Project 10
Xebra: Hydraulic-Electric Hybrid

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1 ABSTRACT

The Environmental Protection Agency is interested in improving the efficiency of electric vehicles by integration of a hydraulic launch system with the electric components. Electric vehicles have an efficiency drop from 90% to 60% during acceleration. By adding a hydraulic launch system to the Xebra for the acceleration phase, the batteries of this electric vehicle will not be burdened during acceleration and overall efficiency of the vehicle will be improved. This project will span several semesters, with the focus of this term on the layout and installation of the hydraulic system onto the Xebra.

2 INTRODUCTION

The following section highlights the background, motivation, and goals of the Xebra project.

2.1 Background and Problem

The sponsor of this project, the Environmental Protection Agency (EPA), an agency of the U.S. government, was established in 1970 to enforce federal pollution reduction laws and to implement various pollution prevention programs [1]. While electric vehicles reduce emissions during driving, they are extremely inefficient. Batteries are designed to maintain a constant load, but during acceleration, electric vehicles require very large loads for short periods of time which not only reduces the efficiency of the batteries to as low as 60% for each charge, but also decreases the overall life of the battery caused by this deep-cycling. The EPA believes that adding hydraulic systems on vehicles can be a key contributor to reducing air pollutants and dependency on fossil fuels and embody their mission to protect human health and the environment. The implementation of this hydraulic-launch system onto the Xebra will also be a major achievement for this future goal.

2.2 Motivation

In previous semesters at the University of Michigan, students used hydraulic regenerative braking systems to accelerate a bicycle. The technology for this system was created and fine-tuned during these projects, and is now ready to be implemented on a vehicle. The EPA would like to implement this system into the Xebra to test the transferability into large-scale applications.

The Xebra is a small three-wheeled electric vehicle that is legally classified as a motorcycle. The vehicle's rear wheels are powered by a 72 VDC electric motor with a continuous horsepower output rating of 5 HP. Six large 12V batteries (72V total) provide the power to the motor, while a smaller 12 V battery provides power to the instruments inside the vehicle's cab. Vehicle dimensions and component layout can be found in Figures 1 and 2 on page 2. The Xebra's top speed is 35 mph and it can travel approximately 20 miles on one charge. This small range can be attributed to low accelerations and high loading on the batteries during vehicle launch. Implementing the hydraulic system will increase the acceleration while also increasing the efficiency of the batteries.

Figure 1: Xebra Electric Vehicle and Dimensions

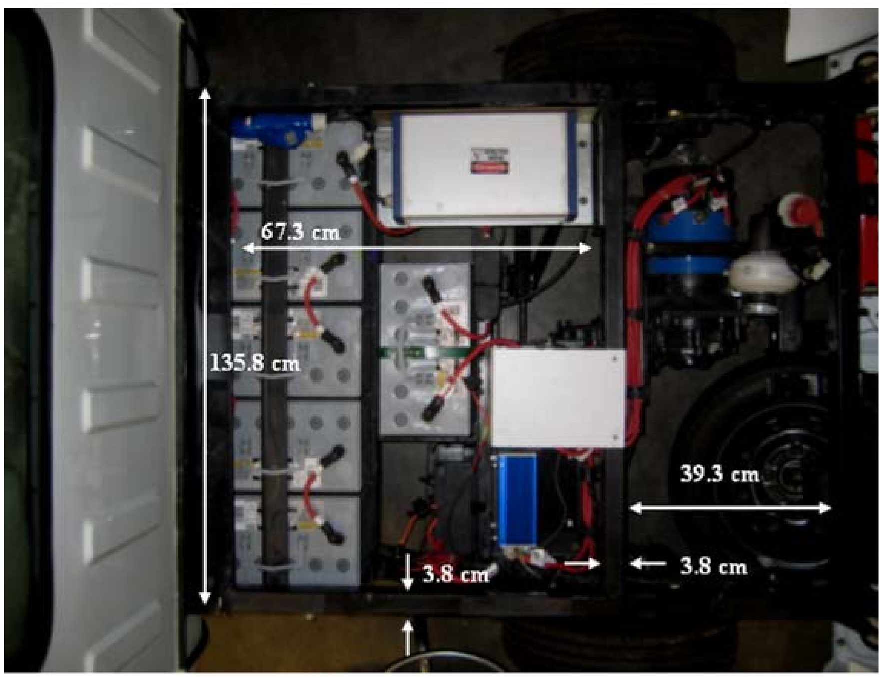


Figure 2: Dimensions of Xebra Components under Truck Bed

2.3 Goals of Xebra Project

This project will span several semesters with the main goal of improving the overall efficiency and acceleration of the Xebra. The focus of the Fall 2007 semester will be to design, layout, and install some of the critical components for the hydraulic launch system. This includes some changes to the body of the current vehicle in order for everything to fit within the vehicle frame. The major components that will be installed will be the low-side and high-side accumulators, valves, motor, pump, sensors, and slow-fill pump. Following semesters will use this design to incorporate the hydraulic motor and regenerative pump into the drive train to complete the hydraulic-launch system. Before all of the components are installed, our team will also complete a base-line performance test on a chassis dynamometer in order to compare before and after data for acceleration and efficiency to quantify the improvements that were made.

3 INFORMATION SEARCH

This section describes the various types of information collected during research.

3.1 Background Information

Most of the background information for this project was available from past ME450 groups that focused on the bicycle regenerative braking system. We had access to all the past final reports, as well as much of the data analysis they had already completed [2]. The hydraulic system that will be implemented into the Xebra is a larger-scale version of the one that was used in the bicycle. It has been developed and tested continuously by a student at the University of Michigan, and a patent application has been filed for this design. The EPA believes that this is the ideal system for the Xebra project. All of the information about the system can be carried over to our project and efficiency losses through the piping can be recalculated. We also have the help and guidance of our sponsor, David Swain of the EPA, as well as a graduate student, Jason Moore, who has worked on developing the project for several semesters.

3.2 Technical Benchmarks

Outside of the bicycle project at the University of Michigan, there are currently no hydraulic-launch systems or hydraulic-electric hybrid vehicles on the market, which means that benchmarking our design against a similar product is not feasible. Instead, this project will have to be benchmarked against the technical specifications for which we are designing. This will include whether the vehicle reaches 27 miles per hour on a single hydraulic charge, and that the overall efficiency of the vehicle is improved. This efficiency improvement will be evaluated by baseline tests that will be conducted at the beginning and conclusion of this multi-term project.

3.3 Patent Search

With regard to intellectual property, the regenerative braking technology developed during the ME450 bicycle projects has been filed as a patent (Patent #: 20070126284) by the University of Michigan in December 2006 [3]. At that time it was confirmed that no other technologies similar to this hydraulic system existed. The patent is specifically for a fixed displacement hydraulic system; past patents and technologies have utilized variable displacement systems. It was attempted to incorporate these variable displacement systems into vehicles with internal combustion or diesel engines, however it wasn't until recently that hydraulic pump and motor systems were efficient enough to be a viable option for launch assist technologies. Additionally, there was a patent filed in 1982 (Patent # 4472944) for a diesel and electric hydraulic system for various modes of transportation or industrial equipment, however this is not comparable because the hydraulic system in the Xebra does not utilize a diesel engine [4]. This project will be the first publicly known hydraulic-electric hybrid vehicle once completed.

3.4 Technical Information

Other information for this project was obtained by consulting the Zap! ® Xebra owner's manual [5] for operating information, a fluid mechanics textbook [6] was used during preliminary calculations, and ME450 lecture notes and resources.

4 HYDRAULIC SYSTEM INFORMATION

4.1 Hydraulic Component Layout

The hydraulic system layout, located in Figure 3, was designed by Jason Moore during his work on the bicycle regenerative braking at the University of Michigan in 2004 [7]. The system consists of the following main components:

- Two High-side accumulators: store high pressure fluid
- Low-side accumulator: stores low pressure fluid
- Hydraulic motor: turns fluid potential energy into vehicle's kinetic energy. This project uses a fixed displacement motor.
- Hydraulic pump (regenerative brake): turns kinetic energy into fluid energy during braking in order to charge the high-side accumulators
- Slow-fill pump: charges the high-side accumulators using electric power from batteries

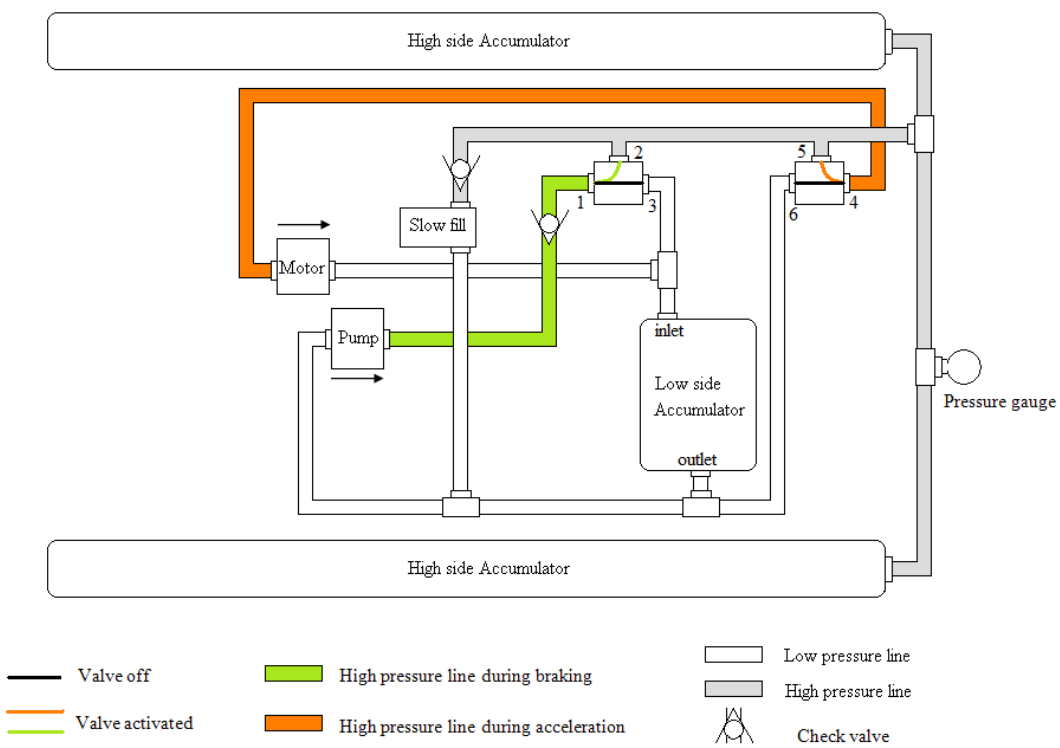


Figure 3: Hydraulic Component Layout

When acceleration is desired, a sensor located on the gas pedal is pressed to actuate the valve controlling the fluid to the motor. High pressure fluid in the high-side accumulators is released and flows through the hydraulic motor, which is coupled to the Xebra's drive train, and accelerates the vehicle. The fluid loses pressure and is stored in the low-side accumulator.

When the brake pedal is pressed, a sensor located on it will actuate the valves so that the two hydraulic pumps can take the fluid from the low-side accumulator and re-pressurize it and store it in the high-side accumulators until another acceleration is desired. The regenerative brake pump will be coupled to one of the Xebra's wheels and will do most of the pressurizing when the brake is pressed. The slow-fill pump works in conjunction with the regenerative brake pump to continuously pump the fluid and will be used only to "top off" the fluid in the high-side accumulators.

Check valves in the system will prevent the fluid from damaging the hydraulic pumps and launching the vehicle forward in the case of failure in the system. When the vehicle is not accelerating or braking, the valves are such that the fluid is freely circulating in the system, without flowing through the pump or motor.

5 CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

This section explains the customer requirements and engineering specifications and how they culminate into a Quality Function Deployment (QFD).

5.1 Customer Requirements

Table 1 shows the customer requirements and their descriptions as determined by our sponsor. Our customer is currently the EPA, but in the future may be large car companies interested in this technology for commercial implementation. These requirements are applicable to the Xebra project, but it is important to note that more specific additions will have to be made for future semesters.

Customer Requirement	Description
Transferable to future semesters	Thorough documentation; layout designed with future goals in mind
Comfortable feel during acceleration	User comfort during acceleration; natural feel
Sufficient acceleration to top speed	Quicker acceleration; stays with traffic
Efficiency in plumbing	Minimize losses due to bends and friction in plumbing
Lightweight	Control component weight
Reliable components	Added components should not fail
Aesthetics	Demonstration vehicle; professional look is essential
Safety	Sensors and emergency stop must be included
Easy to use	Pedal sensors for triggering hydraulic launch
Easy to service	All components must be accessible
Maintains vehicle function	Passenger and load amounts remain unchanged

Table 1: Description of Customer Requirements

The most important customer requirements as indicated by our sponsor were aesthetics, transferability to future semesters, and reliable components.

5.2 Preliminary Calculations

At the beginning of the project, our sponsor asked us to perform preliminary calculations to estimate some of the requirements for the hydraulic system. These calculations allowed us to determine the required technical specifications for the customer requirements. We had to determine the amount of energy it would take to reach a top speed of 27 miles per hour (76.4 kJ), the volume of fluid it would take to acquire this energy (3.71 L), and also the acceleration to the top speed provided by the 22 cc motor (3.26 m/s^2). In these calculations, the ideal state was assumed; no losses due to friction, air drag, etc. were taken into account. The calculations, which can be found in Appendix A, had previously been completed by the EPA who used this information to purchase some of the main hydraulic components before the start of this semester. A list of parts containing those already purchased for this project and those that still need to be purchased is located in Appendix B.

5.3 Technical Specifications

Table 2 shows a list of the technical specifications that will meet the requirements for the customer. Each technical specification is rated to support the customer requirements and the manifestation of this is the QFD, which can be found in Figure 4.

Technical Specifications	Target Value	Units
Flow rate of slow fill pump	1	L/s
Low side accumulator pressure	101	kPa
Pump size	33.19	cc
Motor size	21.65	cc
Size of hydraulic fittings	1	in
Type of actuation touch sensor	<5	lb
Distance of regenerative brakes from LS accumulator	0.5	m
Pressure loss through geometry of fittings	<700	kPa
Total length of hose	30	m
Corrosion resistant materials	100	%

Table 2: Technical Specifications that Meet the Requirements for the Customer

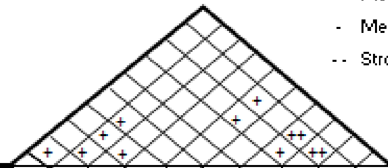
To summarize this chart, the top ratings that each technical specification supports are discussed. The flow rate of the slow-fill pump supports the sufficient acceleration to top speed. The low-side accumulator pressure, pump size, and motor size allow for comfortable feel during acceleration as well as sufficient acceleration to top speed. The size and geometry of the hydraulic fittings is critical to the efficiency in plumbing. The actuator sensor that is chosen will fulfill the customer requirements for safety, ease of use, and maintaining vehicle function. The distance of the regenerative brakes from the low-side accumulator accounts for transferability to future semesters. The total length of the hose required to install the components in the vehicle directly supports transferability to future semesters, efficiency in plumbing, ease of servicing, and aesthetics. Aesthetics are important because the layout of all of the components affects the length of hose. For example, if the accumulators are placed in the truck bed, the hose would be visible on the Xebra exterior, thus reducing aesthetic appeal. Lastly, the materials chosen for each component need to be compatible with the hydraulic fluid and resistant to corrosion for safety purposes.

Quality Function Development (QFD)

key checks ; these should indeed be high

Relationships between technical requirements

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



Customer requirements \ Technical specifications	Weightage	Flowrate of slow-fill pump	Low-side accumulator pressure	Pump size	Motor size	Size of hydraulic fittings	Type of actuation touch sensors	Distance of regenerative brakes from LS accumulator	Pressure losses through geometry of fittings	Total length of hose	Corrosion resistant components	Total (weighted customer requirement)	Normalized to total	Importance rating (% of total)
Transferable to future semesters	8	3	3	3	3	3	1	9	3	9	3	320	0.20	20
Comfortable feel during acceleration	4	0	9	9	9	3	1	0	0	0	0	124	0.08	8
Sufficient acceleration to top speed	4	9	9	9	9	3	1	0	0	1	0	164	0.10	10
Efficiency in plumbing	7	1	3	3	3	9	0	9	9	9	0	322	0.20	20
Lightweight	1	3	9	3	3	1	1	0	0	0	1	21	0.01	1
Reliable component	8	1	1	1	1	1	3	0	3	1	9	168	0.10	10
Aesthetics	9	0	3	0	0	1	3	0	1	9	3	180	0.11	11
Safety	5	3	1	0	0	3	9	3	1	3	9	160	0.10	10
Easy to use	4	1	0	0	0	0	9	0	0	3	3	64	0.04	4
Easy to service	3	1	1	0	0	0	3	3	1	9	1	57	0.03	3
Maintains vehicle function	3	1	1	0	0	0	9	3	0	3	1	54	0.03	3
Measurement Unit		L/s	kPa	cc	cc	in	lb	m	kPa	m	%			
Our target		1	101	22	22	1	<5	0.5	<700	30	100			
otal (weighted technical specifications)		103	172	128	128	144	185	168	128	291	187			
Normalized to total		0.06	0.11	0.08	0.08	0.09	0.11	0.10	0.08	0.18	0.11			
Importance Rating (% of total)		6	11	8	8	9	11	10	8	18	11			

Weightage used throughout
1 - Not related/important
3 - Weakly related/important
9 - Strongly related/important

Figure 4: Quality Function Deployment (QFD) Chart

The targeted values that are associated with the technical specifications were found from the preliminary calculations performed and also from the parts already selected and purchased for this project. An example of this is the fixed size of the pump and the motor, whereas the other values such as the flow rate of the slow-fill pump, the total length of hose, and the distance of the brakes from the accumulator were estimated based on what the system needs using project calculations.

6 CONCEPT GENERATION

The following section highlights our design layout concepts and the process in which we arrived at them.

6.1 Function Analysis System Technique (FAST) Diagram

In order to generate design concepts to meet customer requirements, the main functions to consider during the design process have to be determined. This is achieved through a Function Analysis System Technique (FAST) diagram. The FAST diagram takes the main function of the product and breaks it down into specific sub-functions that are needed to describe the main function. These sub-functions are then used as guidelines for generating design concepts. The FAST diagram for the Xebra project can be found in Figure 5.

It was decided that the main function of the Xebra project was to improve the performance of the vehicle. This was then broken down even further into the sub-functions of assisting the launch phase, capturing the various forms of energy within the system, assuring user safety, convenience, and dependability, enhancing the product, and pleasing the senses.

The launch of the vehicle is assisted using a motor driven by released high pressure fluid. Capturing the energy is accomplished in two ways. The first is to convert energy using a regenerative brake, and the second is by pressurizing hydraulic fluid via a slow-fill pump and storing the high pressure fluid in high-side accumulators. Assuring user safety is accomplished by providing easily accessible emergency shut-off switches. Dependability is assured by storing the hydraulic fluid in a low-pressure reservoir that is compatible with the hydraulic oil, and does not leak. User convenience is obtained by actuating the hydraulic system via easy to use sensors. Additionally, maintaining vehicle function will also assure convenience. This is done by enclosing the components underneath the truck bed, providing access to the spare tire, and maintaining accessibility and serviceability to the original components of the vehicle.

The product is enhanced in three ways. The overall acceleration of the vehicle will be improved and the efficiency will be increased by reducing load on the batteries, as well as recycling energy within the system. Also, the product will save the environment by eliminating emissions associated with diesel or gasoline engines. Finally, the product must please the senses by maintaining the aesthetic qualities present in the original design.

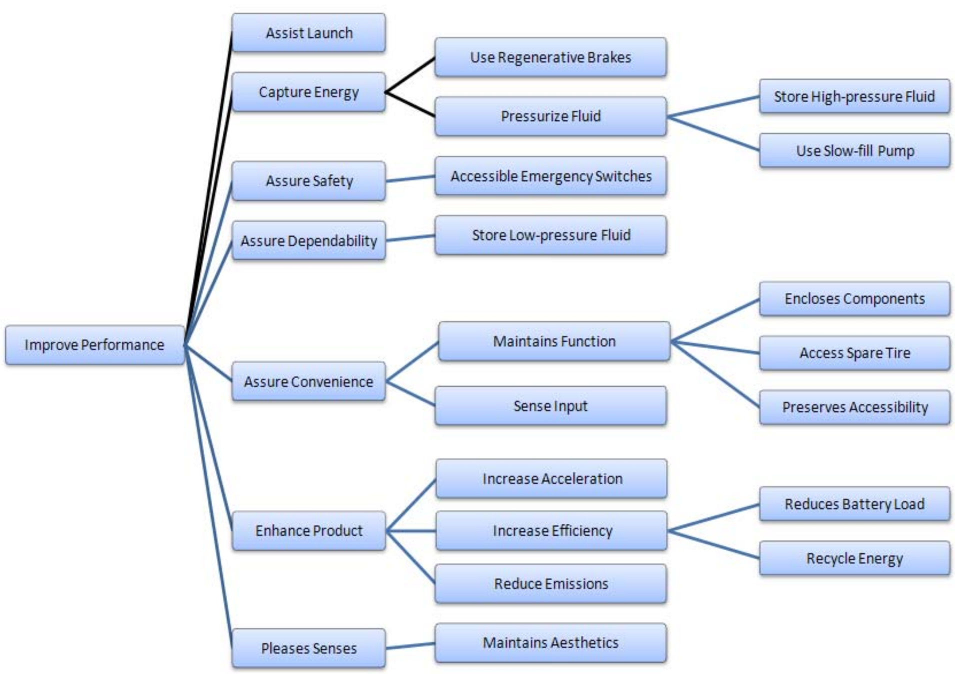


Figure 5: Function Analysis System Technique (FAST) diagram

6.1 Morphological Chart

A Morphological chart was created to generate high-level concepts within the main design parameters of the project. The complete Morphological chart along with descriptions can be found in Figure 6 (page 10). These design parameters were generated from the sub-functions of the FAST diagram. In this figure it is important to note that LS stands for the low-side accumulator, M stands for the hydraulic motor, and SF represents the slow-fill pump. Some of the design sub-functions from the FAST Diagram do not appear on the Morphological chart. Reducing emissions, recycling energy, reducing battery load and releasing pressure are all parameters intrinsically achieved by the hydraulic system design that is being utilized. Using regenerative brakes is a portion of the project reserved for future semesters, and the use of a slow-fill pump is not included because a slow-fill pump was one of the parts provided for this project.

The design sub-functions from the FAST Diagram that were the main focus for this semester included storing high-pressure fluid, storing low-pressure fluid, preserving accessibility, enclosing components, sensing input, and accessing spare tire. Design concepts were generated by group brainstorming, keeping the customer requirements in mind from the QFD. It was also important that each concept fulfilled the function for which it is designed. The concepts described in this section are outlined in red on the Morphological chart, and represent one concept from each sub-function of the FAST Diagram. Those outlined in green are the concepts used in the final design.

Storing high-pressure fluid was crucial for the overall design because the high-side accumulators are the largest components of the system. Concept 1 from the Morphological chart shows moving the trunk bed back by extending the frame to create additional space. The high-side accumulators would then be placed horizontally between the truck bed and the passenger cabin.

The second design function was storing low pressure fluid with a low-side reservoir. Concept 1 depicts one possible solution consisting of two small hydraulic reservoirs connected together. Two separate reservoirs help to reduce air bubbles from the hydraulic lines by having the hydraulic system draw fluid from the lower accumulator where no bubbles are present.

The third design function focused on preserving accessibility while designing the overall component layout. A major limiting factor of the layout was the large size of the slow-fill pump therefore this component is constrained to the rear corner of the frame where there is a large, open space. Concept 3 shows the slow fill pump and the low side accumulator mounted under the truck bed in the open space where the spare tire was originally mounted. This open space allows for many different possible component layouts. With the added components under the truck bed, it was probable that the trunk bed would have to be lifted to allow for the sufficient enclosed space of all the components. Therefore, concepts were generated for redesigning the hinges which hold the truck bed onto the frame. Concept 1 extends the actual hinge connected to the truck bed so that when closed, the bed would rest at a higher level. This would eliminate the need to alter the actual frame of the vehicle.

The fifth design function was determining how the hydraulic system would sense input from the user. Concept 2 depicts using a button on the dashboard that the user could push to activate the hydraulic launch. Lastly, in the event that the spare tire was removed from underneath the truck bed to allow for more space, a design needed to be made for its new placement. One possible solution would be to simply place the spare tire in the trunk bed, which is depicted in Concept 2.

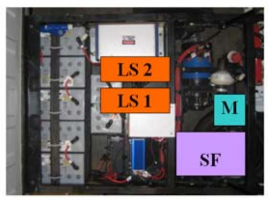
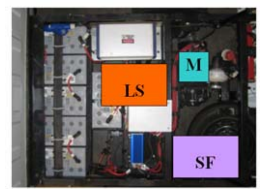
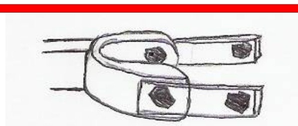
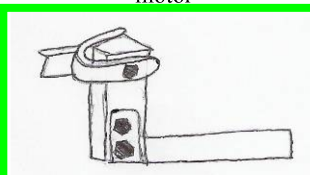
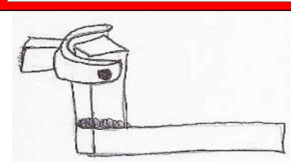
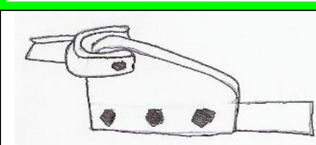
Design Parameters	Concept 1	Concept 2	Concept 3	Concept 4
Store High Pressure Fluid	 Move truck bed back; accumulators lay behind cabin	 Placed vertically behind cabin	 Move truck bed vertically; accumulators under truck bed	 Placed in bed of truck bed
Store Low Pressure Fluid	 Two small 2 Gallon Reservoirs [8]	 One 4 Gallon reservoir [9]	 Plastic gasoline container [10]	 Small low-profile automobile gas tank [11]
Encloses Components	 Spare tire location utilized	 Hydraulic motor near electric motor	 Low-profile low-side reservoir, rotated slow-fill	 Space left near electric motor
Preserves Accessibility	 Extend original hinge	 Extend vehicle frame (bolted)	 Extend vehicle frame (welded)	 Triangular bracket
Sense Input	 Touch sensor on brake and accelerator pedals [12]	 Button on the Instrument Panel [13]	 Manual lever [14]	
Access Spare Tire	 On tailgate, similar to Jeep® [15]	In trunk bed (Loose)	Remove from Xebra	Remain in original position

Figure 6: Morphological Chart

7 CONCEPT EVALUATION AND SELECTION

Once the Morphological chart was created, some possible design concepts could be generated and evaluated in order to select a final concept design. Figure 7 shows the five possible design concepts considered. Each was created using different combinations of the concepts within the Morphological diagram.

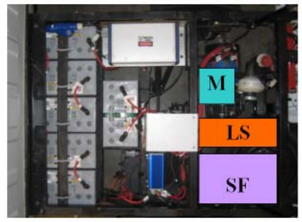
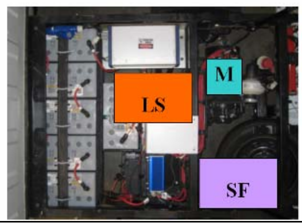
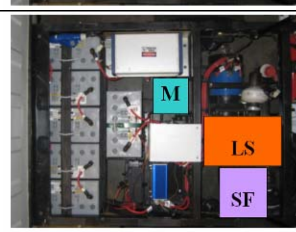
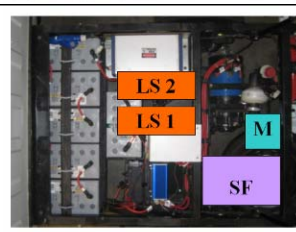
	External view	Under Truck Bed	Details
Design Concept 1			Plastic gasoline container, extend original hinge, manual lever
Design Concept 2			1 hydraulic reservoir, extended frame (bolted), touch sensor
Design Concept 3			2 small hydraulic reservoirs, no hinge redesign, button on instrument panel
Design Concept 4			Small low profile automobile gas tank, triangular bracket, touch sensor
Design Concept 5			2 small hydraulic reservoirs, extended frame (welded), manual lever

Figure 7: Five Selected Design Concepts

Using the Morphological chart as a guide, each various concept was evaluated and considered. Concepts were eliminated as they were found to be in conflict with some of our customer specifications, or were determined to not fully fulfill the respective function. The main limiting factor was the placement of the high-side accumulators. These were the largest components, so all other component placement was dependent upon the location of the high-side accumulators. It was decided that the high-side accumulators would be placed underneath the trunk bed as moving the truck bed backwards or placing the high-side accumulators vertically was not a good choice because the aesthetics of the vehicle would be compromised. Also, accumulators in the truck bed reduces the functionality of the vehicle, as it reduces cargo space and would increase the overall force needed to lift the truck bed to access the vehicle components.

For the storage of low-pressure fluid, the low-side reservoir needed to be compatible with the hydraulic fluid and easy to mount. Therefore, the gasoline container was not a good choice due to the difficulty in mounting due to the thin, plastic walls. The low profile tank was eliminated because it was expensive and wasn't made specifically for our intended application. The selection between using one or two hydraulic reservoirs was more difficult because both options were similar in ease of mounting and material compatibility however using only one large hydraulic reservoir is a better choice due to limited space and the effects of cavitation caused by draining one reservoir to the other.

In order to preserve serviceability of the vehicle, the final layout must maximize the amount of space near the motor; this allows for future semesters to have sufficient space to couple the hydraulic system to the motor. This layout must keep the batteries and electrical components accessible so that they can still be serviced. The only layout to meet all these requirements consists of removing the spare tire and trying to fit as many of the hydraulic components into that space without compromising accessibility.

It was decided to remove the spare tire from its original location under the truck bed because it opened up a substantial amount of space for the hydraulic system to be installed. It was also determined that the spare tire should still be present on the vehicle to ensure functionality and passenger safety. The spare tire will be attached to the rear of the truck bed, similar to a Jeep®. This is the most aesthetically pleasing solution, as simply leaving it in the truck bed would reduce cargo space.

Lastly, it was decided to use touch sensors on the brake and accelerator pedals because it ensures ease of use. A button on the dashboard, or a manual lever present the obstacle that this is another action that the driver will have to control in order to properly operate the vehicle. It is expected that the hydraulic launch will be utilized often in the driving process, especially in city driving conditions, therefore it is easiest for the launch to be integrated into the already present foot controls.

7.1 Pugh Chart

A Pugh chart, located in Table 3 on page 13, was created to help validate which concept was the best among the options. In the Pugh chart, each concept was evaluated based on the customer requirements and was given a rating of 1 or -1 representing a positive contribution or a negative contribution, respectively. Concept 1 was chosen as the datum, or the average design, because it was the simplest design in terms of features and complexities and the rest of the concepts were rated against this concept. The concept that had the highest weighted total compared to this datum is considered the best fit for our criteria. The Pugh chart confirmed that the two best concepts were Concept 2 and Concept 5. All of the customer requirements garnered the same rating in the Pugh chart besides reliable components and efficiency in plumbing. Concept 5 has a negative effect on reliability because it has two low-side accumulators instead of one. Two low-side accumulators translates into more tubing, therefore more efficiency losses, higher possibility of leaks and cavitation in the system due to draining from one reservoir to the other. Thus it was determined that Concept 2 would be the best selection with only one low-side reservoir.

Customer Requirements	Weights	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Transferability to future semesters	8	0	1	1	1	1
Comfortable feel during acceleration	4	0	1	1	1	1
Sufficient acceleration to top speed	4	0	1	1	1	1
Efficiency in plumbing	7	0	1	-1	-1	-1
Lightweight	1	0	1	-1	1	1
Reliable components	8	0	1	-1	-1	-1
Aesthetics	9	0	-1	1	-1	-1
Safety	5	0	1	-1	-1	1
Easy to use	4	0	1	-1	1	1
Easy to service	3	0	1	-1	1	1
Maintains vehicle function	3	0	1	1	1	1
Total		0	9	-1	3	5

Table 3: Pugh Chart

8 SELECTED CONCEPT

The selected concept show in Figure 8 on page 14 is the final design selection as modeled after Concept 2. This concept uses one hydraulic reservoir, requires vertically extending the truck bed, and touch sensors for driver control on the brake and accelerator pedals.

Raising the trunk bed by 7.5 inches will provide enough space to fit all the components of the hydraulic system neatly underneath the truck bed. Metal tubing in all four corners will be used to raise the truck bed. The tubing in the rear will be used to mount the hinges of the truck bed, while the tubing in the front will act support the truck bed when it is closed. These will all be bolted to the original frame.

Due to the length of the high-side accumulators, they can only be mounted directly under the truck bed along the outside perimeter of the vehicle frame. Each accumulator will be secured with a bracket on each end. The low-side accumulator will be secured to the car frame via a bracketed metal plate. The selection of the tank is limited in height by the truck bed, in width by the high-side accumulators, and in length by the batteries which need to be accessible for maintenance. A baffle will be placed into the reservoir to help reduce churning of the liquid and ensure that air bubbles are not drawn out of the tank and into either the regenerative brake pump or the slow-fill pump. This configuration leaves space underneath the reservoir near the drive axle, which allows flexibility for future semesters to couple the hydraulic motor to the vehicle.

The slow-fill pump will be placed at the rear of the vehicle as indicated in the layout. The pump will also be secured to the car frame with a bracket using bolts. Due to the size of the slow-fill pump, the spare tire must be removed from its original location under the truck bed. In this design, the spare tire will be remounted on the back of the truck bed, similar to a Jeep®. The motor will be placed next to the original electric motor that currently powers the Xebra. This motor has already been pre-selected and purchased by the EPA. The valves will be placed towards the rear of the car next to the electric motor. The sensors on the accelerator and brake pedals will be touch activated to control the hydraulic system. These sensors streamline actuating the hydraulic system into normal operation of the vehicle.

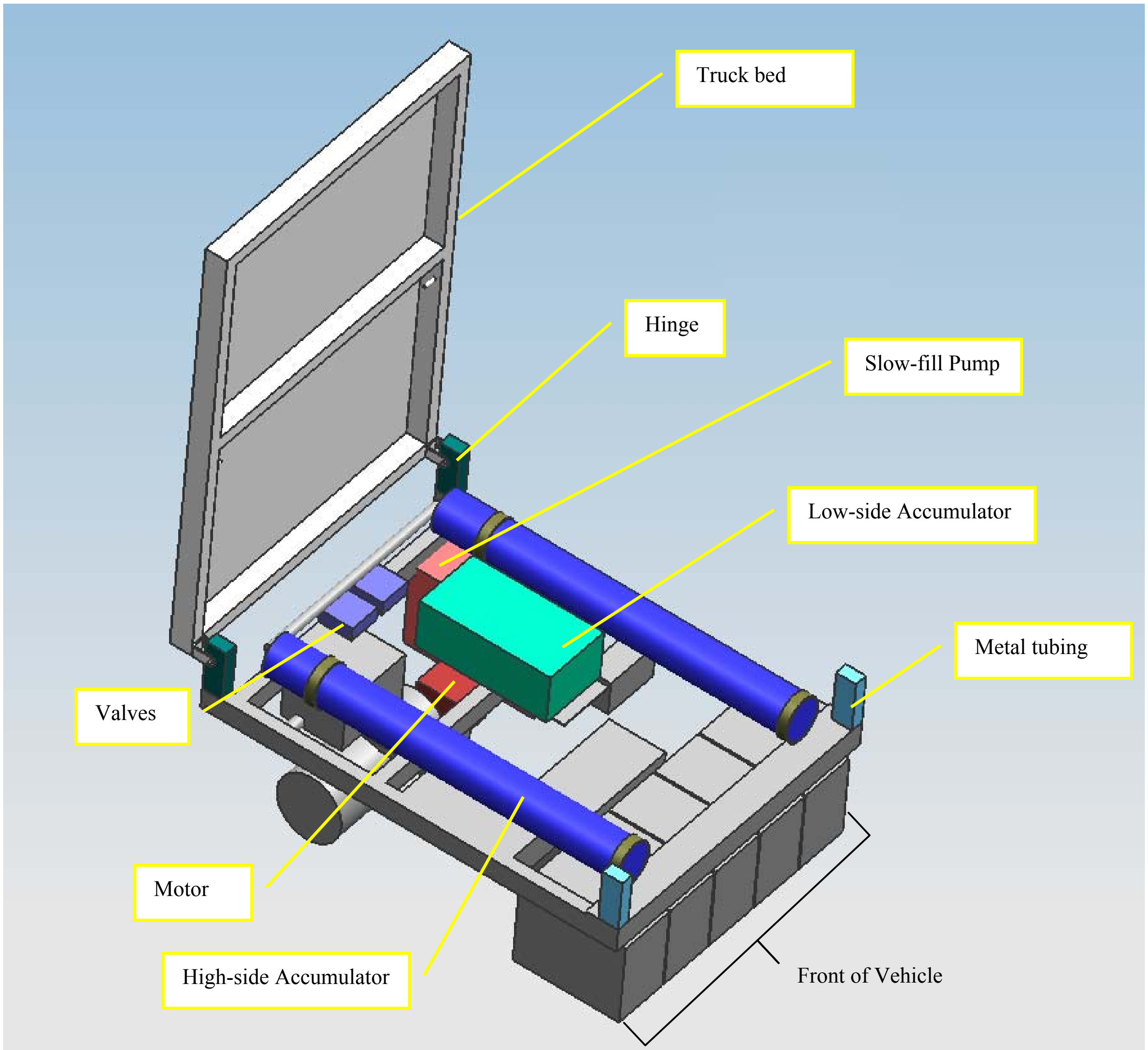


Figure 8: CAD Model of Final Concept Layout

9 ENGINEERING ANALYSIS

The following section provides information about the key variables of the finalized design layout.

9.1 Qualitative Analysis

This section evaluates the final design including the impact that the Xebra will have on the environment when completed and the manufacturability of our design using key qualitative analysis tools.

9.1.1 Design for Environment (DFE) Analysis

The final product must take into account the impact of its use on the environment. There are five guidelines that our design achieves including: new concept development, physical optimization, optimizing material use, reducing impact during use, and optimizing end-of-life systems.

- **New Concept Development:** As a finished product, the Xebra will be the world's first hydraulic-electric hybrid.
- **Physical Optimization:** By adding the hydraulic-launch system, the reliability of the Xebra as well as the range per charge will both increase, thus optimizing the overall vehicle.
- **Reducing Impact During Use:** There is lower energy consumption of the batteries with the addition of the launch system as well as elimination of the use of consumables such as gasoline.
- **Optimizing Material Use:** Replacing the hydraulic fluid is rare and the decreased battery use will lead to longer battery life, thus reducing the amount of materials that need to be used and replaced.
- **Optimizing End-of-Life Systems:** At the end of the Xebra's life, most of the components will be able to be recycled, as the vehicle is made mostly of steel and the components are easy to disassemble. Such environmental considerations help to create a design that is sustainable.

9.1.2 Design for Manufacturing Assembly (DFMA) Analysis

With the focus of our project being on the installation of the hydraulic components, it is very important to account for manufacturability in our final design. We were also limited in this respect because all of the components in our design are purchased, therefore we have no control over the manufacturing assembly of them and we can only account for how we install them into the Xebra. To do this, we designed for the following: assembly system, part insertion, joining of the components, sheet metal forming, and machining. Machining and joining of the components are the main guidelines of concentration for the manufacturing of our system.

- **Assembly System:** By standardizing the bolt sizes for the installation of the components, we will reduce the part variety and thus homogenize hole size and ease the manufacturing process
- **Part Insertion:** We will add alignment and directional features during installation such as grooves or lips on brackets so that the components can be assembled and disassembled in the future with ease
- **Joining of the Components:** We will place the components in areas so that they can be accessed by tools. To aid in joining the components with greater ease, the hydraulic fittings should be standard sizes and specialized to minimize the number of fittings needed between sizes. Also, constraining the high-side accumulators is critical as over-constraining them can lead to piston damage and possible failure if they bend.
- **Sheet Metal Formation:** We had several concepts for the hinge redesign, therefore the final design needed to be chosen such that holes near bends, corners and edges, which adds stress, on the hinge can be avoided.
- **Machining:** This requires that the brackets and other mounts need to be manufactured using standard material shapes and sizes instead of creating and machining our own designs.

9.1.3 Failure Mode and Effect Analysis (FMEA) Chart

A Failure Mode and Effect Analysis (FMEA) Chart was created for the modifications added to the Xebra. This included all of the major components of the hydraulic system, as well as the redesigned hinge. For the entire chart, please see Appendix C. Table 4 on page 17 shows the portion of this chart for the hinge design and the hydraulic fittings. We filled this chart out by first determining all of the components in our design and the ways in which each could fail. The severity, occurrence and detection of each failure mode was rated on a scale between 1 and 10. A high severity indicates a high effect that a failure would have on that component. A high occurrence would mean that the likelihood of this failure is high and a large detection means that the failure is easy to detect. These numbers were each estimated based on our knowledge of the failures that were likely to occur.

The severity, occurrence, and detection information is used to calculate the risk priority number (RPN). Those components with the highest RPN values become the areas of focus to improve the design in an effort to reduce these numbers. Once actions have been taken to reduce these numbers, a new RPN value can be completed. For our final design, those components with the highest RPN values are the material yielding of the hinge from overloading, leaking of fluid from the hydraulic fittings, and the loosening of the fittings over time. The recommended actions were used to help reduce these RPN numbers and reduce the likelihood of failure of these components.

For the hinge, the main failure mode of concern was fracture, especially when the truck bed is fully open. The potential effects of such a failure could injure the user or could cause catastrophic damage to the hydraulic components. The severity of both of these incidents was rated as extremely high because the high pressures present in the system and the weight of the truck bed could cause serious damage. There are several mechanisms of failure if a fracture occurs. The main causes would be buckling due to a bending moment, material yield from overloading, fatigue due to cyclic loading, and misalignment from improper installation. The failure most likely to occur is the material yield from overloading and misalignment. Of these failure modes, the buckling due to a bending moment is the least likely to be detected. All of these mechanisms of failure are currently being controlled and prevented by a force analysis completed before manufacturing the prototype. Additional recommended actions include adding a cross-brace to the design for additional support, or performing durability tests, especially if the design is going to be used for large-scale implementation.

The hydraulic fittings were also an important area to consider for the failure mode and effect analysis. These fittings will connect all of the hydraulic components together, therefore the main failure modes of concern are leaks, corrosion, or the loosening of the fittings over time. The severity of all of these failure modes are marked as moderate because the effect includes only a loss in efficiency of the system, which isn't as important as a safety concern. While the hydraulic fluid can be dangerous to humans at high pressures, a leak will not cause fatality to the user or greatly impact the condition of the surrounding components. Some causes of the hydraulic fitting failure can be attributed to damaged threads and beveled edges on the fittings, or improper installation. The occurrence of such items is high unless extreme caution is taken during installation. The controls that are being implemented to help prevent such failures is conducting physical inspections of the fittings during installation, and using a hand pump to check for leaks throughout the entire system after installation. Leaks are easy to detect because you can visibly check for these, however corrosion is difficult to detect before the fitting fails. Some additional recommended actions to help further prevent such failures would be to take extreme care when handling the fittings, and to use a torque wrench during installation to ensure the fittings are being tightened to the correct specification.

Part	Function	Potential Failure Mode	Potential Effects of Failure	Severity (S)	Potential Causes/Mechanisms of Failure	Occurence (O)	Current Design Controls/Tests	Detection (D)	Recommended Actions	RPN	New S	New O	New D	New RPN
Hinge	Support load of truck bed	Fracture	Danger to user and other components	10	Buckle due to bending moment	2	Force Analysis	8	Add cross-brace to design	160	10	2	6	120
				10	Fatigue due to cyclic loading and crack propagation	2	Force Analysis	3	Conduct durability test	60	10	2	1	20
				10	Material yield from overloading	4	Force Analysis	6	Conduct durability test	240	10	4	3	120
				10	Misalignment from improper installment	5	Physical Inspection	2	Install within tolerances	100	7	3	2	42
				10	Unstable due to unbalanced load	2	Force Analysis	2	Add cross-brace to design	40	7	2	2	28
Hydraulic Fittings	Connect components	Leak fluid	Reduce efficiency	4	Damaged threads and beveled edges	9	Physical Inspection	5	Handle properly	180	4	2	5	40
		Corrosion	Leak fluid	4	Degradation of material	1	Manufacturer Inspected	10	None	40	4	1	10	40
		Loosen over time	Leak fluid	4	Damaged threads and beveled edges	9	Physical Inspection	5	Handle properly	180	4	2	5	40
				4	Insufficient tightening during installation	8	Hand pump check for leaks	1	Torque to spec	32	2	4	1	8

Table 4: FMEA Chart for Hinge and Hydraulic Fittings

9.2 Quantitative Analysis

This section evaluates the final design using quantitative analysis of the key variables. The purpose of this analysis is to account for various losses in the hydraulic system to finalize the amount of fluid that will be needed for one acceleration. This calculation will verify that the high-side and low-side accumulators are large enough to properly store the amount of fluid that will be needed in the system. This section also evaluates our hinge redesign based on a force analysis and the results of the preliminary baseline performance test.

9.2.1 Air Drag Calculations

The maximum speed that the hydraulic system accelerates the Xebra to is 27 mph, or v_{ss} = 12.1 m/s. The maximum drag effects that the system needs to overcome occur at this speed. Using the Bosch handbook for calculations [16], the energy due to drag on the vehicle was interpolated to be 1.60 kW/m^2 using a vehicle frontal area of 2.07 m^2. As a result, the maximum power to overcome drag was found to be P_d = 1.65 kW. Using Eq. 1 and 2, the average acceleration was calculated to be, $a_{avr.}$ = 2.16 m/s^2, with an acceleration time of t = 5.60 seconds.

$$a_{avr.} = \frac{6E_r}{M\pi D} - \frac{2P_d}{Mv_{ss}} \quad \text{Eq. 1} \qquad\qquad t = \frac{v_{ss}}{a_{avr.}} \quad \text{Eq. 2}$$

Finally, the energy loss due to drag, E_d, was found to be 9.25 kJ using Eq. 3. This means that using Eq. 4, 85.2 kJ is required from the hydraulic system, thus requiring a volume of 4.14 L of hydraulic fluid for one acceleration. This volume is 12% larger than that of our preliminary calculations which did not take drag effects into account.

$$E_d = P_d t \quad \text{Eq. 3} \qquad E_h = \frac{SE_d}{\pi D / 6} \quad \text{Eq. 4}$$

9.2.2 Flow Rate Calculations

The maximum flow rate of the fluid during acceleration is the flow rate when the vehicle speed is 27 mph. The hydraulic motor's rotational speed, ω_m was found to be 67.2 revolutions per second with Eq. 5 using v_{ss}, tire diameter of 13.5 inches and a gear ratio of 6:1. This speed is equivalent to 4030 rpm. Since the motor uses 22 cc per revolution, the volumetric flow rate was found to be 23.4 gallons per minute.

$$\omega_m = \frac{6v_{vehicle}}{r_{tire}} \quad \text{Eq. 5}$$

Calculations for the flow rate, $\dot{V}$ as a function of the fluid velocity, V, and time, t, during braking where found using Eq. 6.

$$\dot{V} = \frac{V}{t} \quad \text{Eq. 6}$$

For the regenerative brake pump, we assumed that the vehicle will be braking from 27 mph for 2 seconds, resulting in an average flow rate of 29.3 gallon per minute. The pump uses 33cc per revolution, thus creating an average rotational speed of 3360 rpm during braking. If braking was started from higher than 27 mph or for a time shorter than 2 seconds, then the pump will yield a higher flow rate. Velocity of the fluid was found to be 2.92 m/s in the tubing near the motor and 3.64 m/s in the tubing near the pump.

9.2.3 Plumbing Efficiency Calculations

Pressure losses through the hydraulic system are inevitable and occur due to various parameters such as fitting geometry and hydraulic hose length and can be calculated using basic fluid dynamic formulas [6]. This is important because pressure losses translate to more fluid needed in the system. To calculate the pressure losses through the plumbing of our system, we first had to decide what kinds of fittings we would need, and the quantity of each. We estimated that we would need the following for our system:

- 17 - 90° sharp bends (K_L= 1.5)
- 5 – Tee branches (K_L = 2)
- 2 – Tee lines (K_L = 0.9)
- 2 – Check valves (K_L = 2)

We found the loss coefficient values, K_L, using a fluid dynamics textbook. Then, using Eq. 8 through 10, we were able to calculate the pressure losses through the system.

$$V_2 = \frac{V_1 A_1}{A_2} \quad \text{Eq. 8}$$

where V_2 is the velocity of the fluid through the fitting, V_1 is the velocity of the fluid out of the high-side accumulators, A_1 is the area of the piston in the high-side accumulator, and A_2 is the cross-sectional area of the fittings.

$$h_L = K_L \frac{V_2^2}{2g} \qquad \text{Eq. 9}$$

where h_L is the head (pressure) in the fittings, K_L is the loss coefficient, and g is gravity.

$$\Delta p = \gamma h_L \qquad \text{Eq. 10}$$

where Δp is the pressure loss through the fitting and γ is the specific gravity of the hydraulic fluid. After calculating the pressure loss in the fluid, we added a safety factor of 2 to account for losses in the hydraulic lines and any other additional losses. This leads to a pressure loss of 85 psi in the system when JIC-16 size fittings are used. JIC-16 refers to a fitting that has a diameter of 16/16 inches. These size fittings have minimal pressure loss without compromising the flow rate.

Using this value of 85 psi and also the losses associated with the drag losses, we recalculated the fluid needed in the system to be 4.26 L, a 13% increase from the value found in the preliminary calculations. This is approximately half of the 8 L that the high-side accumulators are able to pressurize at one time. Based on this value, we have determined that a low-side accumulator of 18.9 L (5 gallons) will be large enough to accommodate four times the amount of fluid needed for the system. Four times the amount of fluid allows for better hydraulic performance, because it helps to minimize the amount of air present in the system, thus reducing the risk of cavitation in the hydraulic motor and pump.

9.2.4 Force Analysis on Redesigned Hinge

A force analysis was completed on the redesigned hinge to ensure that it would not fail under normal loading conditions. The redesigned hinge is shown in Figure 9. The new design must be able to withstand the weight of the truck bed, which was estimated at 200 lbs, and all of the resulting bending moments at the various positions of the truck bed. The particular load of concern was that on the metal plate holding the tubing to the vehicle frame when the truck bed was completely open. The weight of the truck bed creates a bending moment on the entire hinge, which could potentially cause material fracture in the plate. Force analysis was completed using the mechanical properties of steel [17] and it was determined that the uppermost bolt in the hinge design would be most likely to fail.

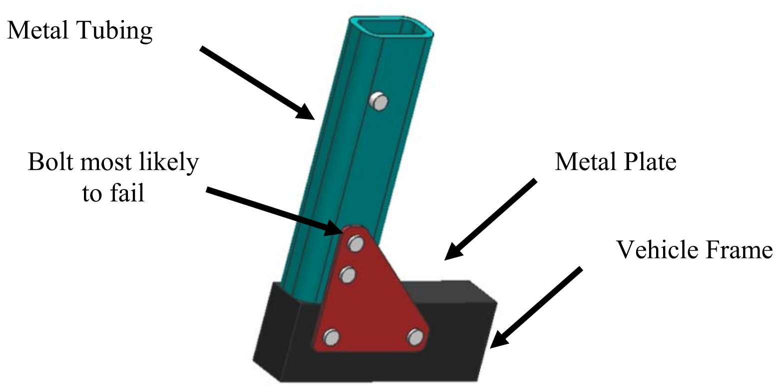


Figure 9: CAD Model of Final Concept Layout

The new hinge must be able to withstand the load of the truck bed and its contents. The weight of the empty truck bed was estimated using the density of steel and the volume of the truck bed. The truck bed was estimated to be a cube with four sides and a bottom, all of equal thickness. Figure 10 shows the estimated shape and applicable dimensions.

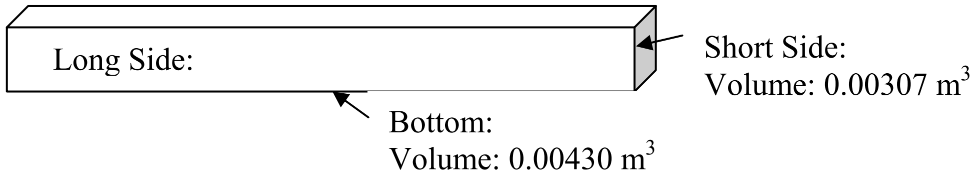


Figure 10: Estimated Truck Bed Shape

Using this information, the total volume of the truck bed was calculated using Equation 11.

$$V_{total} = 2V_{long} + 2V_{short} + V_{bottom} \quad \text{Eq. 11}$$

V_{total} was found to be 0.187 m^3. Using this volume and the density of steel equal to 7840 kg/m^3, Equation 12 was used to determine a mass of 90.5 kg or 200 lbs for the truck bed.

$$m = \rho V \quad \text{Eq. 12}$$

The redesigned hinge consists of a piece of steel tubing which is attached to the vehicle frame via a steel plate. These two components are bolted together. The hinge of the truck bed is then connected using a pin at the top of the steel tubing. There are two main types of loading that must be accounted for on the redesigned hinge. When the truck bed is closed, the four posts must be able to support the load of the truck bed and its contents. Buckling of these posts when the truck bed is closed is not a concern because the load will be carried by the steel tubing which has a thickness of 0.25", more than sufficient to withstand a load of 50 pounds per post.

The main loading condition of concern is a bending moment caused by the weight of the truck bed when the bed is rotated open. The free body diagram for this situation is shown in Figure 11. It was assumed that the truck bed was at an 80° angle with respect to the ground when completely opened. The plate attached to the metal tubing was estimated as a square. The portion of the weight vector, W, in the x-direction is the portion of the force that will create the bending moment that could cause failure at the hinge. The portion of the weight in the y-direction is not of concern because if a moment was created from this force, the truck bed would close, as the hinge is designed to rotate in this direction. Using Equations 13 and 14, the weight vector in the x-direction, W_x was calculated.

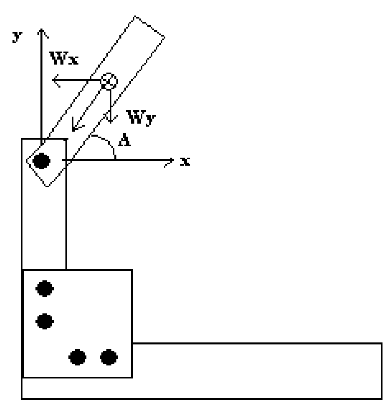


Figure 11: Free Body Diagram of Redesigned Hinge

$$W = mg = 887N \quad \text{Eq. 13}$$

$$W_x = W\cos(A) = 154N \quad \text{Eq. 14}$$

Once this force was known, the forces acting on the metal tubing could be calculated by summing the moments about the bottom left bolt and the forces in the x-direction. Figure 12 shows the free body diagram of the forces acting on the tubing, and Equations 15 and 16 show the sum of the forces. It is important to note that since there are two posts, the W_x value of 154N must be divided by 4 as the weight is equally distributed amongst the two rear posts, each consisting of two plates. The force from the weight in the x-direction is found to be 38.5N per post.

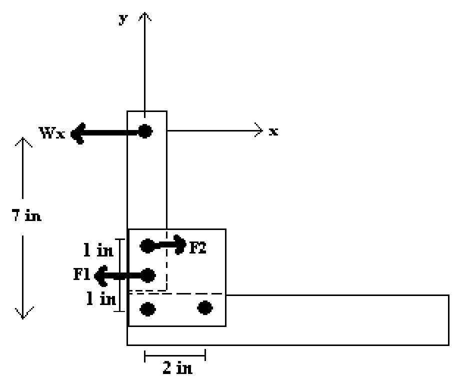


Figure 12: Free Body Diagram of Metal Tubing

$$\sum M_{LeftBolt} : 0 = 7W_x + F_1 - 2F_2 \quad \text{Eq. 15}$$

$$\sum F_{x-direction} : 0 = -W_x + F_2 - F_1 \quad \text{Eq. 16}$$

$$F_1 = 192.5N \qquad F_2 = 231N$$

The forces on the tubing are equal in magnitude to the forces acting on the plate, but opposite in direction, as shown in Figure 13.

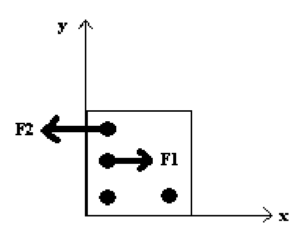


Figure 13: Free Body Diagram of Plate

For the force analysis of the plate, the focus is on the top bolt. This is because F_2 is larger than F_1. We do not focus on the bolts attaching the plate to the Xebra frame because the support from the frame is strong and it is unlikely that the bolts here will fail. By analyzing and designing based on the bolt and hole at the top of the plate, it can be ensured that if the design criteria are met at this "worst-case" position, the rest of the plate will be structurally sufficient as well.

To analyze the stress at the contact of the hole and bolt, Equations 17 through 21 were utilized. These equations calculate the effective contact area between the bolt and the hole. This area can then be used with the F_2 to determine the stress at that point. For this analysis, 0.5" diameter bolts and a hole with a diameter of 0.55" were assumed. The thickness *t* of the plate was assumed to be 0.25". The Young's Modulus, *E*, of steel is 200 GPa.

$$C_E = 2\left(\frac{1-\upsilon}{E}\right) \quad \text{Eq. 17} \qquad K_d = \frac{D_1 D_2}{D_1 - D_2} \quad \text{Eq. 18}$$

$$b = \sqrt{\frac{F_2 C_E K_D}{t}} \quad \text{Eq. 19} \qquad A = bt \quad \text{Eq. 20} \qquad \sigma = \frac{F_2}{A} \quad \text{Eq. 21}$$

Using equations for determining the effective contact area between a bolt and a hole [18], the maximum stress at this bolt was determined to be 122.3 MPa. The yield strength of steel is 250 MPa, therefore the current design has a safety factor of 2.04. This confirms that the design will be sufficient for supporting the truck bed when it is fully opened.

The design was further validated by performing a finite element analysis of the plate. The result of this is show in Figure 14. As is shown in this figure, the maximum stress occurs at the top of the plate and around the upper bolt holes, but the stresses are not high enough to cause it to yield.

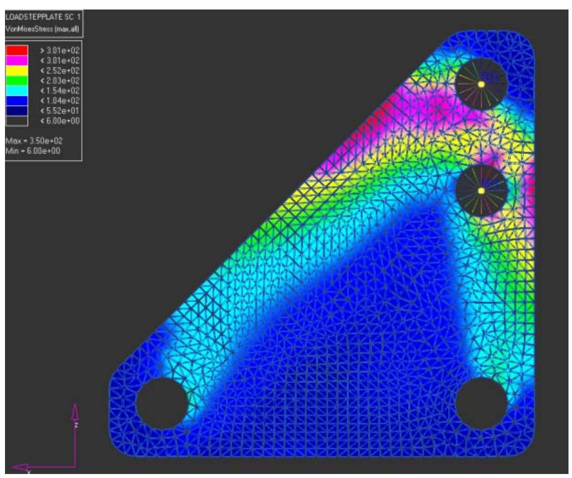


Figure 14: Finite Analysis of Steel Plate

9.2.5 Baseline Performance Test Analysis

To quantify the improvements that will be made to the Xebra, it is important to perform a baseline performance test before and after the hydraulic system has been installed into the vehicle. The baseline tests will include acceleration rates, efficiency of the batteries, as well as overall performance of the vehicle. In the first stages of the project, we contacted a local company, Lotus Engineering to help us with the tests. Lotus Engineering had the correct equipment to perform our desired tests.

9.2.5.1 Coast-down Test

Before we could baseline test the Xebra, coast-down tests had to be performed first in order to calculate the correct road load coefficients. The road load coefficients are based upon various parameters such as the weight of the vehicle and driver, pressure in the tires, as well as coast-down times. These values are then used in the program that runs the dynamometer to more closely simulate the Xebra driving on an actual road.

The coast-down tests were performed to the SAE specification J2263 with the help of Larry Webster from Car and Driver Magazine. This specification needed to be adjusted to accommodate the limitations of the Xebra vehicle. In the SAE J2263 standard, the vehicle must be driven for thirty minutes to ensure the tires are warmed up; however this is not feasible for the Xebra, which only has a driving range of about 20 miles per charge. Additionally, coast-down data is usually taken starting at 40 mph, however the Xebra's maximum speed is 35 mph [20].

Larry set up time at the Chrysler Proving Grounds in Chelsea, Michigan for us to perform the coast-down tests on the straightaway road. He also provided us with a GPS tracking unit to record the data we needed. The temperature during the test was approximately 55°F and each tire was at a pressure of 36 psi. The weight of the driver was around 165 lbs. This data was sent to Lotus Engineering who analyzed it and calculated the road load coefficients for us. The road load coefficients are shown in Eq. 22:

$$F = 30.37 + 0.3009v + 0.02076v^2 \qquad \text{Eq. 22}$$

where 30.37 is in lbs, 0.3009 is in lbs/mph and 0.02076 is in lbs/mph^2.

9.2.5.2 Baseline Performance Test

After calculating the road load coefficients, the baseline tests could be performed. The equation from the coast-down tests was used to calibrate the chassis dynamometer to more closely simulate actual driving conditions by taking into account air drag and frictional losses. The Xebra is designed to drive at lower speeds and shorter distances, therefore we chose to perform the HOT505 test which is an EPA standard test that simulates city driving. A plot of velocity against time for the HOT505 test can be seen in Figure 15, which shows the large amount of accelerations and decelerations associated with city driving. The test was scaled down to accommodate the limitations of the Xebra's top speed of 35 mph.

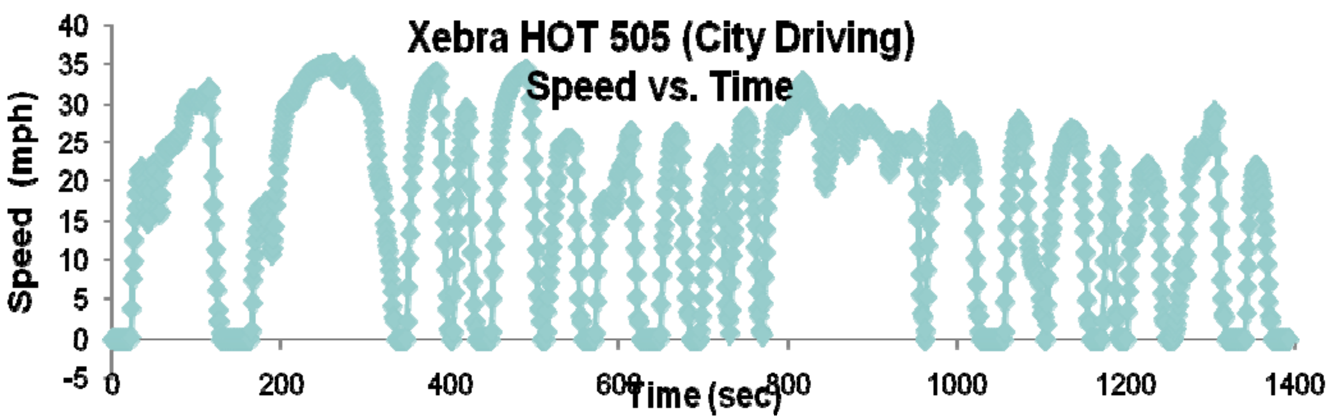


Figure 15: HOT505 test of speed against time to simulate city driving conditions

Parameter	Value
Total Vehicle Range	15.4 ± 0.1 miles
Maximum Velocity	35.00 ± 0.05 mph
Maximum Acceleration	2.19 ± 0.02 m/s^2
Maximum Power	15.4 ± 0.01 kW

Table 5: Xebra Performance Characteristics during Baseline Testing

The Xebra was able to perform two full HOT505 tests and a partial third test on one full battery charge. Table 5 shows the performance characteristics determined from these HOT505 tests. It is interesting to note that the calculated total range of the vehicle, 15.4 miles per charge, is less than what is noted in the Xebra owner's manual.

In addition to these characteristics, the total energy of the vehicle for a single charge was calculated. This was completed using Eq. 23, which is the integration of the power over time. Using this equation, the total energy of the vehicle for a single charge was determined to be 10,800 ± 540 kJ which averages to about 4,700 kJ of energy for a single HOT505 test.

$$P = \int (VI)dt = \sum (VI) \qquad \text{Eq. 23}$$

In addition to the energy provided by the batteries, the HOT505 data was also used to calculate the battery efficiency during positive accelerations. This was calculated using Eq. 24, which takes the kinetic and drag energy requirements from the vehicle and divides it by the output energy of the batteries during positive accelerations. The result is that the batteries were only 49% efficient during acceleration.

$$\eta_{Battery} = \frac{E_{Drag} + E_{Kinetic}}{E_{Battery}} * 100\% \qquad \text{Eq. 24}$$

Lastly, Figure 16 shows a plot of the maximum power outputs over time, during each HOT505 test. As is seen in the graph, with each consecutive test, the maximum power decreased. The third test was not completed, as the batteries ran out of power. All of these performance characteristics will be recalculated via a new set of baseline tests once the entire hydraulic launch system has been coupled to the vehicle.

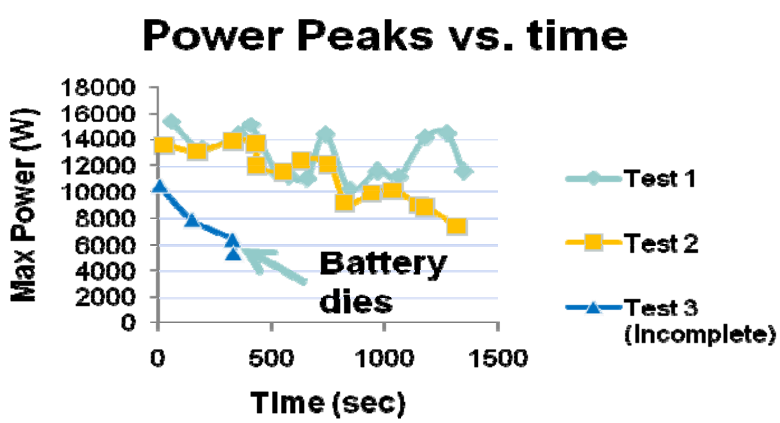


Figure 16: Maximum Power for Each HOT-505 Test

10 FINAL DESIGN LAYOUT

This section describes the final design layout of the project.

10.1 Changes to Concept Layout

Our final design layout incorporated many of the design features chosen in our selected concept with two key changes. These key changes include the placement of the low-side accumulator and the location of the motor and pump. Figure 17 is an engineering drawing containing the final design layout in orthographic and isometric views. To obtain the relative component positions to the vehicle frame, note that the metal tubing at the end of the vehicle represents the location of the original truck bed hinges.

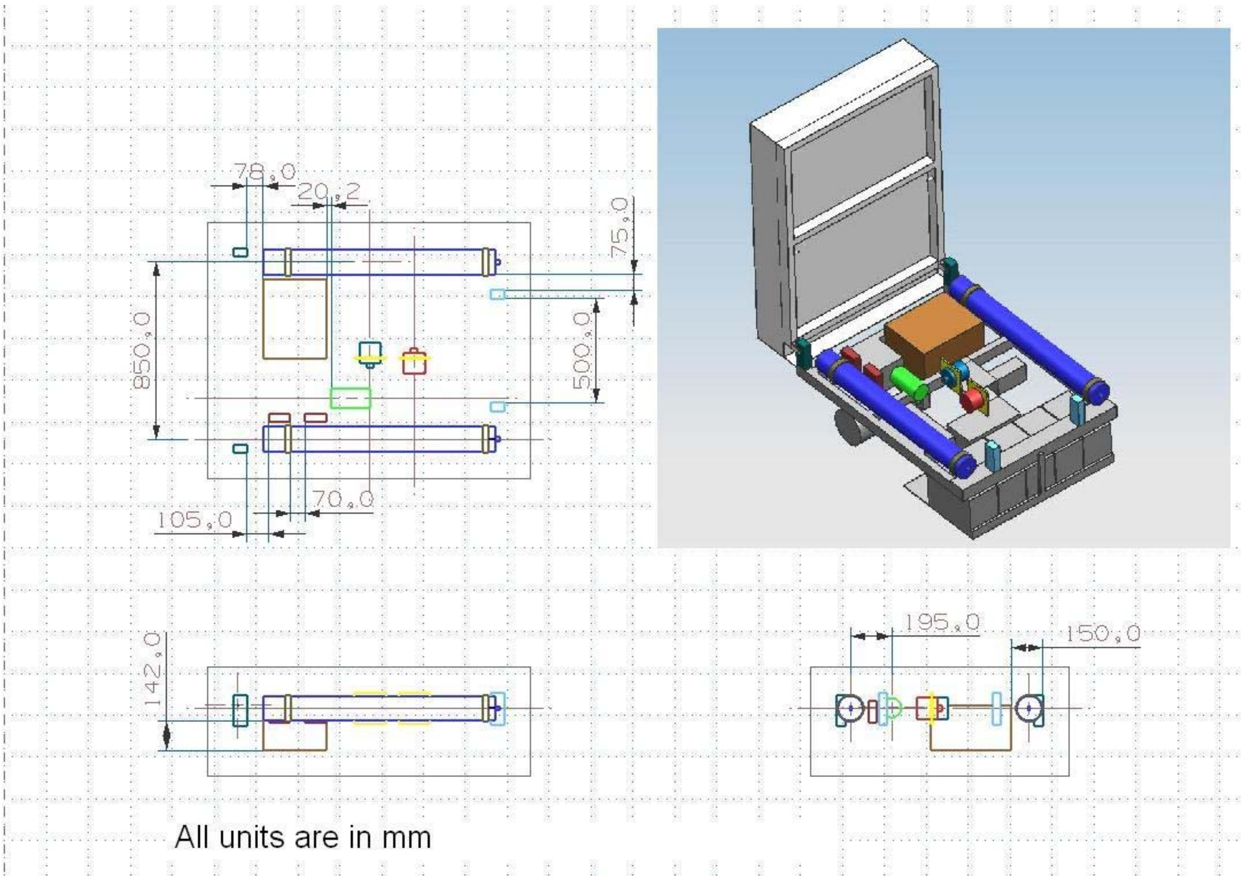


Figure 17: Engineering Drawing of the Hydraulic Layout

In the selected concept, the low-side accumulator was located in the space directly behind the passenger cabin and above the batteries. The hydraulic reservoirs available on the market with the correct capacity of 5 gallons did not have dimensions that would easily fit in this location. These reservoirs would require us to lift the truck bed 9 inches above its current height, which is not only the maximum amount it can be lifted, but is also aesthetically unappealing. We decided that the low-side accumulator would best fit in the space where the spare tire was originally housed. By moving the low-side accumulator here, we have the ability to recess it into the vehicle frame several inches, allowing us to lift the truck bed by only 7.5 inches. Also, there is still room underneath the reservoir for the hydraulic motor to be coupled to the electric motor in future semesters.

Ideally, the low-side accumulator should be located behind the hydraulic regenerative pump, as far back on the vehicle as possible. This helps to reduce the negative effects on efficiency that the momentum of the fluid during braking causes. This adds flexibility for future semesters because it allows the regenerative brakes to be coupled to either the front or rear wheels of the vehicle without significant effects. The slow-fill pump that we originally were going to use could only be located in the original spare tire position due to its large size. We obtained a smaller one to use, allowing us to have greater flexibility in its positioning. This permitted us to use the open space for the low-side accumulator placement, which is the optimal location in terms of regenerative brake system efficiency. The slow-fill pump was moved to the middle of the vehicle near the batteries and will be attached using bolts and a metal plate.

A major design change was the installation of the regenerative pump to the final layout. Originally, installing the pump was not in the scope of our project, but later our sponsor asked us to add the pump to demonstrate the full function of the hydraulic system. It was then decided that the pump and motor should be positioned in an easily visible location to aid in the prototype demonstration. These would both be mounted to metal plates that are bolted to the vehicle frame.

There are several components that remain the same from the original concept: the high-side accumulators are each mounted on the frame along the length of the truck and the sensors on the pedals that activate the valves are touch-sensitive. The hydraulic fittings and hoses that will be used to connect the components are size JIC-16, equipped with cable pulls and will be installed by a professional. The size of the fittings connecting the slow-fill pump to the low-side accumulator and high-side accumulators are JIC-6. The pressurizing of the fluid via the slow-fill pump requires lower flow rates, therefore a smaller diameter fitting can be used.

New additions to the design include various gauges and sensors to provide transient information. A pressure gauge will be placed at one of the high-pressure accumulators. Temperature sensors will be located on the high-side and low-side accumulators, motor, and slow-fill pump. Between the slow-fill pump and low-side accumulator, a flow meter and oil filter will be installed. The level switch will be monitoring the fluid level in the low-side accumulator. A sight glass is present on the low-side accumulator to provide information about the quality of the fluid. A Lexan shield will be mounted on the vehicle for safety purposes. No testing or operation of the hydraulic system can be conducted without the shield in place. There is a hinge down the middle for easy access to the components when the system is shut off.

10.2 Final Hinge Design

To account for the additional components in the final design it is required that the vehicle frame at the hinge be vertically extended 7.5 inches. The three dimensional and engineering drawings of this final design are shown in Figure 18 (page 27). We chose to use metal tubing to accomplish this task. There are two possible ways of securing the tubing to the frame: welding or bolting. Due to the dangers of welding near batteries, bolting the tubing to the frame was our safest option. Based on our preliminary design and force analysis, we chose to use ¼" thick steel plate for the attachment. For the metal tubing that will raise the hinge, a plate will be bolted to both sides of a metal tube with two bolts to secure the plate to the vehicle frame and two more to secure the plate to the metal tubing. The truck bed will bolt to the metal tubing the same way that it was secured originally: using a single pin through the frame. For the metal tubing supporting the other end of the truck bed, an angle rod across the vehicle frame will provide an area to bolt the metal tubing. To increase the contact area between the support and the truck bed, an additional piece of angle rod was bolted on top of and between the two pieces of metal tubing. All the metal plates, tubing, and angle rod will be cut and drilled in-house.

In the original Xebra design, the truck bed was held open by two spring-dampers. In order to mount the high-side accumulators, these spring-dampers had to be removed. Also, after the truck bed is raised the 7.5 inches, the spring-dampers will not be long enough to extend from the truck bed to the vehicle frame, therefore, a prop rod must be manufactured to hold open the truck bed. This will be made of a steel rod and will be held onto the vehicle via a hole in the angle rod used to increase the contact area where the truck bed rests.

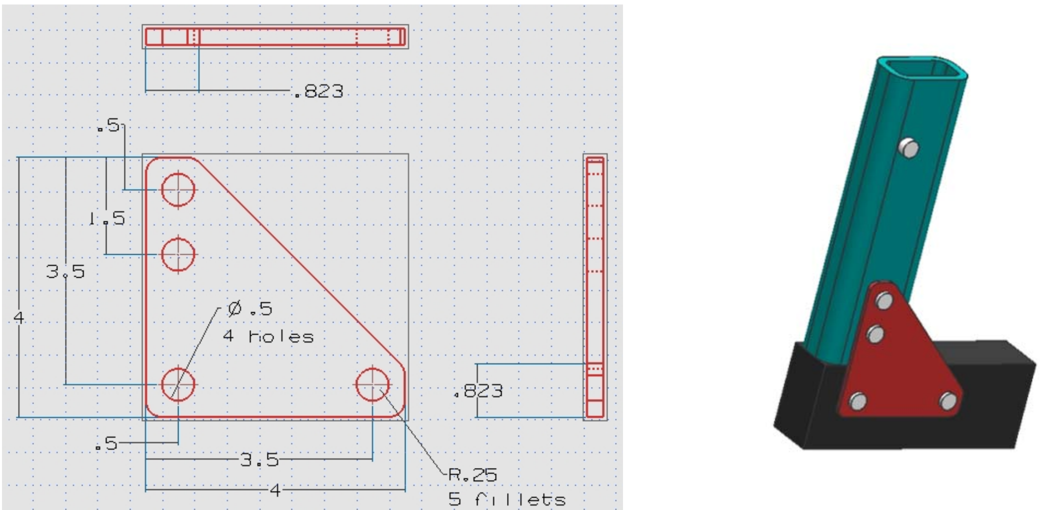


Figure 18: Dimensioned CAD Drawing of Hinge Plate

10.3 Design Changes

Although the final design of the Xebra remains the same, a few key changes were made in terms of some of the work to be completed this semester. A major change in this plan was the decision to postpone the installation of the hydraulic hoses for a future semester. The original reason to install the hose this semester was to be able to demonstrate that the slow-fill pump can pressurize the high-side accumulators, and that the motor will spin when the high-side accumulators are discharged. There were two critical reasons that led to the decision to postpone the hose installation. First, the slow-fill pump that was given to us by the EPA failed in testing by leaking internally and was not able to pump any fluid. It was also discovered that the pump did not have the capabilities to pressurize the high-side accumulators, as they have a pre-charge of 2700 psi. Furthermore, the slow-fill pump that the EPA gave us operates at 12 V. This would decrease the duration of the battery it draws from and in the long-term would damage that particular battery. Ideally the pump should draw from all six batteries or at 72 V. This type of pump currently does not exist in the market and would have to be designed in the future.

The second reason that the hoses were not installed was because the final positions of the engine and regenerative brake pump will not be determined until a future semester. Therefore, the hoses installed would only be temporary and the Hose Doctor would have to come in again to correct the hoses. This means that hundreds of dollars worth of work would have to be redone on a limited budget. Due to the cost of the Hose Doctor and slow-fill pump, both of which will need to be redone in the future, the cost of completing this task tremendously outweighs the benefits of demonstrating the vehicle. There were other ways to satisfactorily demonstrate the project, which will be talked about in the testing and demonstration plan section.

In addition to the hydraulic hose, there were two other small changes made to the final design. First, it was decided not to install the spare tire on the back of the Xebra because in the event that a future group decided to no longer mount the spare tire there, there would be a great reduction in aesthetic appeal, as there will be permanent damage to the outside body of the Xebra. The spare tire placed in the truck bed is a sufficient solution for the current stage of the project. Also, there was a small design change for the steel plates that hold the metal tubing for the redesigned hinge. A weld on the vehicle frame interfered with the original hole locations, therefore some of the holes needed to be drilled in. Also the original design had one corner of the plate removed, however this corner remains in the final design. It was not necessary to remove the corner and the added material increases the strength of the plate. For a full Engineering Change Notice of this steel plate, please see Appendix D.

10.4 Completed Prototype

Figures 19 and 20 are pictures of the completed prototype. For more pictures of the individual components, please see Appendix E.

Figure 19: Outside View of Xebra After Hinge Redesign

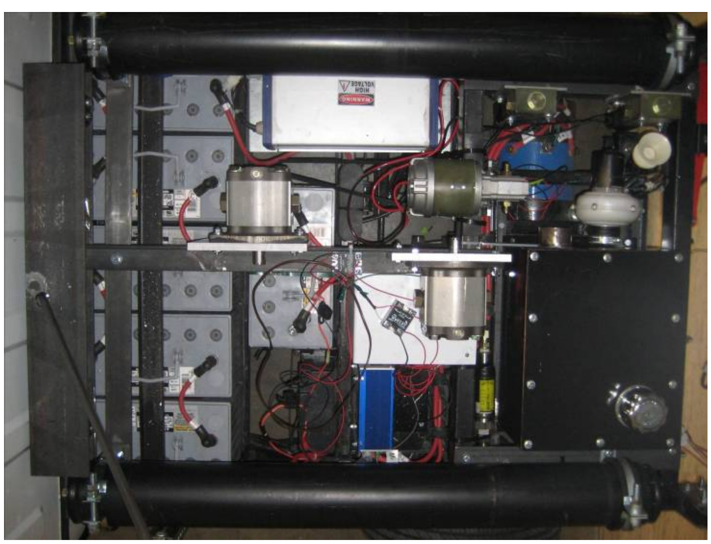


Figure 20: Under Truck Bed View of Xebra after Hydraulic Component Installation

10.5 Bill of Materials

A bill of materials has been created with a list of components, part numbers, prices, and quantity of each. It has been split up between those items purchased by our sponsor and those items purchased using our budget. The bill of materials is located in Table 6.

Parts Puchased outside the Project Budget:				
Quantity	Part Description	Purchased From	Part Number	Price (Each)
1	Motor	UM*	PGM517MA0230BM1H3ND6D6B1B1B1	$555.00
1	Pump	UM*	PGM517MA0330BM1H3ND6D6B1B1B1	$570.00
2	High-side Accumulators	UM*	ACP 10AA 800 E 1 K TE2	$587.00
2	Actuator Valves	UM*		
	Gloves	EPA**		
1	Lexan safety shield	EPA**		$828.00
1	Slow-fill pump	EPA*		
1	Flow meter before slow fill (0.5-5 Gpm)	McMaster-Carr**	4161A71	$89.90
1	Temperature sensor	McMaster-Carr**	59535K13	$11.86
2	Pressure gauges	McMaster-Carr**		$150.00
1	Bolts and metal for attachments	any hardware store	UM Machine Shop	$0.00
				$3,528.76

Parts Puchased through the Project Budget:				
1	Low-side Accumulator	Grainger	4Z980	$76.32
2	Brackets to mount accumulators	Grainger	6Z151	$127.25
1	Aeration plug	Grainger	6W387	$14.83
1	Check valve cartilage for brake pump	RHM FP	CXHA-XAN	$53.00
1	Check valve body for brake pump	RHM FP	ICM/S	$99.80
1	Check valve cartilage for slow-fill pump	RHM FP	CXDA-XAN	$17.50
1	Check valve body for slow-fill pump	RHM FP	GCI/S	$41.26
1	Tubing for brackets	any hardware store		$25.00
1	Hand-held tire pump	Meijer		$10.00
1	Car Cover	Murray's Auto Supply		$37.09
2	Door Hinges	Carpenter Brothers		$4.99
1	Bolts and Nuts	Hardware Store		$25.00
1	Fittings	Hammond Drive		$60.32
1	Oil filter	McMaster-Carr**	44185K66	$64.02
1	Car Starter Solenoid	SpeedwayMotors.com	91064043	$15.00
1	Pedal Sensor for Brake	McMaster-Carr**	7692K4 & 7692K8	$17.41
1	Pedal Sensor for Acceleration	McMaster-Carr**	7692K4 & 7692K8	$17.41
1	Electrical wires	Carpenter Brothers		$5.00
			Total:	**$711.20**
			Overall Total:	**$4,239.96**

* These parts were purchased by a previous University of Michigan team and were available at the start of the project. The costs of these parts are not included in the budget
** These parts were purchased by the EPA for the project but were not paid for through the project budget

Table 6: Bill of Materials

11 MANUFACTURING AND TESTING PLAN

The following sections will detail how the test-vehicle will be manufactured, tested, and demonstrated.

11.1 Manufacturing Plan

It is important to note that this manufacturing plan is solely for the integration of the hydraulic system into the Xebra vehicle. Manufacturing therefore will entail only brackets and mounts for installing the hydraulic components. Mass production of the Xebra as a hydraulic-electric hybrid would be much more complex and require a complete redesign of the vehicle and all of its subsystems.

The manufacturing and assembly of the prototype was performed at the University of Michigan using the student machine shop and included brackets and mounts to secure the components to the vehicle frame. Table 7 details the manufacturing procedure and completion dates. There were several revisions to this manufacturing procedure throughout the duration of the project, however this table highlights the actual procedure used. The Gantt chart for the entire project can be found in Appendix F.

Step #	Completion Date	Assembly Steps
1	11/06	Remove truck bed and excess metal on frame
2	11/12	Drill holes and mount low-side accumulator
3	11/14	Mount valves and slow-fill pump
4	11/16	Mount high-side accumulators
5	11/16	Mount motor and regenerative brake pump
6	11/19	Mount and wire hydraulic actuation system
7	11/20	Manufacture hinges
8	11/21	Install baffle for low-side accumulator
9	11/26	Mount metal tubing and plate to frame and reattach truck bed
10	11/26	Install prop rod to hold truck bed open
11	12/3	Assemble Lexan Shield

Table 7: Manufacturing Procedure

1. **Remove trunk bed and excess metal on frame:** This was completed by removing the pins that hold the truck bed to the vehicle frame. The truck bed was removed to allow for easier installation of the hydraulic components and hinges. The excess steel mounts that held the spare tire were removed using a hacksaw.

2. **Drill holes and mount low-side accumulator:** An inlet for the low-side accumulator was created using a hole saw to cut a hole into the side of the reservoir. A piece of steel stock was cut to size, drilled, tapped and welded to the hole to fit a JIC-16 hydraulic fitting. Mounting the low-side accumulator was completed by bolting it to pieces of angle rod and the frame at its location at the rear of the vehicle.

3. **Mount valves and slow-fill pump:** The valves are bolted to a piece of angle rod that is also holding one of the high-side accumulators. The slow-fill pump is attached to the vehicle frame using a metal plate and bolts.

4. **Mount high-side accumulators:** Special brackets were placed at the far ends of each high-side accumulator. These brackets were bolted to the vehicle via the frame at one end and a flat stock steel strip bolted to the vehicle using angle rod on the other end.

5. **Mount motor and regenerative brake pump:** The motor and the pump were removed from the plate that they were originally attached because it was too large for this purpose. This plate was split in two and made smaller so that the pump and motor could be mounted individually. The motor and pump were bolted to the new plates and then mounted on the vehicle frame using bolts and angle rod.

6. **Mount and wire hydraulic actuation system:** The entire system must be wired with the sensors so that the hydraulic system can be actuated via the brake and accelerator pedals. This involved

mounting the sensors on the pedals and attaching them to the valves, battery, slow fill pump, and nearest 12 V batteries. Solid-state relays and a car starter solenoid were also used to prevent sensor burnout. The complete circuit diagram for this setup can be found in Appendix G. In order to properly install the system, a hole was drilled in the floor of the cabin to allow for the passage of wires from the pedals to the electrical components under the truck bed.

7. **Manufacture hinges:** Four pieces of steel tubing were needed to raise the truck bed. The tubing at the rear of the vehicle where the truck bed hinges required two steel plates each; therefore a total of 4 plates were manufactured. The steel plates in the rear fixed the tubing to the vehicle frame via four bolts. The tubing in the front was bolted to a piece of angle rod that ran along the width of the vehicle. A large piece of angle rod was bolted to the metal tubing in the front in order to help evenly distribute the weight of the truck bed.

8. **Install baffle to low-side accumulator:** The baffle was made of a piece of 1/16" steel plate and was tack welded to the inside of the low-side accumulator across its length in between the inlet and outlet holes. The baffle has grooves cut out of the material to allow for the controlled flow of fluid within the accumulator.

9. **Mount metal tubing and plate to frame and reattach truck bed:** The truck bed was reattached by drilling the holes for the pins in the metal tubing. This will allow the truck bed to operate as before, but at a location 7.5 inches higher.

10. **Install prop rod to hold truck bed open:** The prop road was easily installed by drilling a hole in the angle rod associated with raising the truck bed, and cutting a steel rod to the proper length. The rod then props the truck bed open when placed in the underside of the truck bed and the hole in the angle rod.

11. **Lexan Shield:** The Lexan shield was manufactured in two pieces in another location. Our task was attach the two pieces together using door hinges. The Lexan shield will be used during testing to protect people in the case of an accident.

11.2 Ethical Concerns

There are some key ethical concerns that need to be addressed if this hydraulic electric vehicle were to be placed on the market for mass production. The first is that of the safety of hydraulic systems. It is extremely important that safety features are installed on the Xebra, such as emergency shut-off switches, and that the user is well-educated about the safety of hydraulic systems. Historically, implementation of hydraulic systems in vehicles has been dampened by the fear of the safety of such systems. Therefore, it is extremely important to change this preconceived notion of danger, but also properly inform the user of the exact risks associated with such a product.

Another key ethical issue is that of reporting the performance specifications of the Xebra. Electric vehicles do not achieve the same performance standards as that of a vehicle with an internal combustion engine, therefore it may be hard to compete in the market with such vehicles. It is extremely important that the performance specifications of the vehicle are accurately reported so that the actual performance of the vehicle is indicated. Idealized performance or driving range specifications may increase the initial appeal of the vehicle, but its actual in-use performance will solidify its reputation over time. This ethical concern may arise when it becomes time to market the vehicle to the general public.

Lastly, ethical issues could arise in terms of intellectual property. With the introduction of a new technology such as a hydraulic electric hybrid, it is extremely important to patent new ideas, as well as give credit to those responsible for other ideas. There is significant work in the area of hydraulics on vehicles, therefore care should be taken in recognizing who is truly responsible for which technology. Careful and concise documentation should alleviate most of the problems associated with this potential issue.

11.3 Testing and Demonstration Plan

Following the installation of the components, we completed the wiring of the actuator valves and switches. Testing of the circuitry involved pressing the sensors and verifying that the appropriate action occurred in response. When the sensor on the accelerator was activated, we listened for the “click” of the valve that will eventually control the flow of fluid through the hydraulic motor. When we activated the sensor on the brake pedal, the slow-fill pump turned on and the valve that will control the flow through hydraulic regenerative brake pump “clicked”. There were no problems during testing, but they would have presented themselves in the form of missing or incorrect actuation of the valves. Such issues could have been resolved by checking each of the connections between wires to make sure that there were no open or short circuits.

Upon completion of the manufacturing process, we had permanently installed the high-side accumulators, low side accumulator, valves and slow-fill pump and found a temporary location for the hydraulic pump and motor. The only testing that we were able to perform involved the rigidity of the bracket designs that we manufactured. We applied weight to each of the brackets to ensure that they were secure. We also tested the hinge redesign by opening and closing the truck bed to see if any noticeable increase in effort was now needed. Such an increase in effort would indicate misalignment of the hinge. In all of our testing, no failures occurred, and there was no debugging involved as each component was installed properly.

Upon completion of the entire hydraulic system in future semesters, a hand pump will be used to check for leaks to ensure the quality of the assembly. In addition, the gauges installed throughout the system and the sight glass on the low-side accumulator will help verify that the entire system performs at the expected operating conditions.

At the conclusion of the assembly and testing, the demonstration of the system will serve as a final check to the system. When the accelerator pedal is pressed, the high-side accumulators will discharge the hydraulic fluid. The pressure gauge at the high-side accumulator will confirm the pressure discharge. To verify the connection to the motor is correct, the motor will be seen spinning when the hydraulic fluid is discharged from the high-side accumulator. The fluid will then be stored in the low-side accumulator. As the brake pedal is pressed, the slow-fill pump will re-pressurize the fluid in the high-side accumulator. The pressure gauge at the high-side accumulator will confirm the pressurization. The connection through the regenerative brake pump can be verified by watching it spin slightly as the check valve naturally leaks fluid into the pump. Once the entire hydraulic system has been coupled to the vehicle, the demonstration of the system will be the same, except the success of the demonstration will manifest itself in the form of the acceleration of the Xebra.

12 DISCUSSION FOR FUTURE IMPROVEMENTS

We have completed our goals for the first stage of the Xebra project. The high and low-side accumulators have been installed into their permanent positions, and so have the valves and sensors. The hydraulic pump and motor are currently installed in a temporary location under the bed of the truck for demonstration purposes. The slow-fill pump will be replaced with one that operates at a larger voltage and a higher pressure, but the location can be kept the same.

12.1 Strengths of Design

The final design of the hydraulic components was chosen very carefully. The placement of the low-side and high-side accumulators was such that they will not interfere with the work of future semesters and are easily accessible for service. By accounting for the positions of the pump and motor, we were able to group most of the components together near the back of the vehicle in order to minimize losses due to plumbing layout. The layout also minimized the height that the truck bed was lifted in order to maintain an aesthetically pleasing look.

Safety is important in the design as failures associated with hydraulic systems are high and can be catastrophic. We accounted for this in several ways by ensuring that all calculations were done using safety factors. The hinge redesign for example has a safety factor of about 2 and the calculations for the amount of fluid needed for a single acceleration also have safety factors incorporated in them. The manufacturing and installation of the hydraulic components was also carefully executed in order to ensure that each component was accessible for service and well-secured to the vehicle frame brackets. Lastly, all purchased components are of high quality, and designed for its specific use on the Xebra.

12.2 Weaknesses of Design

The prop rod is important because it prevents the truck bed from falling down while it is lifted. While the current bar is strong enough for this function, it can easily be misplaced when not being used because there is currently no location on the truck to store it. A more permanent design that replaces this bar or developing a way to store the current bar should be explored.

The location of the high-side accumulators is another weakness of our design. While they are placed out of the way of the other components, they are extremely difficult to remove as it requires removal of the truck bed. Unfortunately, there are no actions that can be taken to remedy this, as they are the biggest constraint in the design. By placing them in any other location on the truck, the functionality of the system will be compromised which would actually weaken the design.

The electrical system is permanently wired to the batteries, thus when the vehicle is being driven, the sensors activate the valves and slow-fill pump. This is currently a large problem because running the slow-fill pump without fluid flowing through it can cause severe damage. A switch should be added to close each electrical circuit to the valves so that no damage can occur now and in the future gives the operator the option of not using the hydraulic launch system if desired.

12.3 Information for Future Semesters

12.3.1 Tips about Xebra

To operate the Xebra, first make sure that the red emergency button that is located underneath the driver’s seat is pulled out. This emergency button shuts the power off to the electrical components and the vehicle cannot run or be charged when it is pushed in. The key is located in the compartment on the floor. Similar to a regular car, you have to turn the key all the way to “start” the motor, however there will be no sound. Turn the knob on the dashboard to the “F” position and the vehicle can then be driven using the gas and brake pedals like any normal vehicle. To reverse, turn the knob to “R” and press the Reverse button also located on the dash and then operate it. It is important to note that in order to charge the vehicle, the red button under the driver's seat must be pulled out!

The locations of the main permanent components were chosen such that they would not need to be moved in the future. However, in order to work on installing the hydraulic motor for example, some of the components may need to be taken out. We found that it is the easiest to work on the Xebra with the truck bed off. By removing the pins that hold the bed onto the frame, the truck bed can be lifted off using 4 people. The low-side accumulator can also be removed to work near the electric motor. This is relatively simple as there are only three bolts that hold it to its mounting bracket. The entire bracket can also be taken off by removing the bolts that attach it to the vehicle frame.

12.3.2 Location of Parts for Xebra

All of the parts that are needed for the Xebra project are either located on the Xebra already or can be found in the dark gray cabinet labeled "Xebra" in the X50 build room where the Xebra is stored. This cabinet houses the fittings for the hydraulic components, the check valves, the car cover, pressure gauge, oil filter, and electrical wire.

The Hose Doctor

When all of the hydraulic components are in their permanent positions, future teams can contact the Hose Doctor to complete the system. They can come and install the hydraulic lines and fittings to the components. You can contact them through Exotic Automation and Supply (248-477-2122). The system requires 1" diameter tubing rated to 5000 psi and JIC-16 female swivel head fittings. The connection to the slow-fill pump can be JIC-6 size fittings. Once all of the components are in place, it will be possible to estimate how many fittings will be needed. They charge a service fee, parts, and labor (per hour).

13 PROJECT GOALS FOR FUTURE SEMESTERS

Winter 2008

Next semester's goal should be to install the hydraulic motor to a permanent location near the electric motor and find a way to couple it to the Xebra's drive shaft. We have left room underneath the low-side accumulator and next to the electric motor for this task.

Fall 2008

The focus of the Fall 2008 semester should be to install and couple the regenerative brake system to the vehicle. We believe that the best location would be place the pump on the front wheel, however this team should prove that this is best position.

Winter 2009

The team working on the project this semester should focus on the completion of the hydraulic system. The first task should be to create the correct slow-fill pump. The preferred pump should be capable of running at 72 VDC, however pumps like this are not available. This team will be in charge of purchasing the pump housing and motor with this capability and build their own pump and install it onto the Xebra. Contact Sun Hydraulics for more information about this. Following this task, the team should call The Hose Doctor and get the hydraulic components connected together. The hydraulic fluid can then be added and the system can be tested. The final task for this semester would be to complete the final baseline performance test. Please see the following section for more information about this test.

Lotus Engineering (Final Baseline Performance Test)

The preliminary baseline performance test was performed at Lotus Engineering, therefore it is important to perform the final test here as well. You can contact Don Apple or Pat Barker for more information (734-995-2544). To quantify the improvements of the Xebra, perform as many HOT505 city driving tests that the vehicle can handle. Also, a current and voltage reader will need to be provided for the data analysis.

Before the baseline test can be performed, it is necessary to complete a coast-down test. The data from this will be used on the dynamometer at Lotus to provide more realistic data. The first test was performed at the Chrysler Proving Grounds with the help of Larry Webster from Car and Driver magazine. You will need to run the tests according the SAE Standard J2263, however, do not warm up the vehicle before the tests and take the data starting at the maximum speed of the Xebra vehicle (35 mph). Be careful of the speedometer as the top line reads in kilometers per hour.

14 PROJECTED PERFORMANCE IMPROVEMENTS

The following calculations give the expected maximum possible energy recoverable with the hydraulic system. This calculation gives the expected upper-limit of the efficiency that is achievable. Data for the calculations was obtained from the preliminary baseline performance test.

An estimate of the maximum possible energy that can be recovered from braking can be calculated using Equations 25 -27.

$$\text{Recoverable Work} = \text{Kinetic energy} - \text{Energy loss due to drag} \qquad \text{Eq. 25}$$

$$\text{Kinetic Energy} = \sum_{t=0}^{t=end} \left(\frac{1}{2} m v_{t-1}^2 - \frac{1}{2} m v_t^2\right), \text{ if } v_{t-1} - v_t < 0 \qquad \text{Eq. 26}$$

$$F_{DRAG} = 30.37 + 0.3009v + 0.02076v^2 \qquad \text{Eq. 27}$$

If there is an increment of time where the vehicle decelerates, that represents energy that can be recovered with the hydraulic brakes, therefore all of the increments during the HOT505 test where deceleration occurred were summed. This calculation yields a recoverable energy of 3900 ± 195 kJ. The total energy used during the entire HOT505 test was calculated previously to be 10,800 ± 540 kJ. Using this information and the idea that the maximum efficiency of the hydraulic system is about 90%, the energy saved using the regenerative brakes is 33%.

Finally, this saved energy will be placed back into accelerating the system, which can also partially be recovered. This is quantified by Equation 28:

$$\sum_{n=1}^{n=\infty} (Efficiency^n \cdot E_{original}) = \sum_{n=1}^{n=\infty} (0.33^n \cdot 10800) = 5200 \text{ kJ} \qquad \text{Eq. 28}$$

Therefore, the maximum possible energy recovered is 5200 ± 260 kJ representing a 48% increase in efficiency. Again, this is the maximum possible energy recovered. The true efficiency will be lower because of the assumption that all decelerations are from braking. Also, the additional component weight was not accounted for and the lack of information on the efficiency of hydraulic system will cause the true efficiency to be lower than these calculated values.

15 CONCLUSIONS

The Environmental Protection Agency is focused on maintaining human health and the environment. Along with the University of Michigan, they have helped design and patent hydraulic regenerative braking system technology for bicycles. This system is now ready to be implemented as a larger-scale version; the Xebra will be the first hydraulic-electric hybrid vehicle using this technology. This project will encompass several semesters during which the system will be fully designed, installed and integrated into the Xebra. The scope for the Fall 2007 semester was to focus on the design and installation of the basic hydraulic components.

Customer requirements as well as technical specifications were determined. All of this information was utilized to create a FAST diagram and Morphological chart to generate possible design concepts. A Pugh chart was then used to select the final design concept. This design is such that it will meet the customer requirements and engineering specifications. Quantitative and qualitative analysis of the key variables of the hydraulic system were performed in order to finalize the design layout. These analyses include drag, plumbing efficiency and flow rate calculations, DFE and DFMA analysis, and finally a FMEA chart. Baseline tests were done to quantify the performance of the Xebra before the installation of the hydraulic launch system. At the completion of the manufacturing, the high-side accumulators, low-side accumulator, values, and sensors were permanently mounted to the Xebra, and the hydraulic pump and motor were temporarily mounted. The truck bed was also raised 7.5 inches to account for the added components.

It was decided to postpone the installation of hydraulic hose on the Xebra, as much of this work would have to be redone in the future; this would cause a huge strain on the project budget. The demonstration of the Xebra at the completion of this semester highlighted the correct connection of hydraulic actuation system. Lastly, project performance improvements of the Xebra were calculated using the baseline testing data.

Future semesters should focus on integrating both the hydraulic motor and regenerative brake pump into the Xebra, and upon completion of these projects, the hydraulic hose and fluid should be installed on the system. A final HOT505 test should then be completed to determine the overall efficiency improvements of the Xebra using the hydraulic launch assist. The entire project should be completed by the Winter 2009 semester if the project proceeds at the suggested schedule.

16 ACKNOWLEDGMENTS

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    - Mohammed Shalaby, GSI for ME 450
    - Bob Coury and Marvin Cressey, G.G. Brown machine shop
    - Jason Moore, Mechanical Engineering graduate student
    - Kathy McCrumb, Mechanical Engineering purchasing department
    - Jessica Boria, InterPro Office and planning the Design Expo

17 REFERENCES

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18 TEAM BIOS

Sarah Herman is a 5th year Mechanical Engineering student at the University of Michigan. She plans to obtain a Masters Degree in Mechanical Engineering upon graduation in May 2008, and hopes to work on sustainable energy technologies in the future. She had the opportunity of learning about such technologies at the University of New South Wales in Sydney, Australia. Her favorite courses were Thermodynamics and Advanced Energy Solutions. In her free time, Sarah enjoys running, reading, and spending time outdoors. She is from Livonia, Michigan.
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William Lee is a 5th year dual major in Mechanical Engineering and Industrial/Operations Engineer at the University of Michigan. He is a Midshipman in the Navy ROTC and will be commissioned upon graduation in December 2007. He spent several summers on various weapons platforms and is interested in working in a submarine upon commissioning. His favorite classes are Entrepreneurship, Optimization Methods, and Lean Manufacturing. In his free time, Will enjoys running, playing basketball, and anything involving the outdoors.
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Brittany Warda is a 4th year Mechanical Engineering student at the University of Michigan. Her favorite classes included the Design and Manufacturing series, Mechanical Behavior of Materials, and Statics of Materials. She plans to obtain a Bachelors Degree in Mechanical Engineering in May 2008, and then would like to work in the automotive industry upon graduation. She had the opportunity of working in this industry at BorgWarner Automotive and Wheel to Wheel Powertrain performing testing and validation work for both companies. Her life goals are to own a red Ford Mustang GT and to travel the world.

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Trang Vu is at his senior year majoring in Mechanical Engineering at the University of Michigan. He plans to work for the automotive industry upon his graduation in December 2007. His favorite classes are Thermodynamics, Fluid, and Heat transfer. He also likes physics and wishes to study the subject later on. When not busy being a student at Michigan, he is a part time nail technician and is very good at it. Trang has been in the state for eight years and is a Michigan sports fan (Pistons, Red Wings, Tigers, Lions, Wolverines, etc.) In his free time, he enjoys reading, fishing, bowling, or playing PC games.

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APPENDIX A- PRELIMINARY CALCULATIONS

Appendix A features the preliminary calculations that were performed at the start of the project. The following is a list of the numbers, assumptions and equations that we used in order to determine the specifications of the hydraulic system.

The vehicle is 1800 lbs unloaded. With the estimated 500 lbs payload, the vehicle is 2300 lbs (1043 kg) with payload. The energy required to accelerate the vehicle from 0 to 27 mph (12.1m/s). Using the kinetic energy equation (1)

$$E_k = \frac{1}{2} \cdot M \cdot v^2 \qquad \text{Eq. 1}$$

substituting the mass and velocity yields E_k = 76.4 kJ.

The volume of fluid at 3000 psi (20700 kPa) required for the acceleration was calculated using Bernoulli equation (2) for incompressible fluid

$$\frac{P_1}{\rho_1 g} + \frac{v_1^2}{2 \cdot g} + Z_1 = \frac{P_2}{\rho_2 g} + \frac{v_2^2}{2 \cdot g} + Z_2 \qquad \text{Eq. 2}$$

With V_1=0, Z_1 = 0, and Z_2 = 0, $\frac{P_1 - P_2}{\rho} = \frac{v_2^2}{2}$ was obtained.

Since $\rho = M/V$; where V is volume. The equation becomes: $V \cdot (P_1 - P_2) = \frac{m \cdot v_2^2}{2}$

Finally, Eq. 4 was derived.

$$V = \frac{E}{(P_1 - P_2)} \qquad \text{Eq. 4}$$

For the vehicle, we plan to use atmospheric pressure (101 kPa) at the low-end accumulator. With the energy found above, the volume of fluid needed is 0.00371 meter cube, or 3.71 liters.

Vehicle acceleration, a, for a fixed displacement hydraulic motor at 22cc/rev ($2.2 \cdot 10^{-5}$ m^3)
From Eq. 4, we get $E = V \cdot (P_1 - P_2)$; thus the energy provided by the motor on a revolution was found to be E_r = 453 J.

From energy equation $E = F \cdot s$ and Newton's second law $F = Ma$, we obtained Eq. 5

$$a = \frac{E}{M \cdot s} \qquad \text{Eq. 5}$$

For one revolution of the motor, the wheels turn 6 revolutions. As the result, the vehicle moves the distance $s = \frac{\pi D}{6}$ where D is the wheel's diameter. Finally, we found the vehicle acceleration, $a = 2.42$ m/s^2.

APPENDIX B- PARTS LIST

This appendix contains the parts list that we created at the start of our project. It contains the parts that were purchased prior to the start of the project, parts purchased during the Fall 2007 project and parts that remain to be purchased in the future. Note that we have also labeled where to find these parts, for example if a purchased part is not on the vehicle, the list tells you that you can expect to find it in a cabinet in the X50 lab or where to purchase the parts in the future.

Parts Purchased/Given Prior to Project:

1. Slow fill pump
2. Hydraulic motor
3. Hydraulic regenerative brake pump
4. High-side accumulators (2)
5. Valves (2)

Parts Purchased during Fall 2007:

6. Touch sensors for accelerator and brake pedals
7. Hydraulic fittings for main component inlet and outlets (CABINET)
8. Oil filter (CABINET)
9. Low-side accumulator
10. Temperature sensors (CABINET)
11. Pressure gauge (CABINET)
12. Check valves for pumps (2) (CABINET)
13. Aeration plug
14. Brackets to mount high-side accumulators
15. Lexan safety shield (X50 Lab)
16. Flow meter
17. Electrical wires
18. Bolts for installing brackets and components
19. Metal for brackets and tubing to raise truck bed
20. Gloves (non-latex)

Parts to Purchase for Xebra Project:

21. Hydraulic hose (Hose Doctor)
22. Level switch (McMaster Carr?)
23. Cable pulls for hydraulic hose (McMaster Carr)
24. Hydraulic fluid with high pressure additives (EPA)
25. Emergency shut-off panel
26. Warning sign for operation

APPENDIX C- FMEA CHART

This appendix is the complete FMEA chart that evaluates the rest of the components that were not of primary focus for this semester.

Part	Part #	Function	Potential Failure Mode	Potential Effects of Failure	Severity (S)	Potential Causes/Mechanisms of Failure	Occurence (O)	Current Design Controls/Tests	Detection (D)	Recommended Actions	RPN	New S	New O	New D	New RPN
High Side Accumulators	ACP 10AA 800 E1K TE2	Store high pressure fluid	Leak fluid	Reduce efficiency	4	Crack Propagation	2	Manufacturer Inspected	9	None	72	4	2	9	72
			Leak nitrogen (precharged gas)	Lose pressure/function	7	Crack Propagation	2	Manufacturer Inspected	9	None	126	7	2	9	126
				Reduce efficiency	3	Crack Propagation	2	Manufacturer Inspected	9	None	54	3	2	9	54
			Rupture	Danger to user	10	Cyclic Loading	1	Manufacturer Inspected	9	None	90	10	1	9	90
			Piston seizure/grinding	Reduce efficiency	7	Not concentric	4	Physical Inspection	6	Do not over constrain	168	7	2	6	84
Motor	PGM517 MA0230B M1H3ND6 D6B1B1B1	Convert fluid energy to mechanical energy	Leak fluid	Reduce efficiency	4	Loose Fittings	5	Hand pump check for leaks	1	Torque to spec	20	2	2	1	4
			Cavitation	Reduce efficiency	6	Air bubbles in fluid	4	Sight glass	1	Extra fluid in system	24	2	3	1	6
			Stall	Stop function	4	Overheating	7	Temperature gauge	4	Add blower	112	4	3	4	48
					8	Binding of internal components	2	N/A	7	None	112	8	2	7	112
Regenerative Brake Pump	PGM517 MA0330B M1H3ND6 D6B1B1B1	Pressurize fluid	Leak fluid	Reduce efficiency	4	Loose Fittings	5	Hand pump check for leaks	1	Torque to spec	20	2	2	1	4
			Cavitation	Reduce efficiency	6	Air bubbles in fluid	4	Sight glass	1	Extra fluid in system	24	2	3	1	6
			Stall	Stop vehicle	4	Overheating	7	Temperature gauge	4	Add blower	112	4	3	4	48
					10	Binding of internal components	2	N/A	7	None	140	10	2	7	140
Slow Fill Pump		Pressurize fluid	Leak fluid	Reduce efficiency	4	Loose Fittings	5	Hand pump check for leaks	1	Torque to spec	20	2	2	1	4
			Cavitation	Reduce efficiency	6	Air bubbles in fluid	5	Sight glass	1	Extra fluid in system	30	2	3	1	6
			Stall	Stop function	4	Overheating	7	Temperature gauge	4	Add blower	112	4	3	4	48
					8	Binding of internal components	2	N/A	7	None	112	8	2	7	112

Figure C-1: FMEA Chart that details the failure modes for the high-side accumulators, motor, regenerative brake pump and slow-fill pump

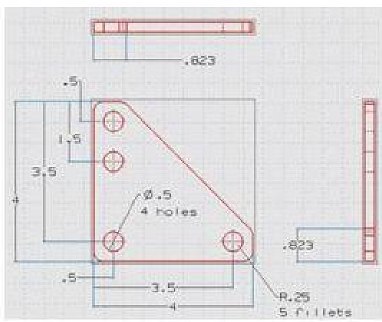
Part	Part #	Function	Potential Failure Mode	Potential Effects of Failure	Severity (S)	Potential Causes/Mechanisms of Failure	Occurence (O)	Current Design Controls/Tests	Detection (D)	Recommended Actions	RPN	New S	New O	New D	New RPN
Hinge	N/A	Support load of truck bed	Fracture	Danger to user and other components	10	Buckle due to bending moment	2	Force Analysis	8	Add cross-brace to design	160	10	2	6	120
					10	Fatigue due to cyclic loading and crack propagation	2	Force Analysis	3	Conduct durability test	60	10	2	1	20
					10	Material yield from overloading	4	Force Analysis	6	Conduct durability test	240	10	4	3	120
					10	Misalignment from improper installment	5	Physical Inspection	2	Install within tolerances	100	7	3	2	42
					10	Unstable due to unbalanced load	2	Force Analysis	2	Add cross-brace to design	40	7	2	2	28
Low Side Accumulator	6Z151	Store low pressure fluid	Leak fluid	Reduce efficiency	4	Loose Fittings	5	Hand pump check for leaks	1	Torque to spec	20	2	2	1	4
			Allow air into system	Reduce efficiency	6	Improperly installed aeration plug and baffle	6	Sight glass	1	Experiment with baffle types	36	4	4	1	16
			Corrosion	Leak fluid	4	Degradation of material	1	Manufacturer Inspected	10	None	40	4	1	10	40
Hydraulic Hoses	N/A	Transport fluid	Leak fluid	Reduce efficiency	4	Loose Fittings	5	Hand pump check for leaks	1	Torque to spec	20	2	2	1	4
			Rupture	Danger to user	10	Pressure exceeds hose rating	2	Pressure gauge	2	Add safety factors to design	40	8	1	2	16
			Corrosion	Leak fluid	4	Degradation of material	1	Manufacturer Inspected	10	None	40	4	1	10	40
Hydraulic Fittings		Connect components	Leak fluid	Reduce efficiency	4	Damaged threads and beveled edges	9	Physical Inspection	5	Handle properly	180	4	2	5	40
			Corrosion	Leak fluid	4	Degradation of material	1	Manufacturer Inspected	10	None	40	4	1	10	40
			Loosen over time	Leak fluid	4	Damaged threads and beveled edges	9	Physical Inspection	5	Handle properly	180	4	2	5	40
					4	Insufficient tightening during installation	8	Hand pump check for leaks	1	Torque to spec	32	2	4	1	8
Brake/Accel. Sensors	7692K4 and 7692K8	Actuate system	Electrical short	Continuous actuation of system	9	Permanent metal to metal contact within sensor	2	Voltmeter	4	Use wire harness	72	7	1	4	28
			Open Circuit	No actuation of system	8	Failure of wires due to fraying	4	Voltmeter	4	Use wire harness	128	7	1	4	28

Figure C-2: FMEA Chart that details the failure modes for the hinge, low-side accumulator, hydraulic fittings, and brake/accelerator sensors

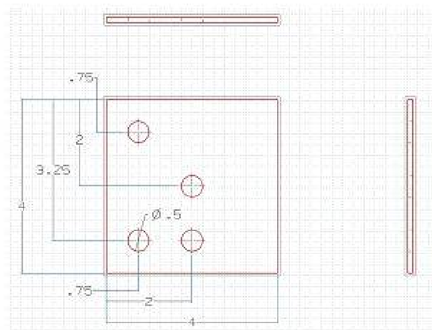
APPENDIX D- ENGINEERING CHANGE NOTICE

The following is an engineering change notice on the design of the steel plates for the hinge design. It includes the updated CAD drawing as well as a picture of the final product.

WAS:



IS:



Notes:
- Square hinge plate makes plate stronger compared to triangular shape.
- Moved hole (Denoted by A) farther out to increase strength.
- Moved hole (Denoted by B) farther in because weld on vehicle frame caused interference

Project: Xebra Team	
Ref Drawing: Hinge Plate	
Engineer: Entire Xebra Team	11/27/2007
Proj. Mgr: Professor Saitou	
Sponsor: David Swain	

Figure D-1: Engineering Change Notice (ECN) showing the before and after CAD drawings of the steel plate to hold the tubing to the vehicle frame to raise the truck bed

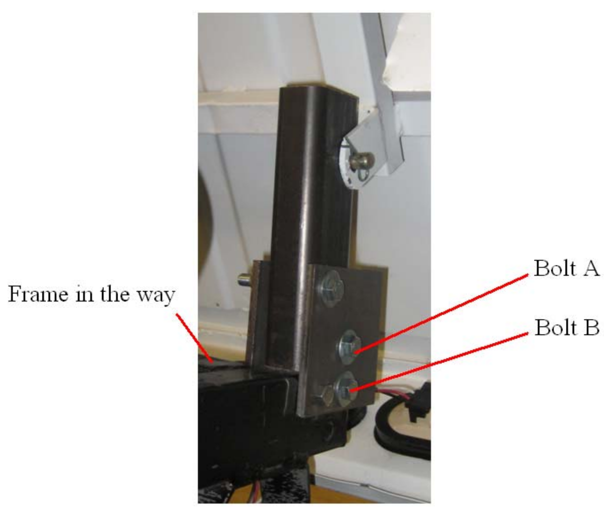


Figure D-2: Photograph of manufactured hinge plate

APPENDIX E- PHOTOGRAPHS OF COMPLETED PROTOTYPE

The following are additional views of the completed prototype, as well as photographs of specific components of the hydraulic system.

Figure E-1: Side View of Xebra with Truck Bed Propped Open

Figure E-2: Rear View of Installed Truck Components with Removed Truck Bed

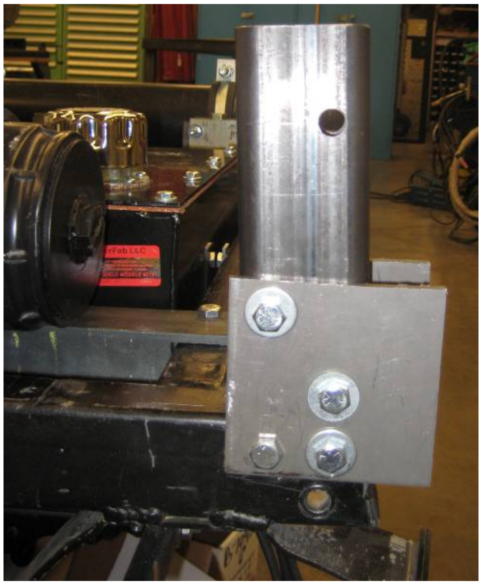


Figure E-3: Hinge Redesign with Truck Bed Removed

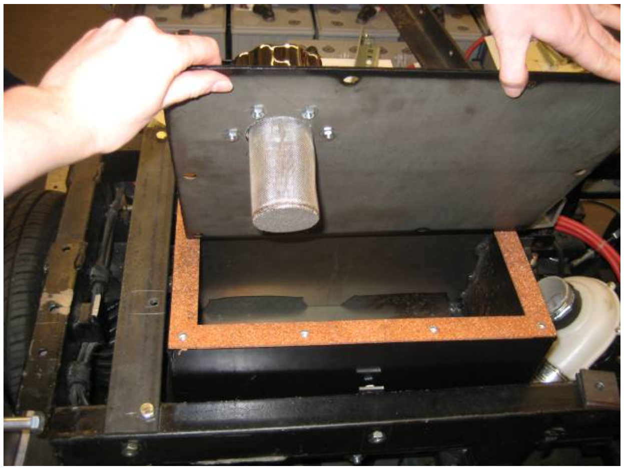
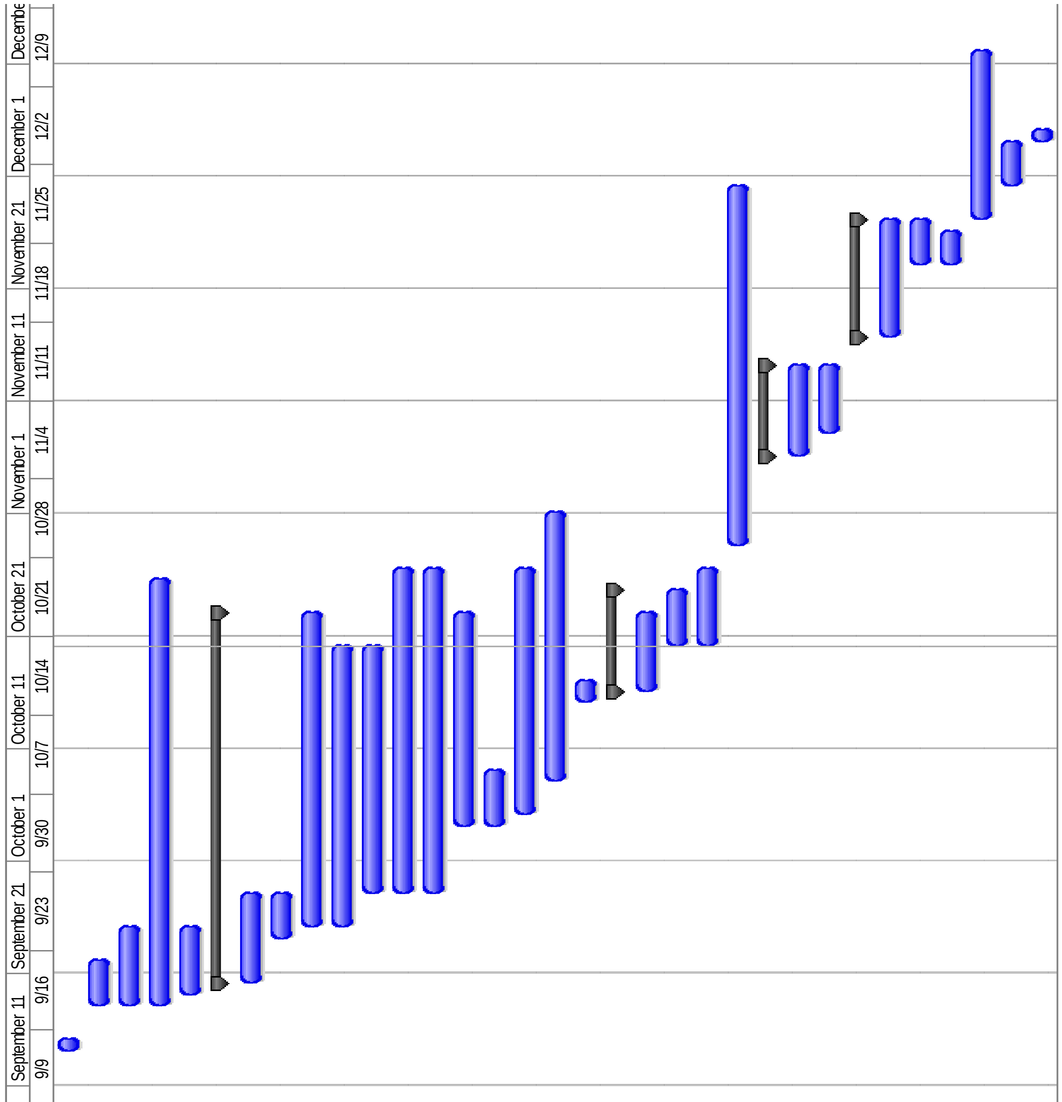


Figure E-4: Low-side Accumulator Open to Show Aeration Plug and Baffle

APPENDIX F- PROJECT GANTT CHART

This Gantt chart shows the plan used to complete our project over the entire Fall 2007 semester.

ID	Task Name	Start	Finish
1	Meet with sponsor	Fri 9/14/07	Fri 9/14/07
2	Calculations to verify design	Tue 9/18/07	Fri 9/21/07
6	Patent Research	Tue 9/18/07	Mon 9/24/07
13	Benchmark dyno testing	Tue 9/18/07	Thu 10/25/07
15	Create current parts list	Wed 9/19/07	Mon 9/24/07
7	**Design Review #1**	**Thu 9/20/07**	**Mon 10/22/07**
8	Written report	Thu 9/20/07	Thu 9/27/07
9	Oral presentation	Mon 9/24/07	Thu 9/27/07
10	Plumbing efficiency data analys	Tue 9/25/07	Mon 10/22/07
11	Calculations with losses	Tue 9/25/07	Fri 10/19/07
3	Conceptual layout designs	Fri 9/28/07	Fri 10/19/07
5	Research sensors and controls	Fri 9/28/07	Fri 10/26/07
14	Mineral oil compatible materials	Fri 9/28/07	Fri 10/26/07
4	Finalize Design	Thu 10/4/07	Mon 10/22/07
31	Contact businesses for sponsorshi	Thu 10/4/07	Mon 10/8/07
16	Create bill of materials	Fri 10/5/07	Fri 10/26/07
28	Order parts	Mon 10/8/07	Wed 10/31/07
30	Fall break	Mon 10/15/07	Tue 10/16/07
17	**Design Review #2**	**Tue 10/16/07**	**Wed 10/24/07**
18	Written report	Tue 10/16/07	Mon 10/22/07
19	Oral presentation	Sat 10/20/07	Wed 10/24/07
12	Low Side Accumulator	Sat 10/20/07	Fri 10/26/07
33	Install hydraulic system	Mon 10/29/07	Thu 11/29/07
20	**Design Review #3**	**Tue 11/6/07**	**Tue 11/13/07**
21	Written report	Tue 11/6/07	Tue 11/13/07
22	Oral presentation	Thu 11/8/07	Tue 11/13/07
23	**Design Review #4**	**Fri 11/16/07**	**Mon 11/26/07**
24	Written report	Fri 11/16/07	Mon 11/26/07
25	Oral presentation	Fri 11/23/07	Mon 11/26/07
29	Thanksgiving break	Fri 11/23/07	Sun 11/25/07
27	Final Report	Tue 11/27/07	Tue 12/11/07
32	Prepare car for expo	Fri 11/30/07	Mon 12/3/07
26	Design Expo	Tue 12/4/07	Tue 12/4/07



APPENDIX G- SENSOR/VALVE CIRCUIT DIAGRAMS

The following shows the circuit diagrams for the hydraulic actuation system in the Xebra.

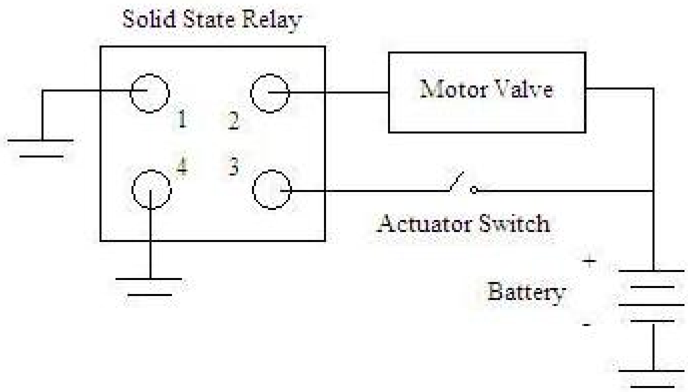


Figure G-1: Circuit Diagram for Motor Valve, Accelerator Pedal Sensor and Relay

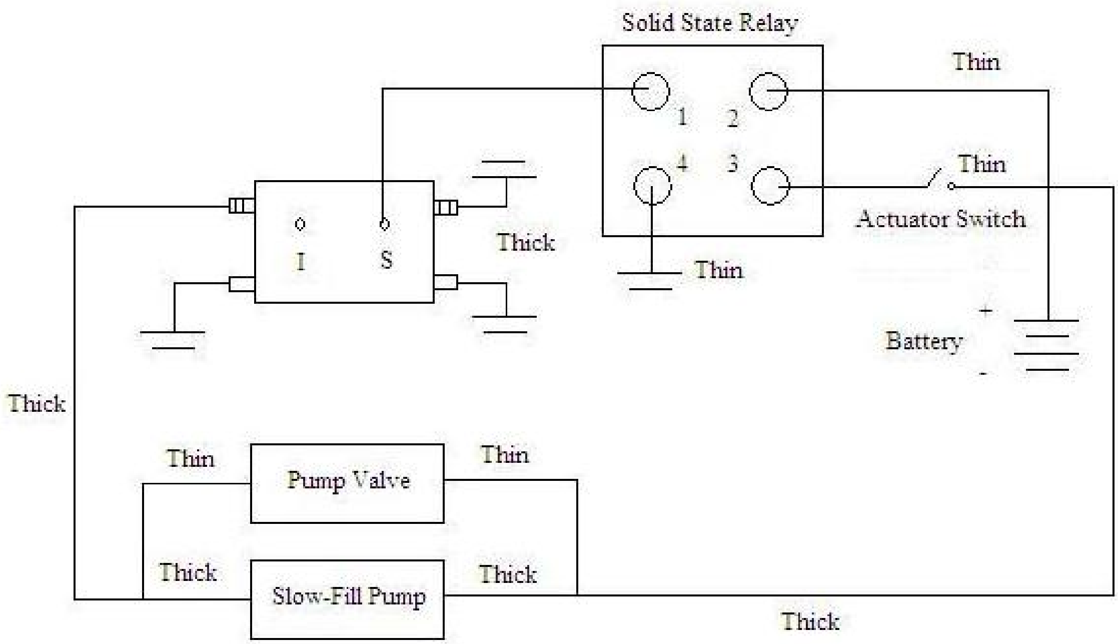


Figure G-2: Circuit Diagram for Pump Valve, Slow-fill Pump, Brake Pedal Sensor, Relay and Car Starter Solenoid