Challenge X: Regenerative Brake Pedal Design

ME 450 Design and Manufacturing III

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Team 23

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ABSTRACT

In order to help reduce fuel consumption and brake wear, a regenerative braking system was designed for the University of Michigan Challenge X vehicle. Our team project was to design the brake pedal assembly on the Challenge X Chevy Equinox to detect brake pedal movement to be used for regenerative braking. Different design choices were developed, and a final design was chosen with a four-bar linkage with a linear sensor to record brake pedal displacement during the dead band space. A full kinematic, electrical, and structural analysis was conducted on the pedal and linkage. For the design expo, a full-size prototype was shown with voltage output displayed.

TABLE OF CONTENTS

INTRODUCTION

Our sponsor, the University of Michigan Challenge X team, tasked us with designing a brake pedal positioning sensor which translates the brake pedal position to the ECU in order to control the regenerative braking system.

Challenge X: Crossover to Sustainable Mobility is a four-year competition where teams reengineer a Chevy Equinox to minimize energy consumption, emissions, and greenhouse gases, with the vehicle's utility and performance maintained. The University of Michigan Challenge X team is the only hydraulic hybrid team in the competition. The vehicle uses a series hydraulic hybrid power train, which uses a diesel engine to pressurize a high-pressure accumulator tank. When coupled to a low pressure tank, this drives the rear axle of the vehicle through a separate pump motor utilizing the pressure differential as its power source.

The current vehicle uses only the stock friction brake system, which consists of a user input to the brake pedal, which is amplified using the pedal and the brake booster, the high pressure fluid hydraulically powers the brake calipers to slow the wheel. The Challenge X team would like to implement a regenerative braking system this year. The new system would give several benefits for performance on our vehicle, including less fuel consumption, less emissions, and less brake wear.

The regenerative braking system would essentially reverse the direction of the fluid through the motor, putting force on the wheels in the opposite direction to slow the vehicle. This would charge the high-pressure tank, taking the strain off the engine.

The problem our ME450 team has been assigned, is designing a brake pedal assembly to collect data to be used for the regenerative brake system. The stock Equinox brake pedal has a certain measurable 'dead band' space, which is the displacement at the beginning of the user braking which does not engage the friction brakes.

Our team came up with different designs in which the 'dead band' space may be increased, and used for regenerative braking. During the 'dead band' space, we would record displacement, and send this data to the regenerative braking controller. Displacement would be measured and sent via a linear potentiometer sensor.

There are several basic requirements that our pedal design would have to follow. The physical position and movement would have to be similar if not the same as the stock brake pedal, to be ergonomically pleasing to the driver. Furthermore, our pedal design would not prohibit the use of the friction brakes, as the regenerative braking may not be enough in emergency situations. Finally, the package should be cost-effective and within the team's planned budget.

INFORMATION SEARCH

University of Michigan Challenge X Vehicle

The University of Michigan Challenge X team modified a Chevrolet Equinox using a series hydraulic hybrid power train. The necessary hydraulic parts of the hydraulic system are: The low and high pressure accumulators, hoses and fittings, valves, engine pump, rear drive motor, batteries, the engine, and other mechanical parts needed for traction and some non-hydraulic components. A bent-axis, variable displacement pump/motor will be used for the engine pump; the same for the rear drive motor. The displacements of the motor/pump will be actuated hydraulically and controlled by a solenoid. The pump/motor will have zero displacement when the axis angle is zero degrees, from there as the angle increases the displacement will as well. The rear drive motor is a 55 cc/rev motor, and the engine pump is also 55 cc/rev.

The two accumulators are made of a carbon/e-glass fiber composite and have a 15 gallon capacity. The low pressure accumulator will have a maximum pressure of 200 psi, while the high pressure accumulator will have a maximum pressure of 5,000 psi. Energy is stored in the accumulators by using oil to compress a nitrogen bladder. For safety there is also a relief and check valve. The purpose of the check valve is to ensure that the flow is in the correct direction when necessary. The relief valve will ensure that the pressure in the accumulator does not exceed 5,000 psi.

The engine used in the Equinox is a GM 1.9 liter diesel engine. The engine is intercooled and turbocharged, and utilizes common direct rail injection. There is an oil conditioning system which is necessary to cool and filter the oil. To clean the oil an inline filter was used and a radiator was used to cool the oil. There is another relief valve in line with the filter. The hydraulic fluid used in the system is synthetic automatic transmission fluid.

Challenge X requires that the SUV contain friction brakes as well as the regenerative braking system. The SUV must have a production braking system or a replacement braking system which is equally or more effective, and the braking system must also comply with FMVSS 135. The braking systems must use a single pedal and act on the wheels directly. Fully functional ABS is required on the SUV in order to compete in any of the Challenge X dynamic events

Stock Vehicle Braking System

The Challenge X Chevy Equinox has four-wheel disc brakes, which come stock on the vehicle. These consist of a caliper, which sits surrounding the disc rotors that rotate at wheel speed. The calipers squeeze the discs when the brake is applied, and uses friction to supply a braking force. These disc brakes reduce stopping distance and are more efficient at high temperatures compared to other systems. The Equinox also comes with four-channel Antilock Brake System, which control the braking pressure to maximize brake force on slippery surfaces.

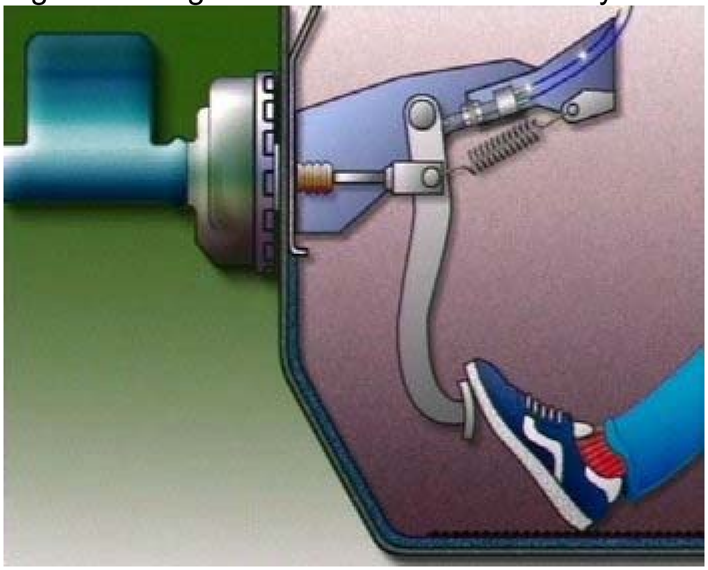
Stock Vehicle Brake Pedal

The stock Chevy Equinox has a brake pedal assembly that focuses on a rotating lever to apply a braking force, as described with the US Patent on brake pedal systems:

> *A brake pedal system includes a brake pedal having a flexible arm with a first distal end adapted to be mounted to the structure of a vehicle and a second distal end having a foot pad. At least one sensor is mounted to the brake pedal and is adapted to sense the amount of deflection of the brake pedal and send a corresponding signal. A stop is adapted to be mounted within the vehicle at a distance from the brake pedal such that the brake pedal will contact the stop after flexing a pre-determined amount. (United States Patent 6571661)*

This brake lever gives a mechanical advantage, which increases the user's force input to the brake fluid. The brake fluid uses hydraulic force multiplication to increase the braking force further to apply at the wheels. Friction on the disc brakes slows the tire, and friction between the tire and road decelerates the vehicle.

Figure 1. Diagram of Stock Brake Pedal System



http://www.howstuffinmycarworks.com/How_stuff_works_brakes.html

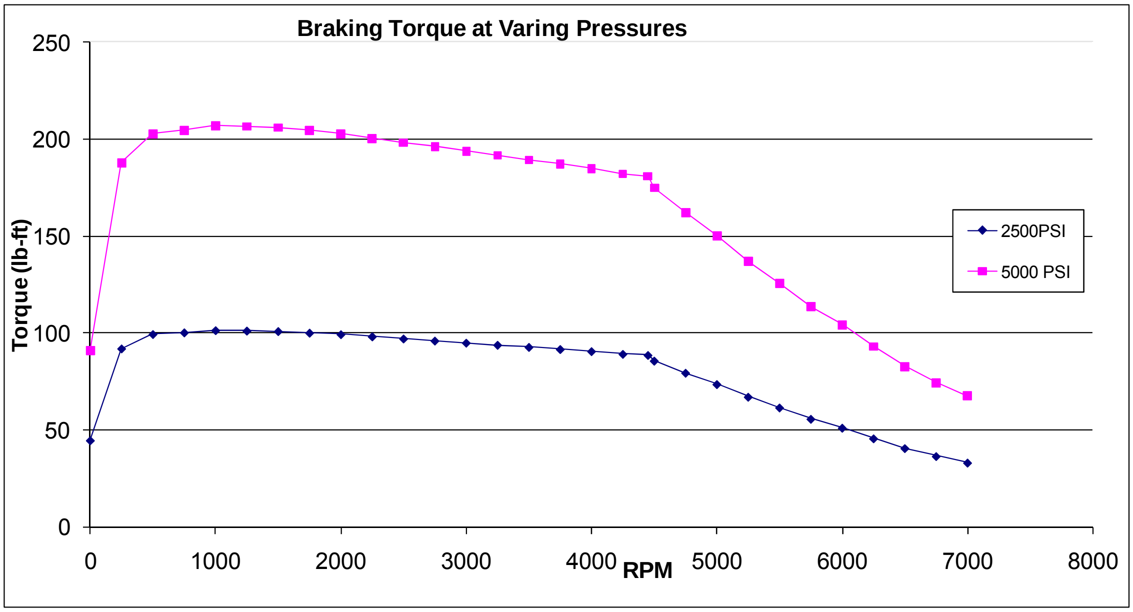
Regenerative Braking and Hydraulic Hybrids

The most essential purpose of modern hydraulic hybrids is to add a regenerative braking system to a standard spark ignition engine car. This is accomplished in the same way that the Challenge X Team's car is designed, only its emphasis is on braking and storing that energy for use in accelerating. These cars are not driven through the hydraulic system by itself. In both types of cars, this braking is accomplished by allowing the energy released from stopping the cars motion to run the hydraulic pump essentially in reverse, storing pressure into the high pressure accumulator, which is then released to aid in accelerating the vehicle. The Challenge X car is powered entirely by the hydraulic system, so the regenerative braking reduces the strain on the diesel engine to pressurize the high pressure accumulator. The result is generally up to a 35% increase in gas mileage. (GreenCarCongress.com)

Further advantages of a regenerative braking system also include reducing emissions and brake wear. The accumulators used to store pressure in the hydraulic fluid endure less wear than standard friction brakes, estimated to last the lifetime of the vehicle. Additionally, regenerative brakes have an estimated 31% increase in electric generation efficiency in vehicles that store the regenerative energy as electrical energy. (Permo-Drive.com)

The Michigan Challenge X car regenerative system operates by reversing the direction of flow through the pump/motor that would ordinarily draw pressure from the high end accumulator to the low pressure reservoir to move forward. This means it is now driving the hydraulic fluid in the opposite direction, or trying to move the car in reverse. Thus, instead of using friction to stop, it simply forces the back wheels to move in the direction opposite it is currently moving. The stock friction brakes will also engage as normal after the dead band space of the brake pedal has been exhausted to allow for a complete stop. The system is estimated to give (at full pump displacement) of roughly 200 ft*lbs of braking torque, as shown in Figure 2. This deadpan space is the length of brake pedal depression before the friction brakes are engaged. This motion (on both stock brakes and the regenerative system) is measured by rotational sensors that relay this information through voltage to the ECU.

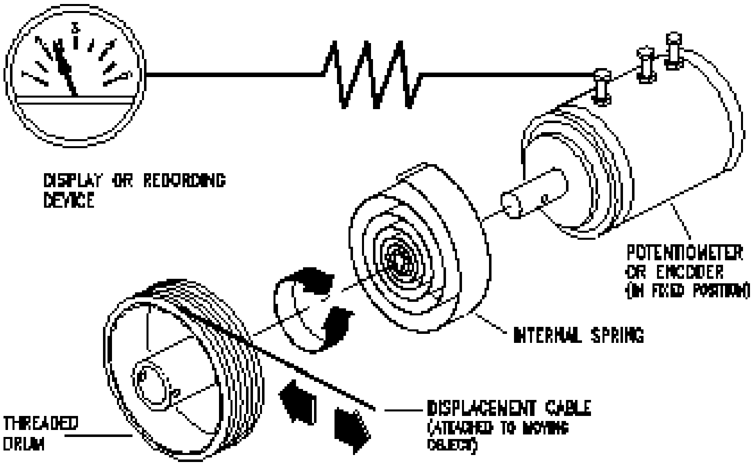
Figure 2. Braking torque changes depending on accumulator pressure



Sensor

Position Transducers take an input as a mechanical movement, and creates an electrical signal as an output. The different types of movement which can be recorded are position, rate of movement, and direction. The transducer is made up of a cable wrapped around a threaded drum which is directly attached to a sensor. To use the transducer it is attached in a fixed place and the cable is attached to the moving object which movements need to be measured. The axes for the cable and the moving object need to be aligned with each other. As the object begins its motion the cable will extract and retract to monitor the objects motion. There is a spring attached to the drum which keeps tension on the cable at all times. As the drum rotates the sensor will rotate and create the electrical signal output. A few of the types of position transducers are: linear, angular, and rotary. Figure 3 illustrates the components and purposes of the angular sensor.

Figure 3. Schematic of Angular Position Tranducer Similar to One Used in Our Design



http://www.spaceagecontrol.com

Benchmarks

Despite being a relatively new technology, there are plenty of current regenerative braking systems out on the roads. These vehicles, however, don't all employ the same system. Two examples of specifically hydraulically powered braking systems include the Hydraulic Launch Assist (HLA) on the Ford F-350 and the Permo-Drive Regenerative Drive System (RDS). The trouble with benchmarking these assemblies lies in the differences in engineering scope between their use and our intended project. It is easy to find information on how the hydraulic systems work and their effect on the car's mileage and brake wear, however without actually obtaining one of them to test their brake pedals against our design specifications, there is not much to compare. This result is what prompted us to benchmark our design in the QFD against just against the stock system, since we are trying to preserve that specific feel to the consumer.

Both systems operate very similarly to the Challenge X vehicle, with the exception that they are parallel hydraulic hybrids and not series. This means that their drivetrains are not directly powered by the hydraulics, but merely assisted by them. The result is nearly the same, however a series hybrid is a more radical conversion of the car (requiring a completely replaced drivetrain) and does not exist currently on any commercial vehicle, unlike parallel hybrids that are already implemented.

Although test data for the Challenge X car does not exist yet (since it hasn't been fully implemented to be tested), we can look at the statistics and results of these benchmark vehicles. In general, hydraulic hybrids with regenerative braking systems see around a 25-35% improvement in fuel efficiency and emissions reduction. The HLA also sees around 50% reduction in friction brake wear, and can accelerate the car from a dead stop to 25-30 mph without using the combustion engine. (GreenCarCongress.com) The RDS claims 15-35% superior energy storage over electric hybrids, as well as being about half the weight of an electric hybrid system. (Permo-Drive.com) Though this information is not entirely relevant to our project, it provides us with a benchmark for performance that we can test once the regenerative brake system is finally implemented.

CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

By beginning with our problem statement, “To create a foot pedal breaking system which would activate a regenerative braking system in Challenge X’s Chevy Equinox”, we were able to develop a list of customer requirements for our brake pedal system. The brake pedal is to “feel” like a stock braking system in every aspect from a rested pedal position to full brake application. We translated the resting pedal position into two engineering specifications: pedal resting height (mm) and pedal resting angle (deg). These specifications allow us to measure the resting feel of the brake pedal, ensuring customer comfort. To quantify the braking experience we set goals of required pedal force (N) throughout the braking application process. Next we created pedal travel (deg) and pedal surface area (mm^2) specifications to avoid creating a high pressure area on your foot. The final specification we created to measure the braking experience was the pedal force derivative curve’s. By reviewing the curves we can set targets to ensure that the braking force has a continuous smooth feel similar to that of a stock braking system.

Other customer specifications included low prototype and production cost. Since production cost is directly related to mass we set our engineering specification for pedal assembly mass (kg). The customer also requested that the brake pedal assembly is durable. Since durability is not a measurable we concluded that we would measure the yield force of the pedal (or at least predict what it theoretically should be) using beam bending equations. The customer repeatedly mentioned that the pedal design must meet all federal regulations as well as Challenge X regulations. This request in itself was a measurable, so we used it as our engineering specification. The final customer request was to consider manufacturability and driver ergonomics. Our team felt that these were already accounted for in other specifications so we omitted any new measurables.

Table 1 shows the engineering specifications for our pedal design, taken from the customer requirements after discussing with the Challenge X team.

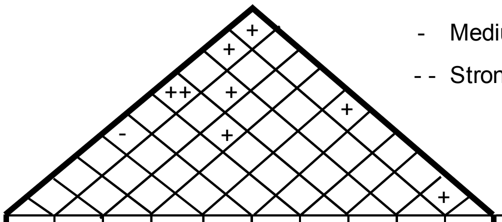
Table 1. Engineering Specifications for Pedal Assembly

Specification	Measurement Unit	Target Value	Importance Rating
Required Pedal Force (-)	N	< 500	1
Pedal Height (+/-)	mm	102	3
Pedal Resting Angle (+/-)	degrees	60	9
Pedal Surface Area (+/-)	mm^2	5847	7
Pedal Travel (+/-)	degrees	30	6
Pedal Assembly Mass (-)	kg	6	10
Pedal Force Derivative Curve (-)	#	Stock	8
Sensor Output Voltage (+/-)	V	5	4
Pedal Yield Force (+)	N	1500	5
Fails to Meet Regulations (-)	Y/N	Y	2

Figure 4. QFD Diagram for Pedal Design.

Relationships

++ Strong Positive
+ Medium Positive
- Medium Negative
- - Strong Negative



Benchmarks

(+) => more is better
(-) => less is better

	Weight*	Required Pedal Force (+/-)	Pedal Height (+/-)	Pedal Resting Angle (+/-)	Pedal Surface Area (+/-)	Pedal Travel (+/-)	Pedal Assembly Mass (-)	Pedal Force Derivative Curve (-)	Sensor Output Voltage (+/-)	Pedal Yield Force (+)	Fails to Meet Regulations (-)		Stock Equinox Pedal (-)		
Pedal position similar to stock vehicle.	4		9	3	3						1		5		
Brake application similar to stock vehicle.	4	9	3	3	3	9		9			1		5		
System is durable.	7	3						1		9			4		
System sensors integration.	8	3	3			3			9		1		4		
System meets all regulations.	9	3									9		5		
Low prototype cost.	3				1		1		1				5		
Low production cost.	2				1		3		1				5		
Driver Ergonomics	5	1	3	3	3	3							4		
Manufacturability	4						1			3			4		
Measurement Unit		N	mm	Deg	mm^2	Deg	Kg	#	V	N	Y/N				
Target Value		500	102	60	5847	30	6	Stock	5	1000	Y				
Importance Rating		**1**	**3**	**9**	**7**	**6**	**10**	**8**	**4**	**5**	**2**				
Total		113	87	39	44	75	13	43	77	75	97				
Normalized		0.17	0.13	0.06	0.07	0.11	0.02	0.06	0.12	0.11	0.15				

Key:
9 => Strong Relationship
3 => Medium Relationship
1 => Small Relationship
(blank) => Not Related

***Weights are figured on a scale of 1 to 10**
(ten being most important)

CONCEPT GENERATION

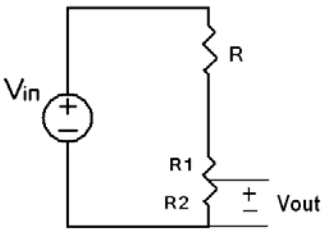
In the concept generation phase we first created a FAST diagram to help develop the basic functions and secondary functions that the final design should exhibit. By creating a list of all functions of our system then separating them by basic/secondary status showed us where to focus our thinking. The primary function of the sensor is to relay brake pedal position to the ECU to activate the regenerative braking system. This is the primary function of our design because nearly all other functions or actions of our system are used to aid in completing the basic function. The secondary functions include maintaining comfort, assuring dependability and the convenience of regenerative braking. We were able to identify basic vs. subsidiary functions by looking at their lineage on the FAST diagram (where a basic function could break into more functions, and a secondary function deals more with characteristics), and also judging if they were autonomous or simply existed to aid some other function.

Once the function list was generated using the Fast diagram we began sketching concepts. The concepts were created by reviewing the primary and secondary goals and placing sensors in locations that allowed us to satisfy these goals. The resulting concepts were broken down into three categories based on the type of sensor used. The first group relied on angular sensors while the second group implemented rotational sensors. The third group was composed of concepts that used linear sensors used to measure linear displacement of a point on the brake pedal linkage.

Angular Sensor

The most logical choice to measure the displacement of a brake pedal that rotates around a pivot point would be an angular sensor. This reasoning led us to place an angular sensor at the pivot point of the brake pedal linkage. The angular sensor concept allowed the output voltage to have a linear relationship with the pedal displacement:

Figure 5: Potentiometer



$$Rp = R_1 + R_2$$

$$Vout = Vin * \frac{R_2}{R+Rp}$$

$$R_2 = Rp * (1 - \frac{\varnothing}{\varnothing max})$$

$$Vout = Vin * \frac{\varnothing max * Rp - \varnothing * Rp}{\varnothing max * (R+Rp)}$$

Rotational Sensor

Our next concept implemented a rotational sensor in place of the angular sensor which also measured the angular displacement of the brake pedal linkage. The concept utilized a linear sensor and a wheel mounted to the pivot point. The wheel was attached to a wire which was attached to a linear sensor. The sensor measured the displacement of a point on the outer radius of the wheel.

$$S_{Displacment} = R_{Wheel} * \emptyset$$

Linear Sensor

Our final group of concepts all utilized a linear sensor that measured the linear displacement of a single point on the brake pedal linkage. This measures the displacement of a point near the center of the brake pedal linkage in respect to a plate located on the firewall. The formula for the output voltage is no longer linear and must be modeled using computer software such as ADAMS or SIMULINK.

Figure 6. FAST Diagram

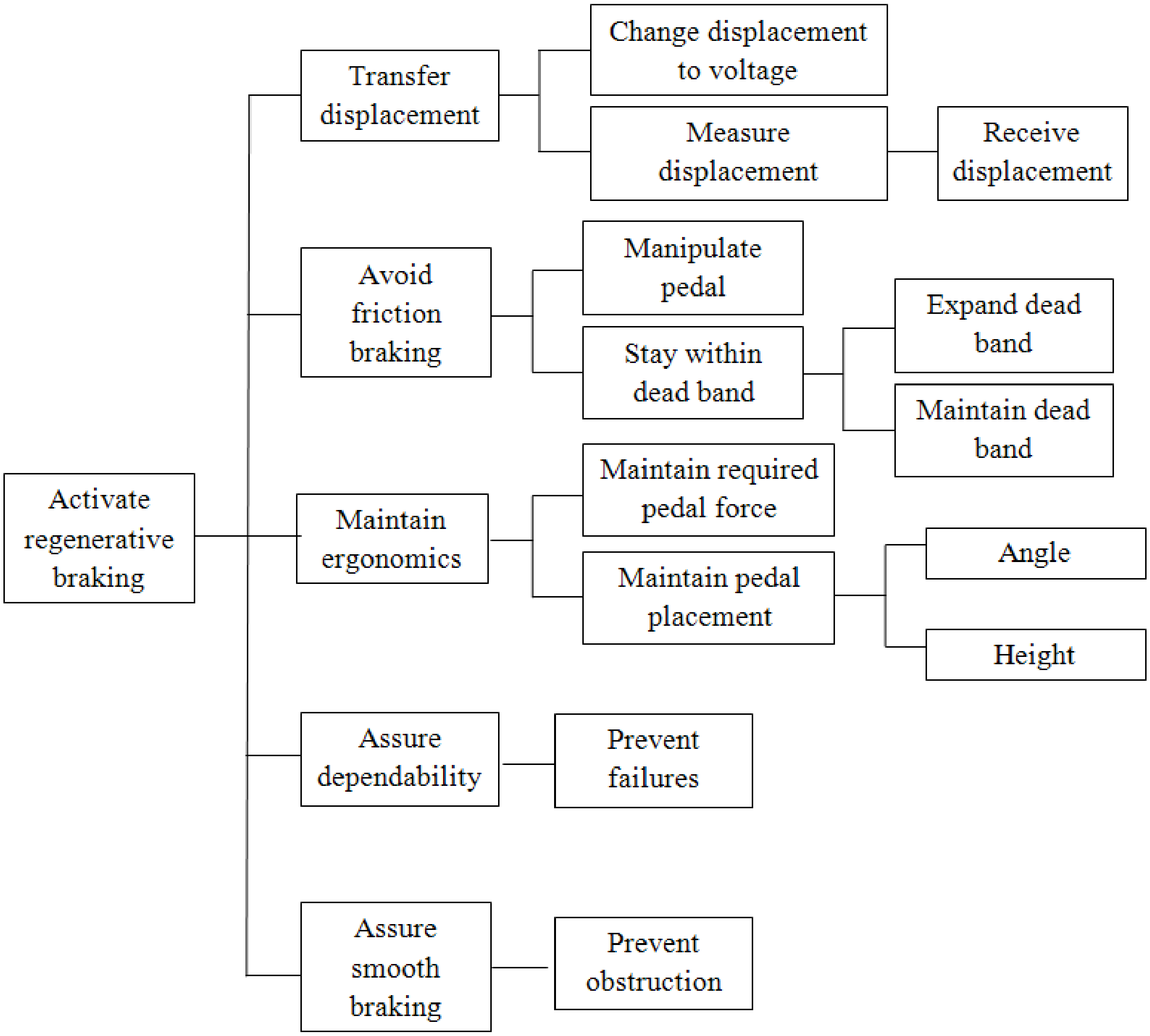
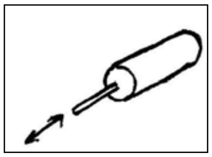
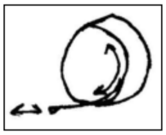
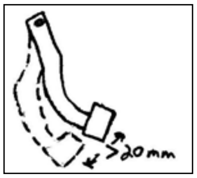
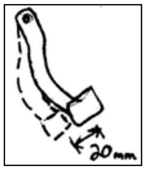
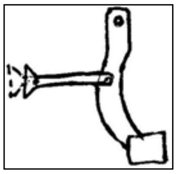
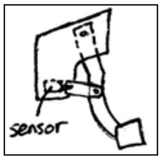
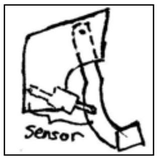
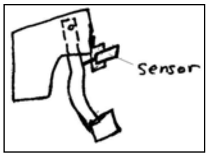
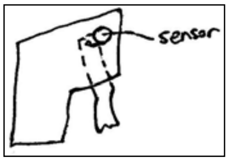
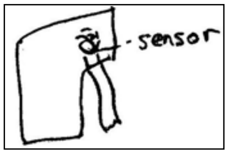


Figure 7. Morphological Chart

Function	Concept 1	Concept 2	Concept 3
Displacement Measurement	Angular Sensor 	Linear Sensor 	Rotational Sensor 
Reduce Friction Brake Wear	Increase Pedal Dead Band Space  	Use Stock Dead Band Space  	
Dead Band Space Modification	Shortening Master Cylinder Link 		
Attach Linear Sensor	Mount to Pedal and Back Bracket Four-Bar Linkage  	Mount to Pedal and Back Bracket Directly  	Mount to Pedal and Additional Top Plate 
Attach Angular/Rotational Sensor	Mount to Bracket  	Mount to Rotating Pedal  	

CONCEPT EVALUATION AND SELECTION

Five feasible brake pedal concepts were generated using a Morphological chart. From these five concepts, some were too expensive to produce and others would not be durable enough to withstand the force on the brake pedal. One of the concepts, which included increasing the dead band space, was not necessary. The amount of dead band space was measured in the Equinox and it was discovered that the stock dead band space is sufficient enough to perform regenerative braking. The concept of maintaining the stock dead band was incorporated into all of the other concepts.

Another main concept principle was which type of sensor to choose. The options for types of sensors were: linear, angular, or rotational. The angular and rotational sensors can be mounted to the bracket or rotating pedal without involving much work. These sensors will cost a great deal more than the linear sensor, which ruled them out as viable options for the brake pedal design. The last main decision, which needed to be made, was how to attach the sensor to the pedal. Our final concepts were put into a Pugh chart to weigh how the customer needs would be fulfilled by each of the concepts. Through the Pugh chart we could rate the concepts and decide which one would be the best to produce.

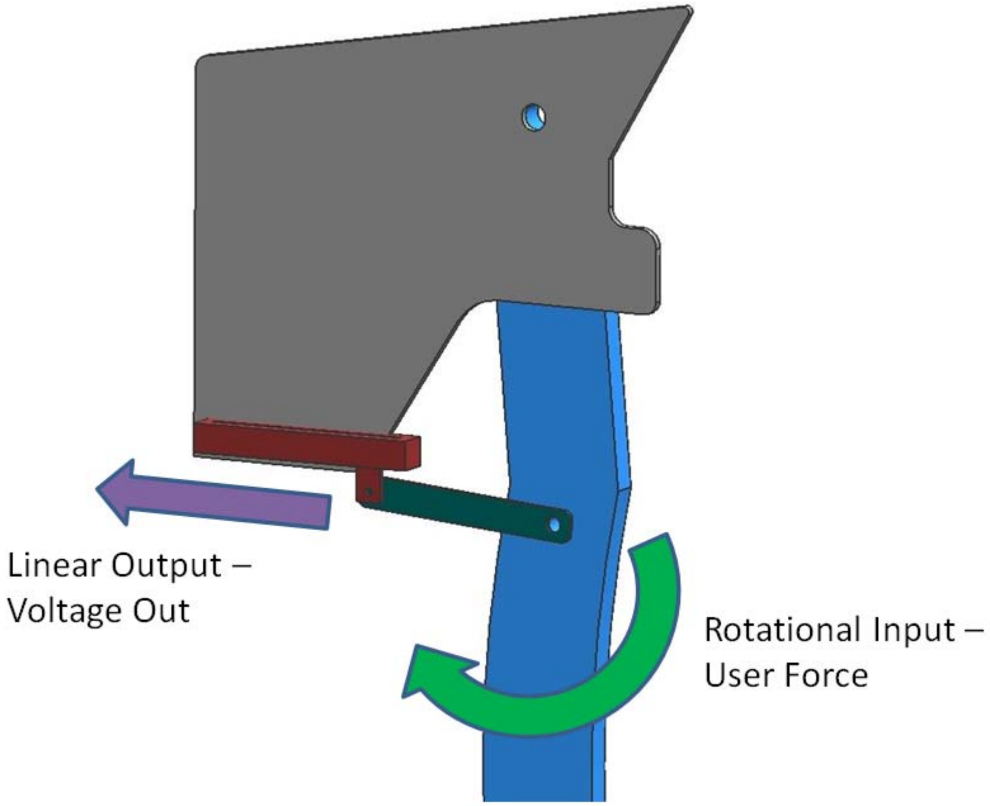
Figure 8. Pugh Chart

		Concepts									
		Mount sensor to pedal and back bracket with a four-bar linkage		Mount sensor to pedal and back bracket directly		Mount sensor to pedal and additional top plate		Mount angular sensor to pedal and back bracket directly		Mount rotaional sensor to pedal and back bracket directly	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Pedal position similar to stock vehicle	0.08696	5	0.4347826	5	0.4347826	5	0.4347826	5	0.4347826	5	0.4347826
Brake application similar to stock vehicle	0.08696	5	0.4347826	5	0.4347826	5	0.4347826	5	0.4347826	5	0.4347826
System is durable	0.15217	4	0.6086957	3	0.4565217	4	0.6086957	4	0.6086957	4	0.6086957
System sensors integration	0.17391	5	0.8695652	5	0.8695652	5	0.8695652	5	0.8695652	5	0.8695652
System meets all regulations	0.19565	5	0.9782609	5	0.9782609	5	0.9782609	5	0.9782609	5	0.9782609
Low prototype cost	0.06522	4	0.2608696	4	0.2608696	4	0.2608696	2	0.1304348	2	0.1304348
Low production cost	0.04348	3	0.1304348	4	0.173913	3	0.1304348	2	0.0869565	2	0.0869565
Driver ergonomics	0.1087	4	0.4347826	4	0.4347826	4	0.4347826	4	0.4347826	4	0.4347826
Manufacturability	0.08696	4	0.3478261	4	0.3478261	3	0.2608696	4	0.3478261	4	0.3478261
Total Score		4.5		4.391304348		4.413043478		4.326086957		4.326086957	
Rank		1		3		2		4		4	

SELECTED CONCEPT

Our concept utilizes a linear potentiometer, which will record the displacement of the pedal as a voltage. As the pedal is displaced, the resistance of the potentiometer decreases, allowing for more voltage to be outputted to the Engine Control Unit (ECU). This is set up using a four bar linkage with the pedal, a connecting linkage, the sensor, and the pedal support bracket. The power source is 12 V coming from the automotive battery, and the output will be zero to five volts to the ECU. Figure 8 shows our selected concept, modeled using CAD.

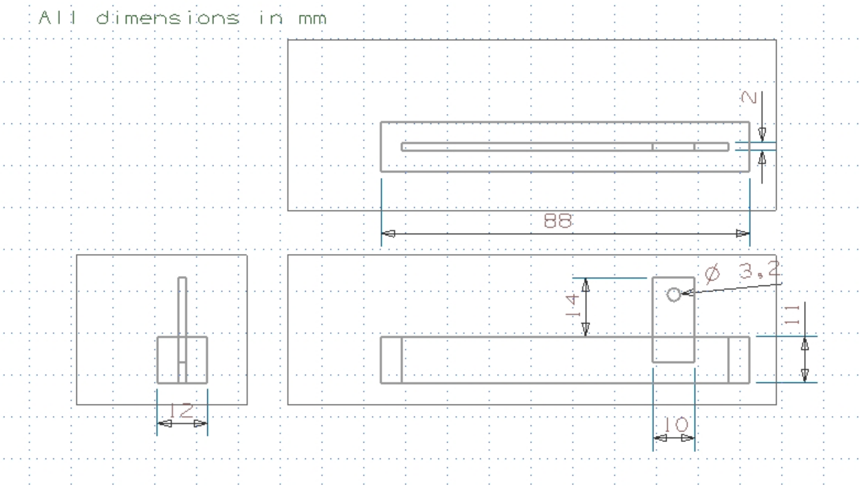
Figure 9. CAD Drawing of Pedal Assembly



Sensor

We selected a linear potentiometer to determine the displacement of the pedal. It has a maximum resistance of ten kilo-ohms. Figure 9 shows a detailed dimensioned drawing of the potentiometer chosen.

Figure 10. Sensor Dimensioned Drawing



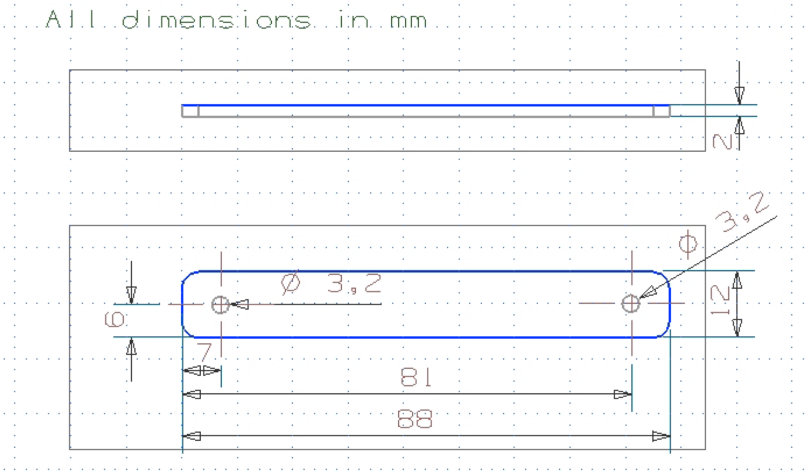
Pedal Assembly

The pedal assembly is a stock brake pedal for the Chevy Equinox, attached along with an accelerator pedal to the pedal support bracket. The pedal is 31.2 cm long, with the pin for the linkage is located 14.3 cm from the pedal pivot.

Linkage

In order to connect the pedal to the sensor, we chose to use an aluminum linkage bar, attached by pins on the sensor and pedal to allow for rotation. Figure 10 shows the dimensions of our design for the linkage bar.

Figure 11. Linkage Dimensioned Drawing



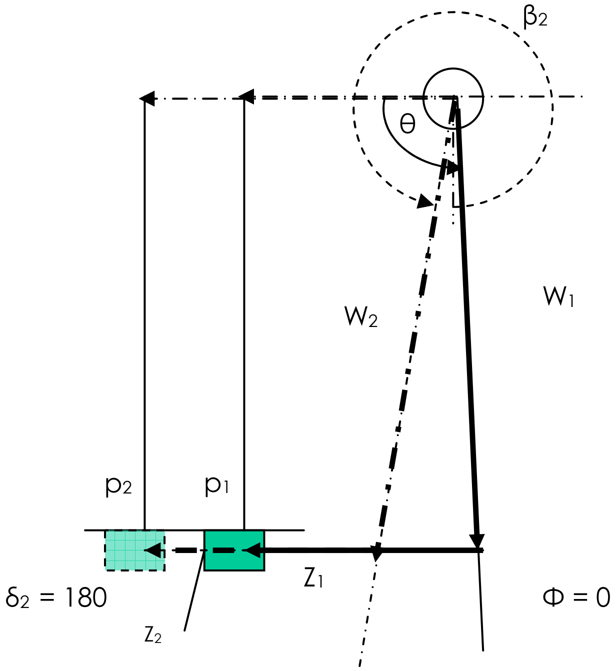
ENGINEERING ANALYSIS

To proceed with our chosen design, a full kinematical, structural, and electrical analysis had to be completed.

Kinematical Analysis

Our pedal design incorporates a four bar linkage to create a crank-slider mechanism. The setup transfers a rotational input by a user into a linear translational output of our sensor. For our application, we know the brake pedal starting and ending position, thus the angular displacement. Also known is the designed link length. For our analysis, we determine the linear displacement of the sensor output, in order to properly set up our electrical circuit.

Figure 12. Crank-slider four bar diagram with variables shown.



We first start with the vector loop equation:

$$W_2 + Z_2 - P_{21} - Z_1 - W_1 = 0$$

Substituting the complex number equivalents for the position vectors leads us to:

$$we^{j\theta}(e^{j\beta 2} - 1) + ze^{j\varphi}(e^{j\alpha 2} - 1) = p_{21}e^{j\delta 2}$$

The Euler equivalents are substituted:

$$w(\cos\theta + j\sin\theta)((\cos\beta_2 + j\sin\beta_2) - 1) + z(\cos\varphi + j\sin\varphi)((\cos\alpha_2 + j\sin\alpha_2) - 1) = p_{21}(\cos\delta_2 + j\sin\delta_2)$$

Separating into the real component:

$$w\cos\theta(\cos\beta_2-1) - w \sin\theta \sin\beta_2 + z\cos\varphi (\cos\alpha_2-1) - z\sin\varphi \sin\alpha_2 = p_{21}\sin\delta_2$$

We can then solve for p_{21}, so we can know the total displacement our linear sensor will encounter, using the following given values from our design:

$W_1 = W_2 = 14.3$ cm

$Z_1 = Z_2 = 7.0$ cm

$\theta = 95$ degrees

$\beta_2 = 348$ degrees

$\varphi = 0$ degrees

$\alpha_2 = 4$ degrees

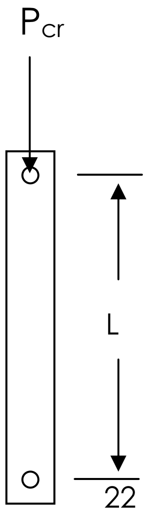
These parameters give a value of $p_{21} = 3.00$ cm. Therefore, we can expect to see a linear travel of 3 cm of the linear sensor.

Structural Analysis

We can determine the maximum force applied longitudinally to our link before buckling occurs, to ensure it will not fail under the applied load.

The equation and diagram for the critical force to cause buckling on a member is given by:

P_{cr} = ((pi^2)*E*I) / (L^2)

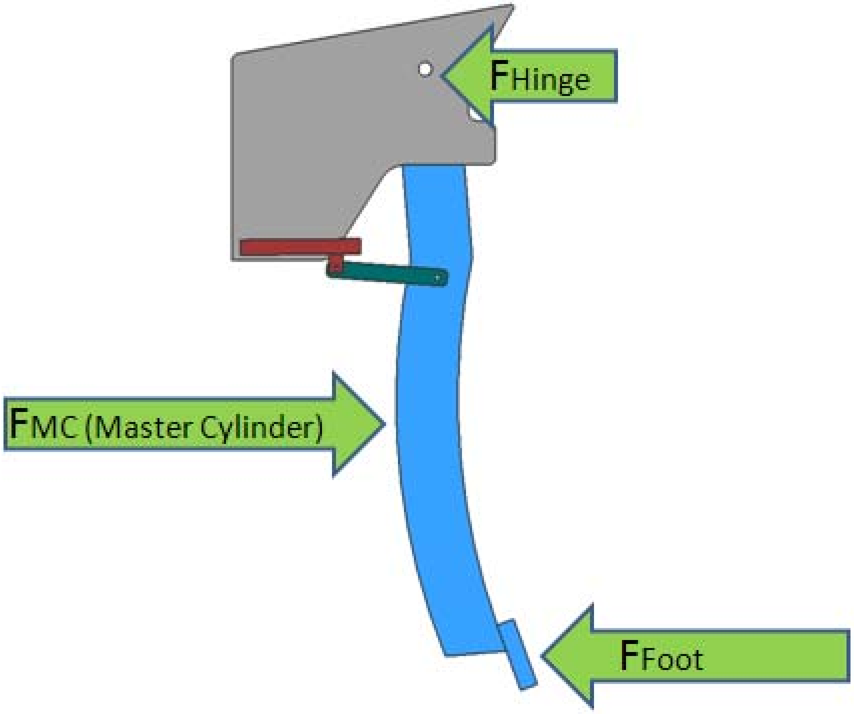


Where *E* is the elastic modulus, *I* is the moment of inertia, and *L* is the length.

We used Aluminum 6111, which has a elastic modulus of 72*10^9 Pa, and a length of .07 meters. The moment of inertia is b*h*L^2, in our case equaling to 8.82*10^-8 m^4. This gives us a critical force for bucking of 145.02 N.

Brake Pedal Bending Moment Analysis

Figure 13. Pedal Bending Moment Analysis



Static Analysis:

∑ Hinge Moments

$$-F_{Foot} * D_{Foot} + F_{MC} * D_{MC} = 0 \qquad F_{MC} = \frac{F_{Foot} * D_{Foot}}{D_{MC}}$$

∑ Forces in X

$$-F_{Foot} + F_{MC} - F_{Hinge} = 0 \qquad F_{Hinge} = F_{Foot} - F_{MC}$$

Figure 14. Brake Pedal Moment at Max Input Force

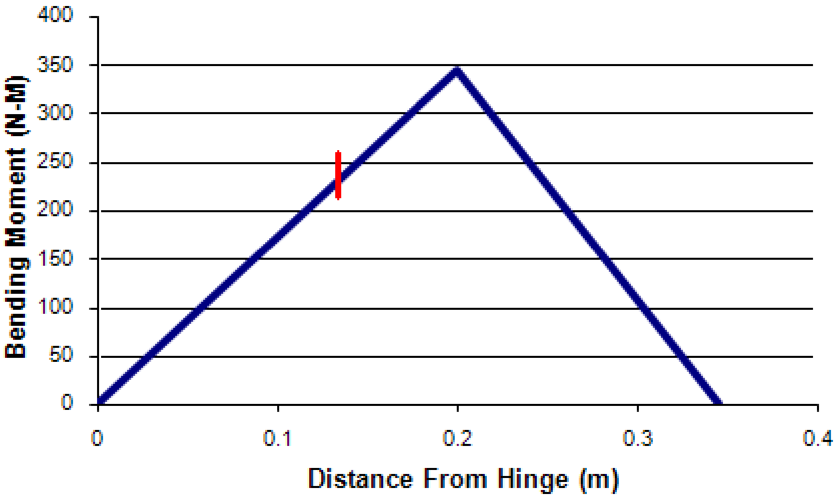
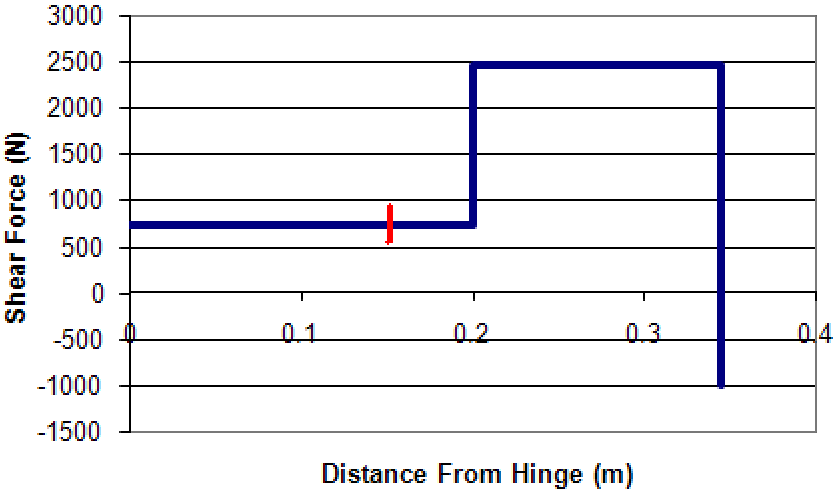


Figure 15. Brake Pedal Linkage Shear Force at Max Input Force



Inertia Moment Analysis

$Ix = \int_A x^2 dA$ (pg 289)

For a Beam: $Ix = \frac{1}{12} bh^3$

For a Beam with a hole at the center: $Ix = \frac{1}{12} bh^3 - \frac{1}{64} \pi * d^4$

Our Bending Inertia Before and After

$$I_{Intial} = \frac{1}{12}(.007m)x(.0375m)^\wedge 3 = 3.0762x10^\wedge{-8}m^4$$

$$I_{Final} = \frac{1}{12}(.007m)x(.0375m)^\wedge 3 - \pi\frac{(.003175m)^\wedge 4}{64} = 3.0757x10^\wedge{-8}m^4$$

After carefully reviewing our brake pedal linkage inertia analysis we concluded that our hole would have nearly no effect on the strength of our linkage. The first reason is that the pin hole location was chosen at a position where the bending moment and thus shear stress was relatively low (Figure 14 and Figure 15). The second and more important reason is that our second moment of inertia was reduced by less than 1/60th of 1 percent (00.0162%). This remarkably small reduction in inertia was achieved by choosing a small pin diameter and placing it at the center of the pedal linkage to eliminate inertia loss due to the parallel axis theorem.

In the brake pedal setup nearly all of the force being pressed down on the pedal will be absorbed by the plunger to the cylinder. There will be a small force on the connecting pins from the friction force of the potentiometer. Using a force meter to pull on the flange of the potentiometer this friction force was found to be 3.34N. Based on a few trials this was the greatest force required.

The force on the bolt, which is attached to the potentiometer, can be simplified to a single force from the friction of the potentiometer flange sliding. To find out if the chosen size and material bolts will be sufficient a cantilever beam equation was used. One side of the bolt is attached and then the force is acting one millimeter from the part which is attached. From this setup the maximum bending moment needs to be calculated. First the mass of the bolt was calculated to be 0.0019 kg using the density of the material and the dimensions of the bolt (Equation 1). Then the moment of inertia is calculated, based on the dimensions of the bolt and treating it as a simple cylinder (Equation 2). The bending moment is calculated from the force of the potentiometer multiplied by the distance between the link and flange, which 3.34 E 10^{-3} N-m. The final step in calculating the bending stress is plugging all of the previously found values into the equation for bending stress (Equation 3). The maximum bending stress is 2 kPa which is much less than the tensile strength for A307 steel (bolt steel), 413.7 MPa, therefore this is an acceptable selection for size and material of the bolt. This stress would be the same for both bolts on both pin joints.

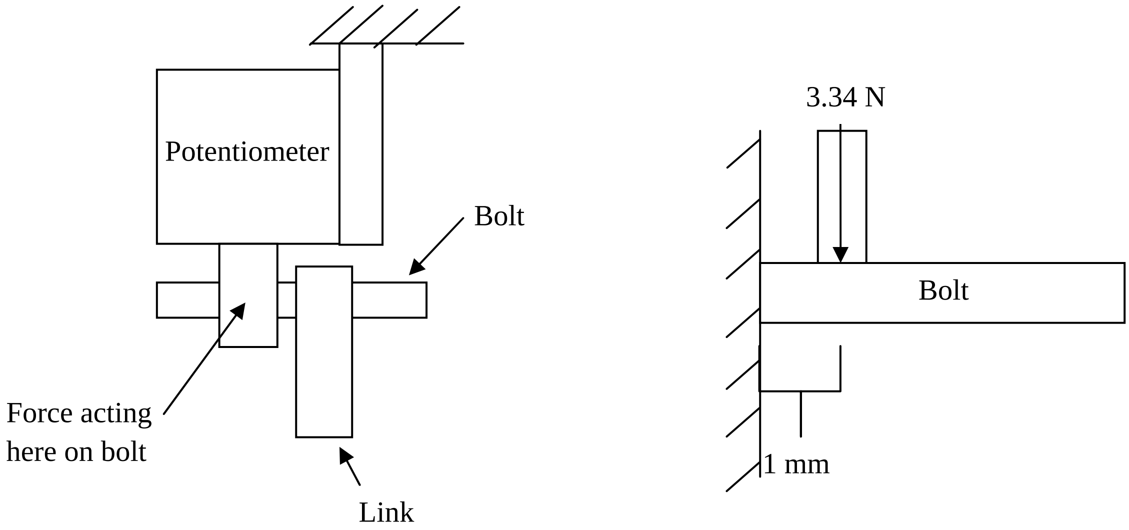
$\rho = m/V$ *(Eq. 1)*

$I = 1/2mr^2$ *(Eq. 2)*

$\sigma = My/I$ *(Eq. 3)*

ρ is the density, m is the mass, V is the volume, I is the moment of inertia, σ is the bending stress, M is the bending moment of the cylinder, and y is the distance from the force to the center of the cylinder.

Figure 16. Diagram of pin (bolt) forces

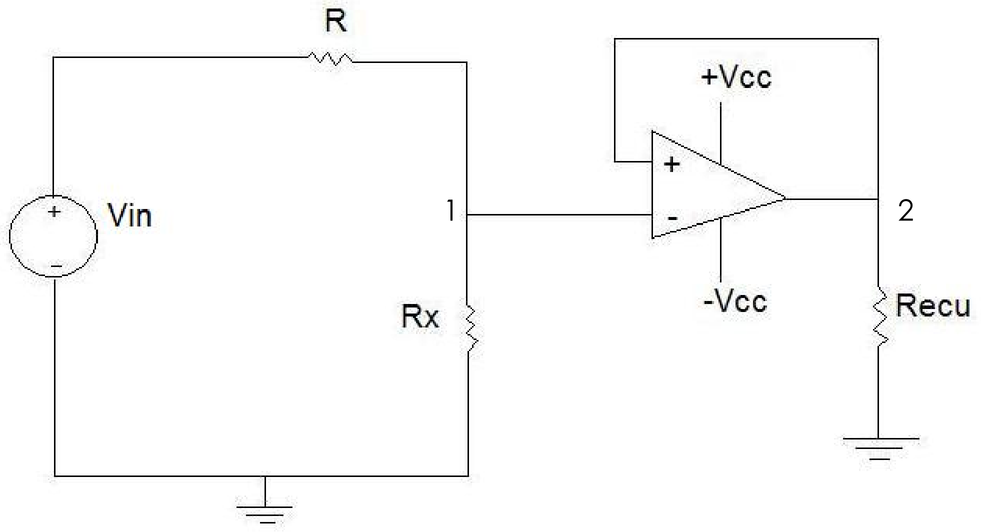


We also calculated the sheer force on the pins to determine if they would fail that way. Using the measured force of 3.34 N, the shear nominal stress is equal to the force over the area of the pin. The local stress concentration at the pin is approximately three times the nominal stress, equal to 835 kPa. This value is much less than the yield stress of the material, thus will not yield.

Electrical Analysis

In order to convert a mechanical signal into an electrical one, we had to select a sensor that could accomplish this within our specifications of the ECU. LVDTs and other forms of linear or rotational sensors were considered, but we selected a linear potentiometer and a custom circuit to act as our sensor because it gives us the same functionality as the pre-made sensors but with more control over its response and with much less cost. The finished circuit diagram is shown below in Figure 17.

Figure 17: Circuit diagram showing voltage follower connected to vehicle ECU.



Our circuit consists of a power supply (the car battery) as a 12V input V_{in}, set resistor R, potentiometer resistance R_x, ECU resistance R_{ECU}, and an operational amplifier with its feedback set up to create a voltage follower. A voltage follower ensures that the voltage difference at node 1 is that same at node 2, regardless of what is connected to the op amp. This also means that the ECU will only see enough current to match the voltage seen at node 1, and will not overload if set to our parameters (V_{ECU} being between 0-5V). Thus, we need to be cognizant of the selection of R to ensure these specifications are met. By performing a voltage loop from V_{in} to the ground (ignoring the op amp at node one because it draws no current) we obtain Equation 1.

$$V_{out} = V_{in} \frac{R_x}{(R + R_x)} \tag{1}$$

This tells us our first parameter case, which is what R needs to be for Vout = 0. The only way for V_{out} to be zero is if R_x is zero, which corresponds to a closed potentiometer (or a potentiometer in its zero resistance position). Thus, it does not matter what R is set to. Therefore, we further the equation by solving for R explicitly and obtain Equation 2.

$$R = \frac{V_{in} R_{x,\max}}{V_{out}} - R_{x,\max} \tag{2}$$

Here, since V_{out} is 5V (the maximum the ECU can take), this would correspond to the potentiometer at its maximum position, which is after the 30mm full pedal travel. The value of $R_{x,max}$ is found from the potentiometer characterization, shown in Appendix B, and is about 8300 Ohms. Using this value, along with V_{in}=12V, we obtain R = 12 kOhm. Thus, selecting a resistor with this resistance or slightly more (since resistor choice is dependent on availability) will ensure that we never see more than 5V at the ECU. It should be noted, however, that although the potentiometer is meant to measure only dead band travel (since this is where regenerative braking will occur) it needs to ensure only 5V is the max ever seen by the ECU, otherwise we would need a step down converter to avoid overloading it. The controls system in the actual vehicle can adjust, based on the changing voltage range for dead band, the amount of regenerative motor displacement and therefore how much regenerative braking occurs electronically – something we cannot do for the design expo.

DFMA – Design for Manufacturing

We have followed the guidelines given to us for DFMA, and adherence to these guidelines is very apparent in our project. Each compliance to the DFMA standards are outlined below.

1. Minimize part count – In order to accomplish this, our pedal design only incorporates the most essential parts while still being fully functional. We have only our circuit and a four-bar linkage to make up the sensor. The majority of our part count is contained in the circuit itself, and if we were to make the move to mass production, this could be overcome by switching to a pre-made sensor design. The reason we did not do this in our project was to reduce costs (since an LVDT or rotational sensor can cost anywhere from \$50-\$400) and to give us more direct control over how our circuit will respond. We did not want to be stuck with an expensive sensor that cannot be adjusted, since this would cause a greater monetary and time deficit.

2. Modularize multiple parts into single subassemblies – This guideline holds very little relevance to our project. We do not have multiple part sections to be modularized. Thus, we took this as a guide to instead focus on reducing the complexity of both our circuit and our linkage. Essentially, the linkage is just a bar connecting the pedal to the sensor, so in essence it is a modularization of a complex four bar system into a simple crank-slider. Also, we are condensing our circuit onto a small, inexpensive (~\$5) circuit board that will house all components except for the potentiometer, which serves as a slider. This represents a single subassembly that could then be installed onto the pedal as a single unit.

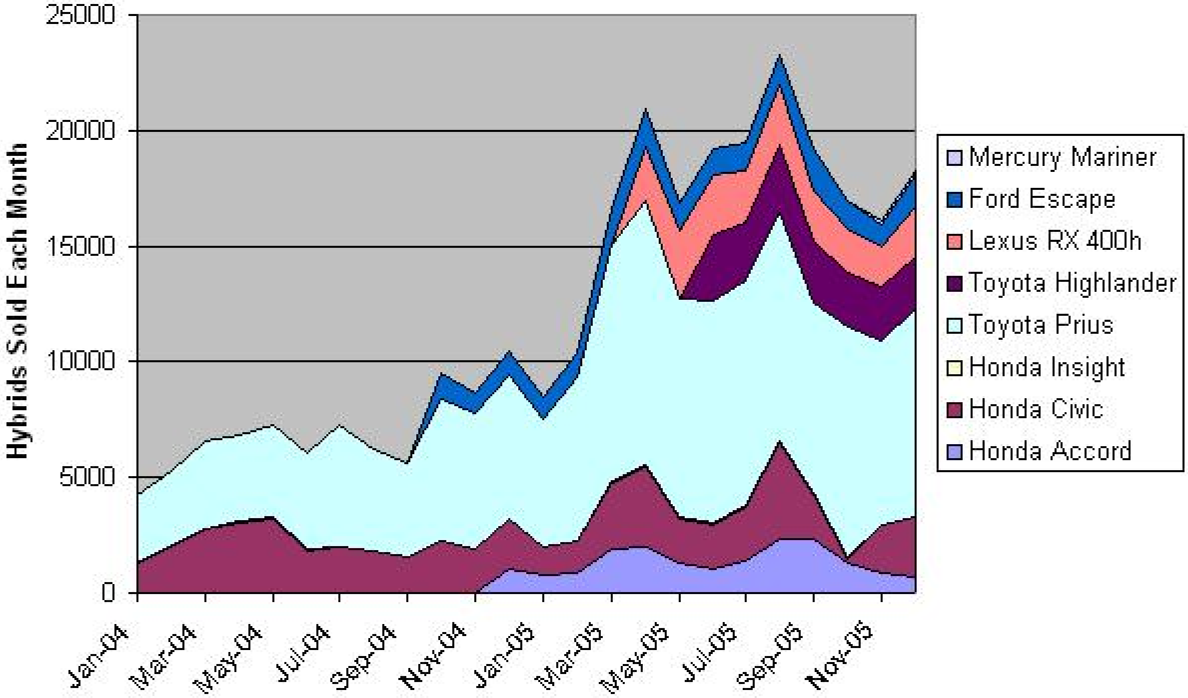
3. Permit assembly in open spaces – The installation of all system parts on the pedal itself had to be done in a very constricted space. Thus, adherence to this guideline was simple. By making our linkage and circuit connected to the outside of the pedal housing, we do not run into any obstacles when we install. This means assembly is done completely in open space, saving time and difficulty in attaching components.

4. Standardize to reduce part variety – Aside from using standard circuit components and materials (common and regular resistors, potentiometers, aluminum for the linkage) we do not really have enough parts to vary to justify a strong need to standardize. Our system contains a total of 8 fasteners (not including the soldering done for the circuit) in the form of 8 bolts. These bolts are necessarily made to be different sizes. We need a larger bolt attached to the pedal to withstand higher forces (slamming on the brakes) and we need a smaller pin attached to the potentiometer since its connection point is small. If we moved to mass production, we could adjust the size of the potentiometer link to standardize it to the size of the pedal pin, but for our project this is just not feasible. The difference in bolt size is still minimal (2 bolt types is not a large amount of variety) and it makes no large impact on the safety/specifications of our system, as outlined in the pedal bending and linkage buckling analyses shown earlier in this section.

DFE – Design for the Environment

With a world population of over 6.5 billion people it is now more important than ever to design for environmental impact. Our regenerative brake sensor was designed for a single application however if successful it has the possibility of being massed produced and thus having a much larger impact on the environment.

Figure 18. Chart to show projected sales per month of hybrids



http://hybridreview.blogspot.com/2006/01/record-number-of-hybrids-sold-in-us-in.html

During the concept development phase we concentrated on minimizing the amount of material we needed by performing stress analysis on each component of our design. Based on these results each component was then sized accordingly with an appropriate safety factor. By performing these simple calculations our team was able to reduce the material used which directly reduced the cost and the environmental impact.

During our material selection process we consider many materials for the sensor link including high-density polyurethane, PVC and aluminum. PVC was considered for its low cost however was ultimately eliminated due its environmental and health issues including but not limited to the use of the known toxin vinyl chloride during its production. Aluminum was eventually chosen as the material for the sensor link due to the fact that it is easily recycled and its light weight. By using materials that are recyclable we optimize the end of life cycle by eliminating waste and increasing reusability.

Energy optimization was Challenge X’s main goal and is why the regenerative braking system was implemented into the Chevy Equinox. The concept was applied to our sensor by minimizing the current drawn to the ECU to deliver the sensor position by implementing a voltage follower using an op-amp. The energy consumed by our device is far outweighed by the energy saved by the regenerative braking system.

FMEA - Failure Mode and Effect Analysis

Figure 19 shows the Failure Mode and Effect Analysis (FMEA) for our brake pedal assembly design. It is for the assembly system, since the entire system is composed of basically 4 components: link, pedal, sensor, and pins. It addresses possible things that could go wrong, what could the consequences be, and what can be done to prevent them from happening.

Figure 19. Design Failure Mode and Effect Analysis

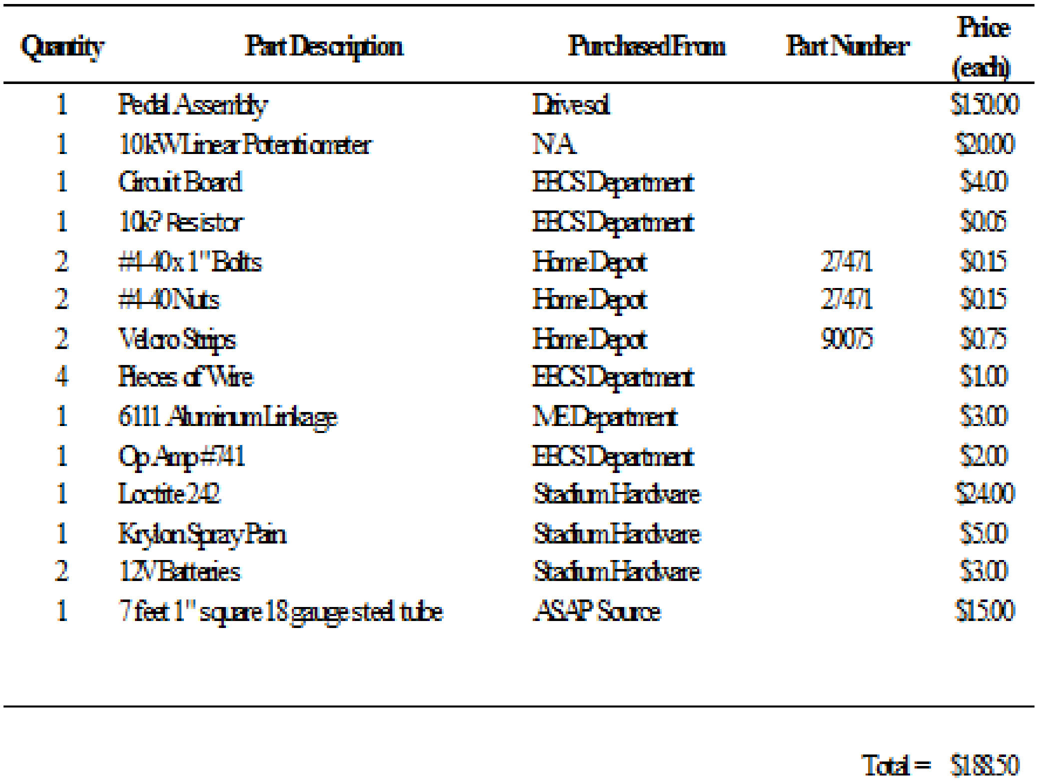
Product Name : Regen Pedal Assembly			Development Team: ME 450 Team 23				Page No. 1 of 1		
_X_ System							FMEA Number - 01		
___ Subsystem							Date: 11/08/2007		
___ Component									
Part	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes/ Mechanism(s) of Failure	Occurrence (O)	Current Design Controls/ Tests	Detection (D)	Recommended Actions	RPN
Pedal Stem	Stem fractures under load with additional hole	Loss of regenerative and friction braking	10	Fracture / Fatigue	1	Visual Check and Structural Analysis	8	Visual Check	**80**
Linkage (pins)	Pins fail under load	No regenerative braking	2	Fracture / Fatigue	1	Visual Check and Structural Analysis	8	Visual Check	**16**
Linkage (bar)	Bar buckles under load	No regenerative braking	2	Buckling	1	Visual Check and Structural Analysis	8	Visual Check	**16**
Sensor	Sensor 'wears out' and doesn't give electric signal output	No regenerative braking	2	Friction wear	2	Test Electrical Output	1	Test Electrical Output	**4**

As shown, the possible failures would include structural failure in the pedal stem, linkage bar, and linkage pins, as well as our sensor wearing out. The only severe failure mode would be the pedal failing with the additional hole placed in it, however all modes would be extremely low occurrence probability.

FINAL DESIGN

The cost of our prototype is summarized below in Figure 20, our bill of materials.

Figure 20. Bill of Materials



Quantity	Part Description	Purchased From	Part Number	Price (each)
1	Pedal Assembly	Drivesol		$150.00
1	10kW Linear Potentiometer	N/A		$20.00
1	Circuit Board	EECS Department		$4.00
1	10k? Resistor	EECS Department		$0.05
2	#1-40x 1" Bolts	Home Depot	27471	$0.15
2	#1-40 Nuts	Home Depot	27471	$0.15
2	Velcro Strips	Home Depot	90075	$0.75
4	Pieces of Wire	EECS Department		$1.00
1	6111 Aluminum Linkage	ME Department		$3.00
1	Op Amp #741	EECS Department		$2.00
1	Loctite 242	Stadium Hardware		$24.00
1	Krylon Spray Pain	Stadium Hardware		$5.00
2	12V Batteries	Stadium Hardware		$3.00
1	7 feet 1" square 18 gauge steel tube	ASAP Source		$15.00
			Total =	$188.50

The final design consists of a linear potentiometer being attached to the bracket of the brake pedal assembly. The potentiometer is connected to an aluminum link using a steel bolt, and the link is allowed to rotate about the bolt. The other end of the link is attached to another steel bolt which is attached to the brake pedal. A hole has been drilled through the brake pedal in order for the bolt to connect the pedal and the link. Hooked up to the potentiometer is a circuit containing an Op-Amp and a resistor, which allows for the potentiometer to take an input voltage and return a voltage by varying the resistance.

At the design expo, our team will have a full size prototype mock-up to display. Figure 21 shows the pedal assembly in CAD, while Figure 22 shows the designed link bar, and Figure 23 shows the sensor design chosen.

Figure 21. Pedal Assembly

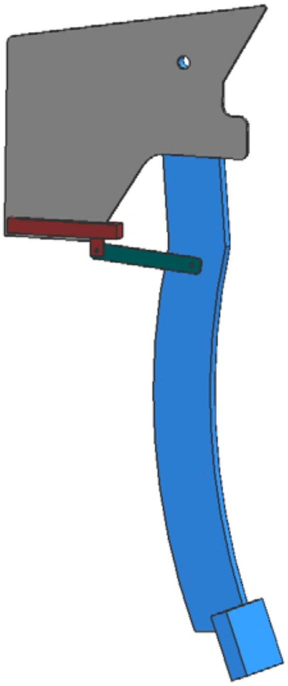


Figure 22. Linkage Bar

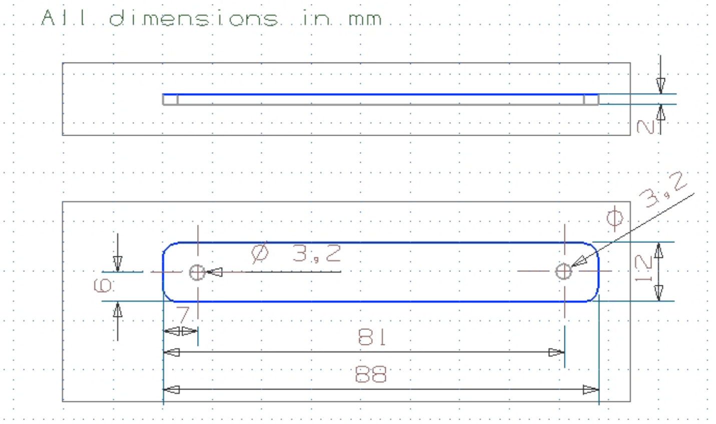
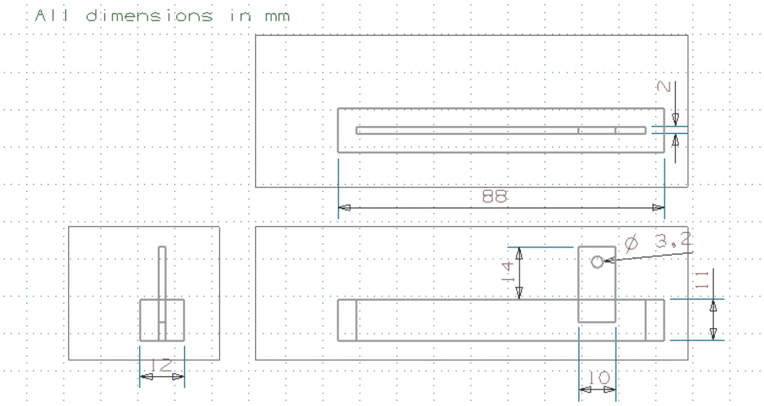


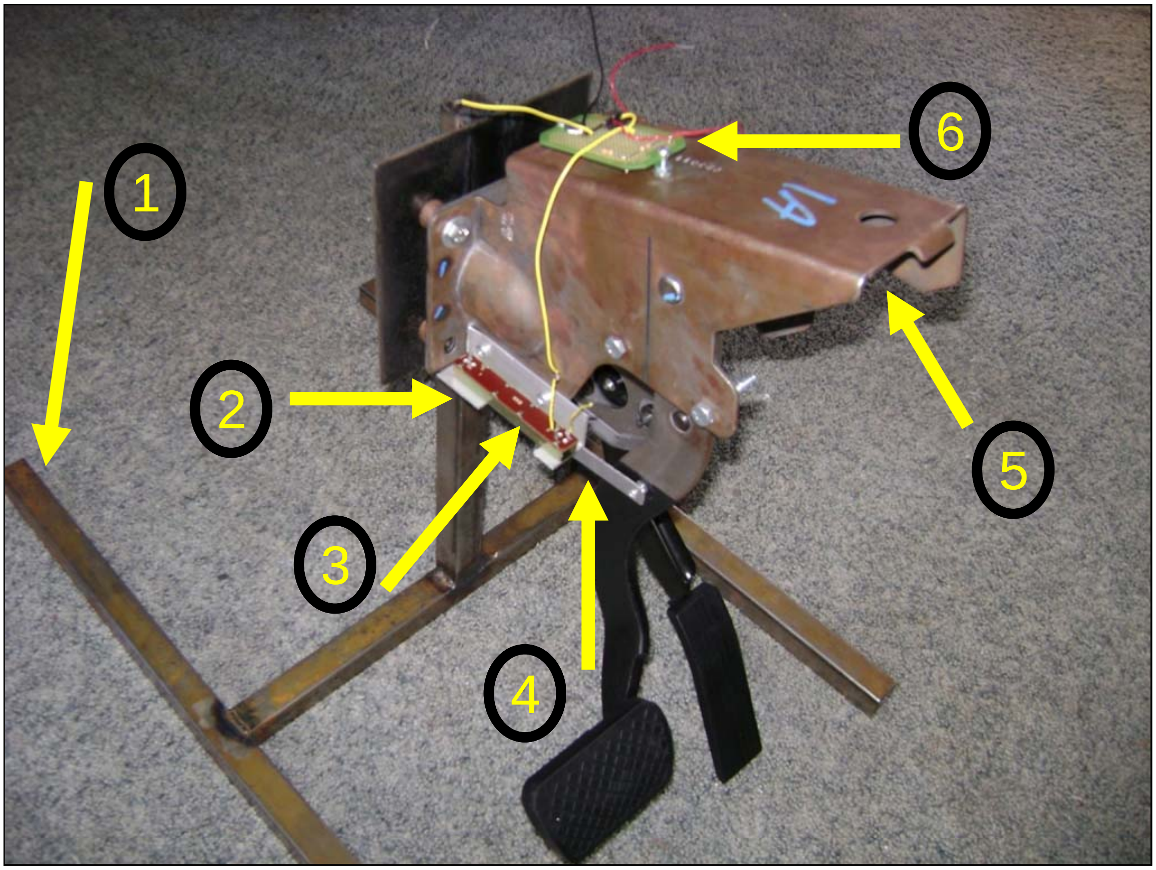
Figure 23. Sensor Design



MANUFACTURING

The prototype manufacturing was divided into 6 sections: The stand, the potentiometer, the potentiometer bracket, the potentiometer linkage, the brake pedal assembly and the electrical circuit (see Figure 22).

Figure 22. Components of Pedal Assembly



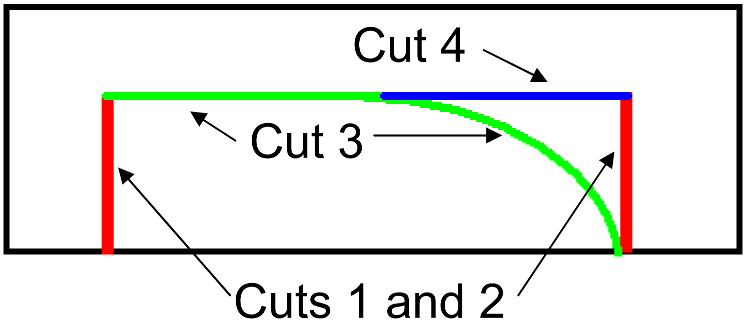
1: The Stand

The actual sensor was installed into the Challenge X Chevy Equinox and since logistics prevented us from displaying the vehicle at the design expo we created a mock set-up which allowed our team to display the brake pedal senor mechanism. We created a steel stand to represent the Equinox's firewall due to the rigidity and durability of the material. One inch 14 gauge square tubing was purchased at ASAP and cut into 4 sections of varying length determined from the dimensions of the pedal assembly. The cuts were performed on a band saw, which allowed smooth strait cuts. After the sections were segmented the stand was mocked up using magnets and then tack welded to hold everything in place. After it was tacked together it was clamped to a welding table and the final welds were performed. Once the stand was welded a 6"x 6" metal plate also purchased from ASAP and drilled using a drill pressed with a ¼ inch drill bit. This allowed the plate to be bolted to our brake pedal assembly as the firewall was attached. After it was drilled it was clamped into place tack welded and then finally tig welded.

2: The Potentiometer Bracket

The potentiometer had two mounting screw holes on the top surface which made it inconvenient to mount anywhere on the brake pedal assembly. This indicated that a mounting bracket was needed. The bracket was produced using one inch lightweight aluminum angle. The angle bracket was cut to four inches using a band saw and four holes were drilled for mounting the bracket using a hand drill. Next four cuts were performed using a band saw to achieve the rectangular cutout: two cuts came indirectly from the side, one curved cut was executed which allow the fourth cut to be straight down the back (see Figure 23).

Figure 23. Process for cutting bracket



3: The Potentiometer

Six linear potentiometers were donated by Joe Recchia from Saturn Electronics and Engineering. The potentiometers max resistance varied from 2 KΩ to 10 KΩ giving us ample freedom to design our electrical circuit.

4: Potentiometer Linkage

Three separate aluminum plates were donated by Professor Jwo Pan of the University of Michigan. After performing the failure criteria it was found that all three samples were significantly stronger then needed which provided the linkage a large safety factor. Once the appropriate sample was chosen it was cut to size using a band saw and drilled using a hand drill with a 1/8 inch bit. The holes of the linkage were de-burred to prevent any possible injury.

5: Brake Pedal Assembly

The brake pedal assembly was donated by Greg Rutkowski from DriveSol the company which manufactures the Chevy Equinox's brake pedal. 7 additional holes were drilled in the pedal assembly using a hand drilled for various features. Two holes were drilled to mount the potentiometers bracket, two were drilled to mount the electrical circuit, two were drilled to mount brake pedal stops which only were needed for the design expo and the last hole was drilled through the brake pedal linkage to mount the potentiometer linkage. All holes were first marked with a scribe and then punched to ensure the bit would not "walk" during drilling.

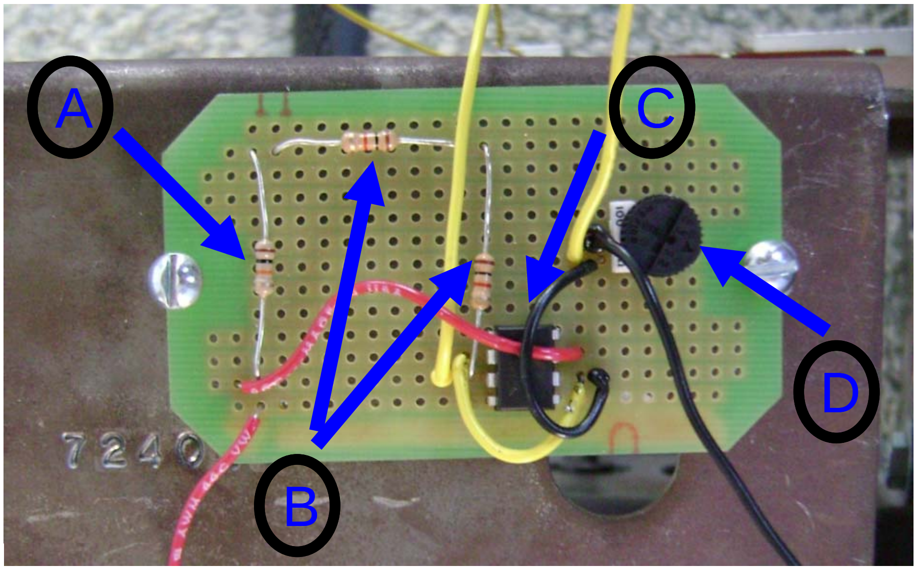
6: Electrical Circuit

Three resistors, two op-amps, a 10 KΩ rotational potentiometer, a circuit board and wire was donated by The University of Michigan's Electrical Engineering department.

Our designed electrical circuit called for a 12KΩ resistor which was produced by soldering a 10 KΩ (A) and two 1 KΩ (B) resistors in parallel.

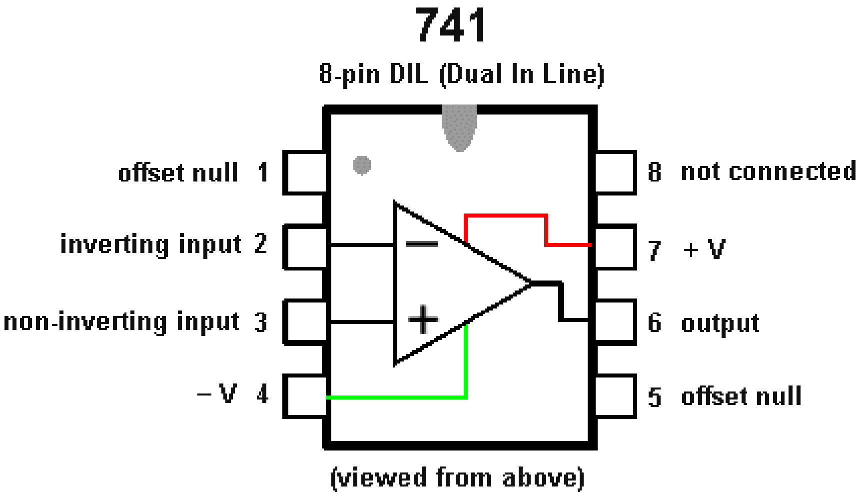
$$R,_{Equivalent - Series} = R1 + R2 + R3 = 10\text{K}\Omega + 1\text{K}\Omega + 1\text{K}\Omega = 12\text{K}\Omega$$

Figure 24. Circuit components



After the resistor was in place the op-amp (C) was solder so the resistor output was connected to the non-inverting input, Pin 3 (See Figure 24 and 25). A wire was solder from pin 2 to pin 6 producing a voltage follower. Next pin 6 was solder to the rotational potentiometer to simulate the variable resistance of the ECU. The final soldering connections were performed and the circuit bored was installed on the brake assembly.

Figure 25. Operational amplifier pin assignments



http://www.talkingelectronics.com/projects/OP-AMP/OP-AMP-1.html

Prototype Finalization

After the prototype was complete and tested the metal stand was removed and painted with H20 Latex Caribbean Blue Krylon paint to reduce oxidation and enhance visual appeal and school spirit. Next all the fasteners were loosened, coated with blue Loctite 242, and retightened to ensure that the fasteners did not come loose during operation.

Mass Production

Many of the sensor mechanisms which were benchmarked for our design were injection molded parts which had relatively low cost. If our design was mass produced the sensor linkages would be made of a similar injection plastic instead of aluminum to reduce cost and increase profitability. The fasteners would be communized to GM’s fastener library and minimized in size to further reduce cost. The aluminum potentiometer bracket would be integrated into the pedal assembly and made of steel to reduce cost and decrease total part count. The circuit would be integrated into a single chip and the op-amp would be removed since the ECU voltage would be known.

TESTING

To ensure that our project meets the engineering specifications discussed in the QFD, two simple tests were performed. Although the majority of our specifications were ergonomic and placement oriented, the two most important criteria were those pertaining to the output voltage and input force. Both tests were performed on our prototype as displayed at the design expo.

The output voltage of our sensor was required to be within the range of 0-5 V. This does not mean, however, that it needed to traverse this entire range or have a specific resolution of voltage per unit displacement. We cannot exceed 5V due to risk of overloading the ECU, yet we can begin with any voltage we want. A high resolution means greater sensitivity to motion, which is good, but any appreciable change in voltage for slight movement of the pedal is acceptable. To perform this test on our prototype, we simply measured pedal displacement and monitored the voltage output on a multimeter and recorded values for different pedal distances. The results, with error, are shown in Figure 26.

Figure 26: Test results show we are within specifications for output voltage

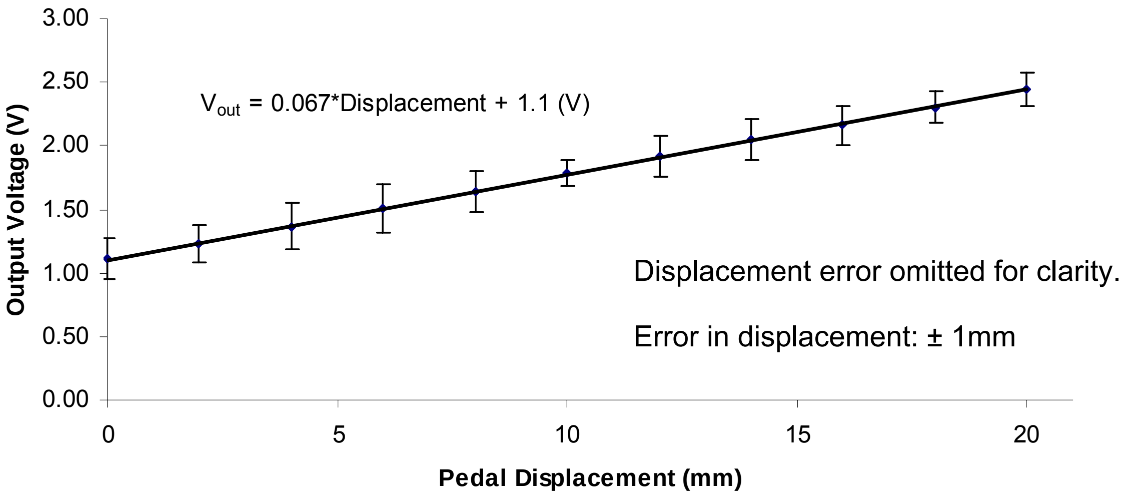
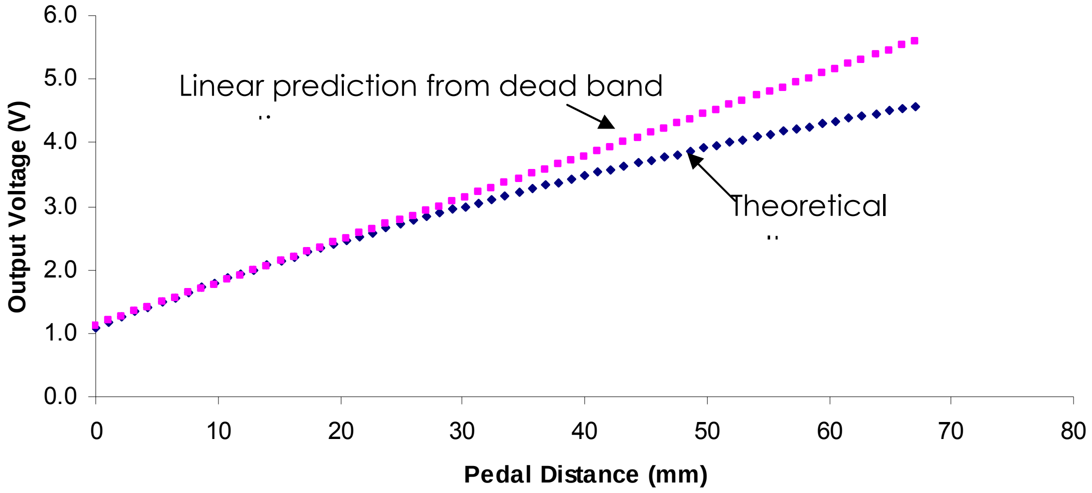


Figure 26 shows us that our resolution is about 0.083V per mm of pedal travel for the dead band spacing, which is around 20mm pedal displacement. We focus on this area of travel because it is what we are most interested in. Therefore, we have met the specifications for our output. The only problem we encountered in performing this test was that we could not measure voltage against potentiometer displacement, as we had done for our resistance graph earlier. This was remedied by using pedal displacement instead, and noting that this range is for dead band space *and* friction braking together.

Also, the relationship of pedal displacement to potentiometer displacement is just a scalar. Thus, we are still valid in performing this test and analyzing the results.

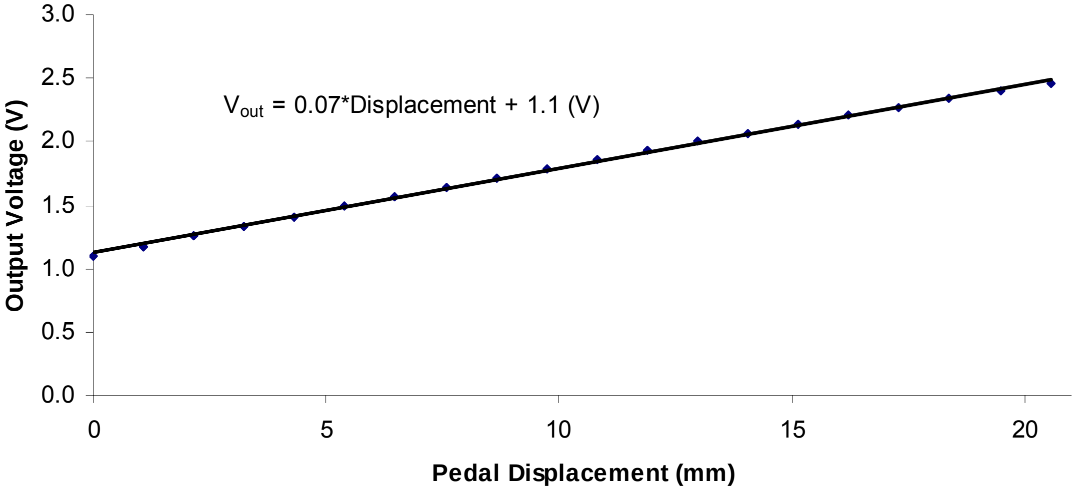
If the trend line equation shown in Figure 26 above were true for the entire pedal travel, then we would hit 5V output at around 47mm of pedal travel, which is during a full depression of the pedal (which is around 80mm)! This does not happen in our prototype, and is not predicted theoretically, however, and can be proven by looking again at Equation 1 on pg 27 shown earlier in the Engineering Analysis section. V_{out} is not a linear function of R_x. Thus, we should not expect a linear relationship for the entire pedal displacement between these two variables. Figure 27 below illustrates what we predict for output voltage over the entire pedal travel distance along with an extended data series for the linear equation shown for the dead band voltage.

Figure 27: Dead band linearization is not accurate for entire output result



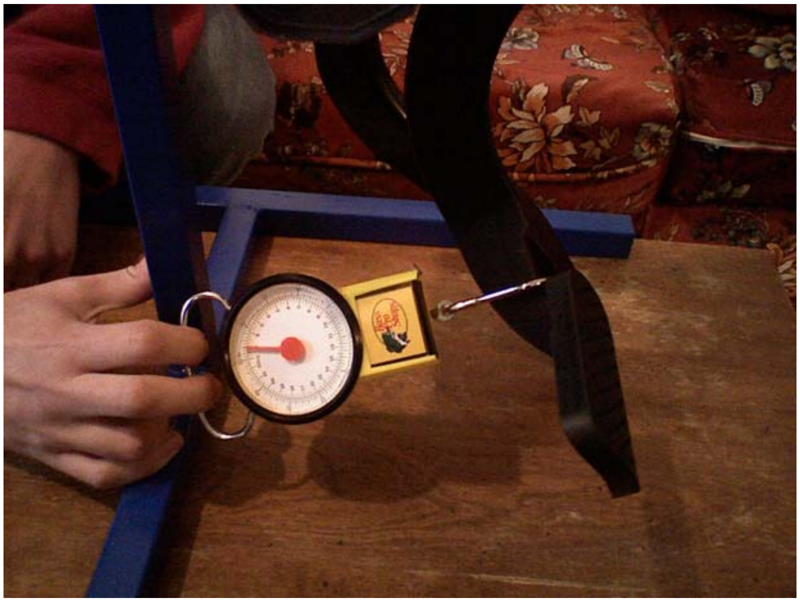
What we see here is that although the dead band output voltage can be predicted as linear, this does not hold for all output voltages seen. Our analysis predicts that we will see well below 5V at 80mm of pedal travel, and this is verified by our prototype in demonstration at the expo. The dead band equation exceeds 5V before the end of pedal travel. If we zoom in to the dead band portion of this graph, we observe Figure 28 below, showing our test results from Figure 26 to be accurate. It should be noted that the theoretical graphs are offset to begin at 1.1V, which is what our potentiometer was set to on the prototype. This is because the potentiometer was not linear for very low resistances, and this correction avoids any odd response from our circuit.

Figure 28: Dead band portion of theoretical graph matches testing



Another test we performed was a verification of the amount of force required to move the pedal (without the spring attached that simulates the master cylinder resistance force). The test was done by using a force meter to pull the pedal and its reading observed and recorded. This force was found to be around 3.3 N, as we had determined earlier during analysis. Again, this small force leads to no possible threat of mechanical failure or yielding in our linkages and fasteners. Figure 29 shows the process of measuring the force required to move the pedal.

Figure 29: Force required to move pedal is small



FUTURE IMPROVEMENTS

There are several ways to improve our design of the brake pedal assembly in the future. There are many strengths, and weaknesses in our design. Our design is robust, with high safety factors for fatigue and fracture in all components. Another strength of our system is the electrical circuit, which delivers an intended output of 1-5 Volts, with high precision. One of the weaknesses of our design is the packaging of the system, which takes up room on the outside of the pedal bracket. The pedal assembly sits in a very crowded area under the I/P in a car, so maintenance of our system would be difficult. Another one of our concerns is that the operational amplifier we chose for our circuit requires both a positive and negative voltage, and requires an additional battery other than the automotive battery to power it.

In order to improve the weak points of our design, it could be altered to incorporate the potentiometer and circuit on the inside of the pedal support bracket, to help with packaging issues. Also, the linkage and pin sizes could be chosen in smaller sizes, given the high safety factors for the forces on them.

For the current electrical circuit and operational amplifier, there would have to be an additional battery packaged with the sensor to provide the negative voltage. To get around this, a different operational amplifier which does not require a negative voltage to power itself could be specified and used in a circuit, or changing the circuit to use the car battery's 12 volts and dividing it into two 6 volt signals.

There are future design problems for teams to continue on this subject. A team could propose a different design for the pedal assembly, perhaps using an angular sensor. Furthermore, a team could look at the regenerative controls to maximize the amount of regenerative braking possible for the vehicle. Also, it may be possible for a team to alter the brake booster or brake lines to lessen the friction brakes, or add to the dead band space of the pedal to achieve more regenerative braking over friction brakes.

Our design worked properly, without any components braking, so there is no need for further engineering analysis on our design, only if additional changes were made.

CONCLUSIONS

Our team was tasked to design a brake pedal sensor to help implement regenerative braking on the Challenge X Chevy Equinox. To do this, the position of the brake pedal must be relayed to the ECU to determine the amount of regenerative braking to issue.

To achieve our problem, we developed a crank-slider four-bar linkage, which converted the rotary displacement input of the pedal to a linear output sensor that delivered an electrical signal of 1-5 volts to the ECU.

Our team developed a FAST diagram to determine the basic and secondary functions of our pedal design. From this, we developed broad concepts which met these criteria, based on the type of sensor used in our assembly. We then created a Morphological chart based on the functions in the FAST diagram. Five detailed designs were chosen from the morph chart, and evaluated using a Pugh chart. The designs were judged on the customer requirements, with weighted values. From this chart, we selected the concept involving a linear sensor with a four bar linkage to connect to the pedal assembly.

We chose a linear potentiometer for the sensor, which varies resistance in a voltage divider circuit. The input voltage would come from the vehicle battery, and the output voltage would be 1-5 V, depending on displacement.

We performed a full engineering analysis: kinematical, structural, and electrical. These analyses provide us with the assurance that out prototype is valid and optimized. From our kinematical analysis, we have determined the output of the linear sensor to be 0-3 cm for given rotational input to the pedal. From the structural analysis we found that the stresses in our system are not enough to cause failure in our assembly. The electrical analysis showed that our electrical system would produce a valuable output.

Our prototype turned out to be a high quality solution to our problem. The output of the electrical sensor varied between 1 to 5 volts as specified. Also, the assembly including the linkage, pedal, and sensor did not fracture or fail under testing conditions.

ACKNOWLEDGEMENTS

Team 23, the Challenge X regenerative brake pedal assembly team would like to thank the University of Michigan Challenge X team. Without the guidance and monetary assistance team 23 would not have been able to research and then design the brake pedal assembly. Thanks are also due to the University of Michigan EECS department for their donation of circuit components and the use of their laboratories for testing and production. Team 23 was able to acquire a Chevrolet Equinox pedal from a generous donation by Greg Rutkowski, Account Manager at DriveSol Worldwide. Without this donation the prototype production would not have been possible. Professor Jwo Pan was also generous with his donation of a few pieces of 6111 aluminum used in our brake pedal link. Joseph Recchia from Saturn Electronics and Engineering donated linear potentiometers that were used for our sensor. Finally, thanks are due to the University of Michigan machine shop and Bob Coury for the help, which was received in the process of manufacturing and assembling the parts.

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BIOS

Ryan Carnago is currently a senior in Mechanical Engineering at the University of Michigan. He is from Sterling Heights, Michigan, currently staying in Ann Arbor.

Ryan chose Mechanical Engineering through his interest in math and science, and an interest in all things involving cars. He has several family members who are engineers and work at automotive companies.

He had internships at DaimlerChrysler the past two summers, in the Supplier Quality department. These positions deepened his interest in the combination of the technical and business aspects of the industry. Prior to these he worked at Porsche Engineering, which gave an opportunity to be on the design end of the industry.

Career plans after graduation this spring include working at Chrysler starting in July 2008 in the Procurement and Supply organization, and going back to school for a Masters in Business. In his free time, he also enjoys playing and watching most sports including soccer, football, tennis, and golf.

Sam Koch currently resides in Dexter, Michigan where he has lived his entire life. He lives across the street from a retired Ford engineer who has been his lifelong mentor and was a major factor in choosing his college degree program. The other factor was his love for dynamics and kinematics.

Sam raced motocross growing up and found himself constantly working on dirtbikes and ATVs. When he came to Michigan he joined the SAE Mini-Baja team and found it to be very enjoyable however it consumed a tremendous amount of his limited free time. Sam was responsible for vehicle flotation and was assigned a lot of little jobs during his first year.

Mr. Koch received his first internship at a small company, Vconverter in 2006. The company primarily designed and produced catalytic converters for Ford, GM, and Toyotas prototype cars. His second internship was at Toyota where he performed FEA to predict vehicles crashworthiness. His final internship was at Chrysler where he worked in Supplier Quality at the World Engine Plant in Dundee, Michigan.

Next year Sam plans to attend graduate school at Michigan through the SGUS program. He would like to study auto body structure and finite element analysis. In the future he would like to work in vehicle performance assessment or vehicle validation (i.e. crashworthiness, NVH, or drivability).

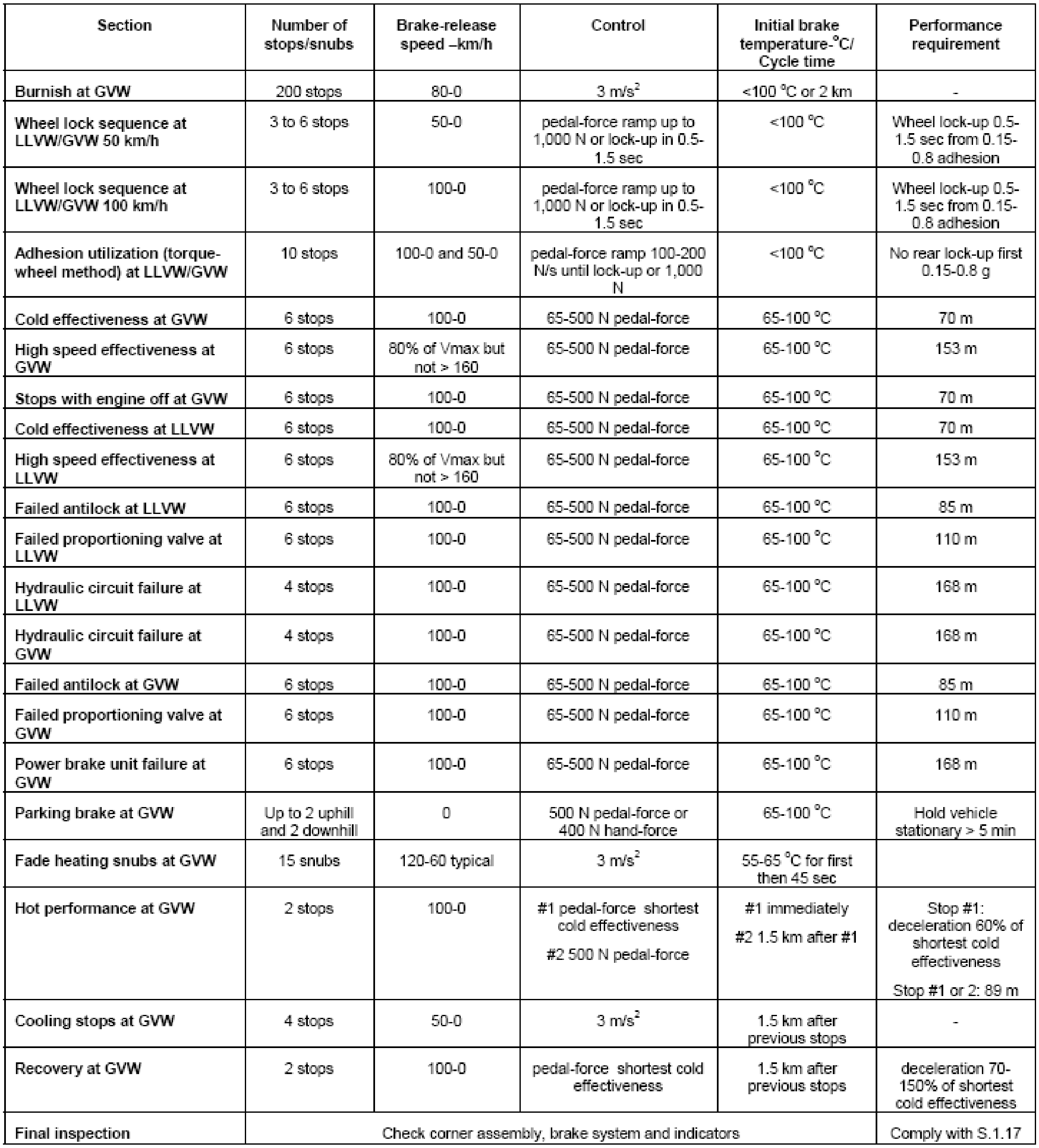
Brendan Pawlik is a senior who was born in Saginaw, Michigan. He lived in Frankenmuth, Michigan for several years until his family relocated. The family moved to Williamston, Michigan where he lived until 5th grade. He spent the rest of his years before college living in Clarkston, Michigan. He attended high school at Pontiac Notre Dame Preparatory. Going through middle school and high school he always had an interest in math and sciences. He also enjoyed finding out how things functioned. This led him to choose engineering, which combined both of his likes.

His plans after graduating will be to find a job right away or attend graduate school. He plans to find a job focused more on the design side of engineering, rather than a different part. If he plans to attend graduate school he will most likely attend the University of Michigan. In his free time he enjoys playing lots of intramural sports and attending Michigan football games. He also enjoys hanging out with friends and watching movies.

Paul Smith is a senior from Clarkston, Michigan, a small city about one hour north of Detroit. He has also lived in Tucson, Arizona and Toronto, Ontario at some point in his life. He is a Hispanic American, being that his mom was born (and has family in) Bogota, Colombia. His interest in ME is twofold: both pertaining to his interest in technical science (most particularly mechanical systems and components) and his interest in the degree’s versatility. He has a deep interest in the automotive industry, both because his entire family is employed in it and because he has grown up around Detroit most of his life. His desire to obtain a degree in mechanical engineering first began from his knowledge that it would allow him to do whatever he wanted to after completing college - be it law, engineering, or medicine (incidentally all three were once considered by him!). His current future plans, however, reside in obtaining a Master's degree from either Michigan or Texas, and then moving on to do work in the automotive industry focusing on alternative fuel technology.

APPENDIX A

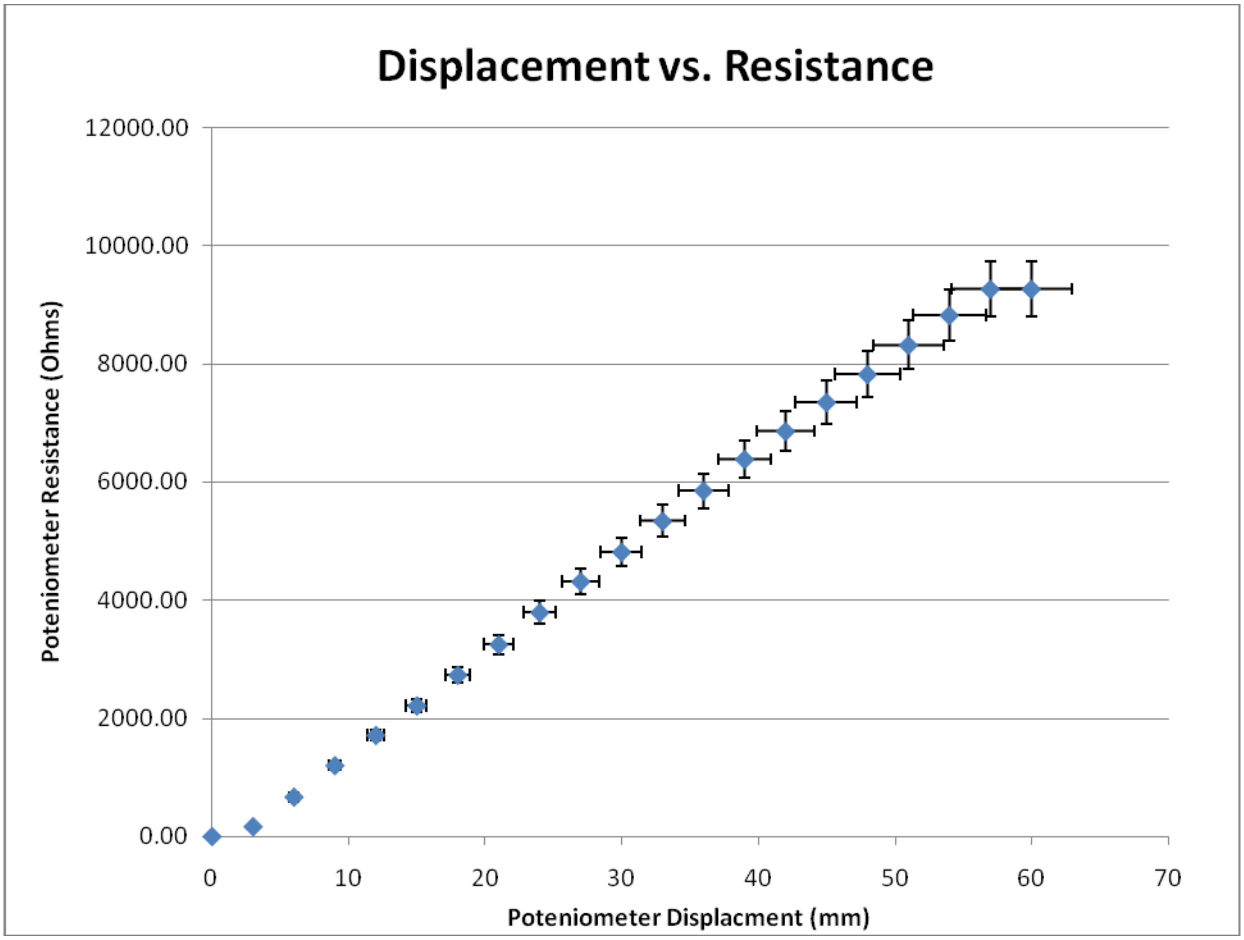
Federal Motor Vehicle Safety Standard 135 Test Summary



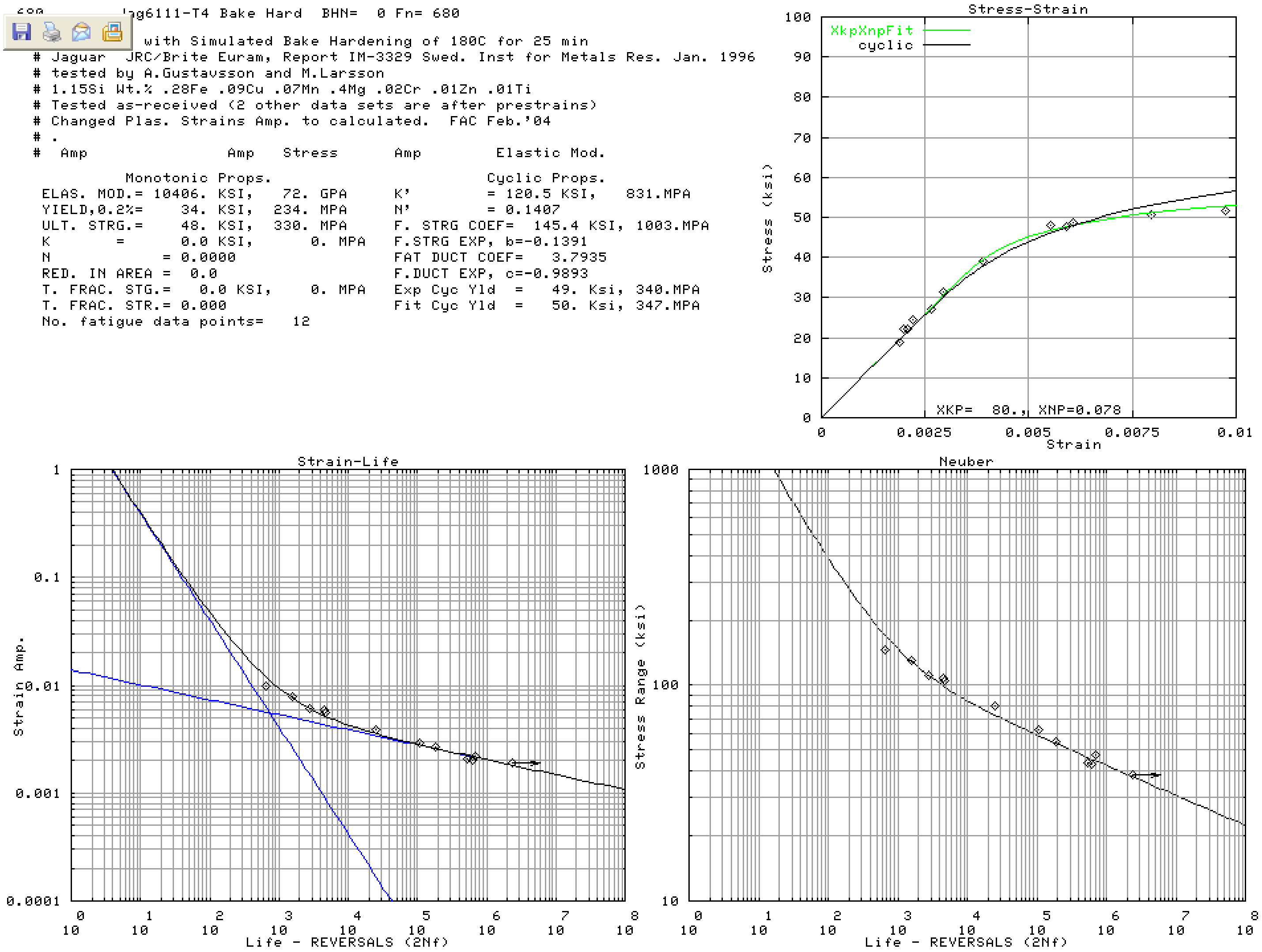
Section	Number of stops/snubs	Brake-release speed –km/h	Control	Initial brake temperature-°C/ Cycle time	Performance requirement
Burnish at GVW	200 stops	80-0	$3\ m/s^2$	<100 °C or 2 km	-
Wheel lock sequence at LLVW/GVW 50 km/h	3 to 6 stops	50-0	pedal-force ramp up to 1,000 N or lock-up in 0.5-1.5 sec	<100 °C	Wheel lock-up 0.5-1.5 sec from 0.15-0.8 adhesion
Wheel lock sequence at LLVW/GVW 100 km/h	3 to 6 stops	100-0	pedal-force ramp up to 1,000 N or lock-up in 0.5-1.5 sec	<100 °C	Wheel lock-up 0.5-1.5 sec from 0.15-0.8 adhesion
Adhesion utilization (torque-wheel method) at LLVW/GVW	10 stops	100-0 and 50-0	pedal-force ramp 100-200 N/s until lock-up or 1,000 N	<100 °C	No rear lock-up first 0.15-0.8 g
Cold effectiveness at GVW	6 stops	100-0	65-500 N pedal-force	65-100 °C	70 m
High speed effectiveness at GVW	6 stops	80% of Vmax but not > 160	65-500 N pedal-force	65-100 °C	153 m
Stops with engine off at GVW	6 stops	100-0	65-500 N pedal-force	65-100 °C	70 m
Cold effectiveness at LLVW	6 stops	100-0	65-500 N pedal-force	65-100 °C	70 m
High speed effectiveness at LLVW	6 stops	80% of Vmax but not > 160	65-500 N pedal-force	65-100 °C	153 m
Failed antilock at LLVW	6 stops	100-0	65-500 N pedal-force	65-100 °C	85 m
Failed proportioning valve at LLVW	6 stops	100-0	65-500 N pedal-force	65-100 °C	110 m
Hydraulic circuit failure at LLVW	4 stops	100-0	65-500 N pedal-force	65-100 °C	168 m
Hydraulic circuit failure at GVW	4 stops	100-0	65-500 N pedal-force	65-100 °C	168 m
Failed antilock at GVW	6 stops	100-0	65-500 N pedal-force	65-100 °C	85 m
Failed proportioning valve at GVW	6 stops	100-0	65-500 N pedal-force	65-100 °C	110 m
Power brake unit failure at GVW	6 stops	100-0	65-500 N pedal-force	65-100 °C	168 m
Parking brake at GVW	Up to 2 uphill and 2 downhill	0	500 N pedal-force or 400 N hand-force	65-100 °C	Hold vehicle stationary > 5 min
Fade heating snubs at GVW	15 snubs	120-60 typical	$3\ m/s^2$	55-65 °C for first then 45 sec	
Hot performance at GVW	2 stops	100-0	#1 pedal-force shortest cold effectiveness #2 500 N pedal-force	#1 immediately #2 1.5 km after #1	Stop #1: deceleration 60% of shortest cold effectiveness Stop #1 or 2: 89 m
Cooling stops at GVW	4 stops	50-0	$3\ m/s^2$	1.5 km after previous stops	-
Recovery at GVW	2 stops	100-0	pedal-force shortest cold effectiveness	1.5 km after previous stops	deceleration 70-150% of shortest cold effectiveness
Final inspection	Check corner assembly, brake system and indicators				Comply with S.1.17

http://www.linktestlab.com/Brochure%20PDFs/Link%20Technical%20Report%20FEV2005-01.pdf

APPENDIX B


Displacement vs. Resistance
Poteniometer Resistance (Ohms)
12000.00
10000.00
8000.00
6000.00
4000.00
2000.00
0.00
0
10
20
30
40
50
60
70
Poteniometer Displacment (mm)

APPENDIX C

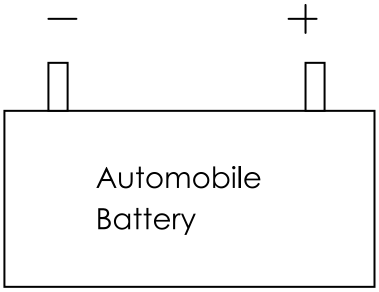


```
680          ag6111-T4 Bake Hard  BHN=  0 Fn= 680

             with Simulated Bake Hardening of 180C for 25 min
 # Jaguar  JRC/Brite Euram, Report IM-3329 Swed. Inst for Metals Res. Jan. 1996
 # tested by A.Gustavsson and M.Larsson
 # 1.15Si Wt.% .28Fe .09Cu .07Mn .4Mg .02Cr .01Zn .01Ti
 # Tested as-received (2 other data sets are after prestrains)
 # Changed Plas. Strains Amp. to calculated.  FAC Feb.'04
 # .
 #  Amp                 Amp   Stress       Amp         Elastic Mod.

          Monotonic Props.                           Cyclic Props.
  ELAS. MOD.= 10406. KSI,   72. GPA      K'          = 120.5 KSI,   831.MPA
  YIELD,0.2%=    34. KSI,  234. MPA      N'          = 0.1407
  ULT. STRG.=    48. KSI,  330. MPA      F. STRG COEF=  145.4 KSI, 1003.MPA
  K       =      0.0 KSI,     0. MPA     F.STRG EXP, b=-0.1391
  N            = 0.0000                  FAT DUCT COEF=   3.7935
  RED. IN AREA =  0.0                    F.DUCT EXP, c=-0.9893
  T. FRAC. STG.=   0.0 KSI,    0. MPA    Exp Cyc Yld  =   49. Ksi, 340.MPA
  T. FRAC. STR.= 0.000                   Fit Cyc Yld  =   50. Ksi, 347.MPA
  No. fatigue data points=   12
```

APPENDIX D

Engineering Change Notices

Was:



Is:

Notes: This change will affect the circuit. For the prototype a small 12V battery was used instead of an automobile battery as the power supply. For the prototype and in the actual assembly a small 12V battery will need to supply -12V to power the op amp.

Challenge X:
Project: Brake
Paul Smith
Sponsor: Jwo Pan

APPENDIX E

Measuring force required to move potentiometer