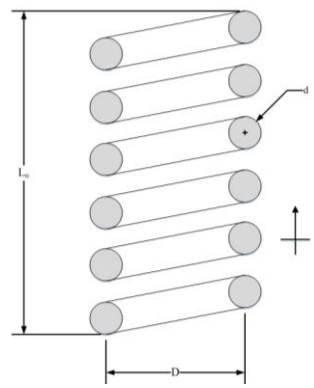

Figure 10: Helical Compression Spring

The spring stiffness and maximum shear stress experienced during loading can be calculated using the equations shown below.

$$k = \frac{d^4 G}{8D^3 N}$$

$$\tau = K_B \left(\frac{8FD}{\pi d^3} \right)$$

Many spring materials (hard-drawn or oil-tempered steel, music wire) would be inappropriate for a car suspension. Most manufacturers use either chrome-vanadium or chrome-silicon alloys; chrome-silicon was selected as it has a higher yeild strength.

The commercially availalble spring that was ultimately purchased was made of chrome-silicon alloy, and had charactersitics very close to the spring that was optimized during analysis, as shown in Table 5.

Table 5: Spring Characteristics

Specification	Bought	Target	% Diff
Free Height (mm)	248	257	3.56
Spring Rate (N/mm)	52.5	50	4.88

FEA was performed on ANSYS Workbench using a 5000 N compressive axial load, which is the upper limit of the range of forces that the spring is expected to experience during operation. The shear stress distribution is shown in Figure 11.

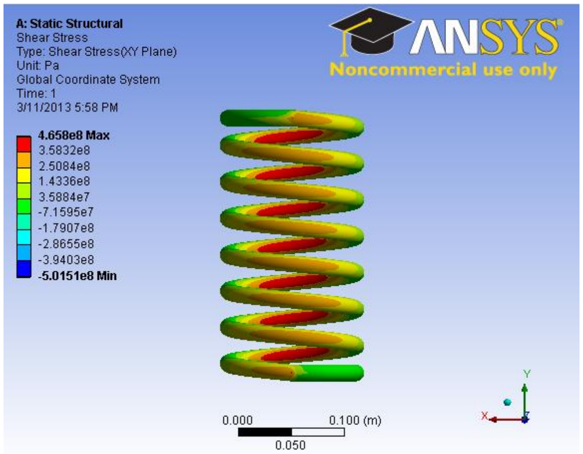

Figure 11: Shear Stress Analysis of Spring

In general, the finite element analysis results compared favorably with the theoretical results, as shown in Table 6. Acceptable safety factors were found, and the spring rate was verified.

Table 6: Theoretical vs. FEA Calculations

Parameter	Theoretical	FEA	% Diff.
τ (MPa)	456	502	9.60
n_s	1.67	1.52	9.40
δ (mm)	100	101	1.00
k (N/mm)	50	49.51	0.98

A supplemental project was also completed which consisted of performing transient finite element analysis (FEA) on a trailer hitch design. An example for one of the loading conditions is shown in Figure 12 and Figure 13.

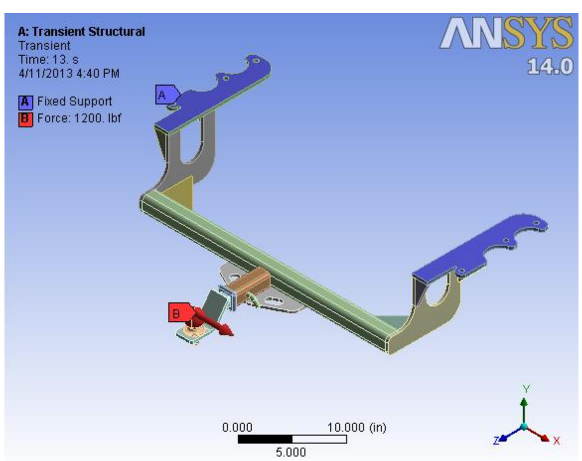

Figure 12: Boundary Conditions

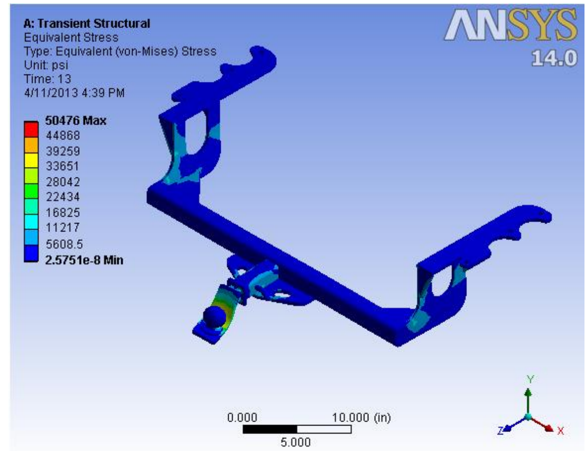

Figure 13: Stress Distribution

Testing

The springs were selected to match the installation geometry, but were tested to correctly fit in the car. In order to fit properly, end caps were designed and fabricated, as shown in Figure 14.

Figure 14: End Caps Design & Fabricated

After checking the fit, the spring rate had to be verified. Therefore, a device was constructed to uniformly apply an axial compressive load to the springs. The deflection could then be measured to calculate the spring rate.

Figure 15: Test Rig Design & Fabricated

The deflection of the spring was measured five times during loading. The repetition ensured accuracy. The standard deviation was found to be zero because the precision of the measurements was not high enough to identify different lengths.

Table 7: Summary of Experimental Data

Spring	F (lbs)	Δy (in.)	σ (in.)
1	150	0.625	0
2	150	0.500	0
3	150	0.500	0
4	150	0.500	0

From this data, the spring rates were calculated using Hooke's Law.

Table 8: Spring Rates

Spring	Desired k (lbs/in.)	Real k (lbs/in.)	% Error
1	300	240	20
2	300	300	0
3	300	300	0
4	300	300	0

As can be seen from the table, one of the first two springs had the wrong spring rate (20% Error), which is why two additional springs (#3 and #4) were purchased. Both of these new springs had the desired spring rate (300 lbs/in).

Conclusion

The goal of team Malibu Gone Wild: Suspended Edition was to design an effective yet economical suspension system that would ensure proper clearances on the Chevy Malibu while also maintain stock steering and handling characteristics. Static, harmonic, and transient analyses were performed on the vehicle. Once it was determined that a rear spring replacement (combined with removal of the rear sway bar) would restore performance, finite element analysis (FEA) verified the structural integrity for the selected chrome-silicon alloy coil springs. Transient FEA analysis was also conducted on the custom trailer hitch designed by the EcoCar2 team.

The designed suspension solution works well for both the EcoCar2 team and General Motors, thanks to the simplification of suspension components and manufacturability of the parts replaced. The springs are designed for a long service life and require no interval of maintenance, only periodic inspection for rust and damage. The omission of the rear sway bar helps to correct for variances in steering feel and ride quality, while also saving money and weight.

Acknowledgements

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EcoCAR 2 Non-Year Specific Rules

EcoCAR 2 Year 2 Event Rules

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