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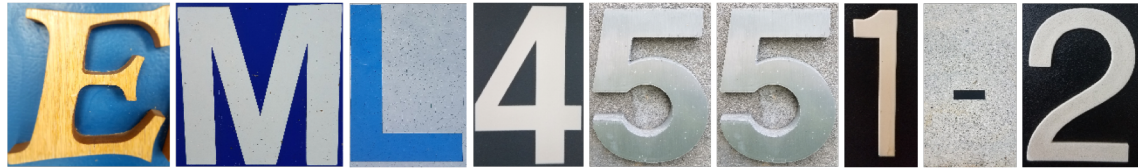
Team 2: The Examination of Occupant and Vehicle Responses to Low Speed Rear-End Crashes

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Abstract

This project seeks to create an evidence-based model for the reaction of passenger and vehicle to a low speed, rear-impact car crash. Project sponsor, Cummings Scientific, LLC. takes hundreds of cases each year involving occupant claims of serious injury from this type of collision. Cummings Scientific will use these models to assess the probability of injury in future applicable cases.

Data for the models will be collected through live crash testing. The project will focus on the effect of different bumper structures on the passenger and vehicle responses. In order to measure this effect, a bumper mount device has been designed. This device will be able to mount to multiple vehicles and bumper types for repeated crash testing with few test vehicles. Since the crash is low-speed, the vehicle will not be permanently damaged, so repeated testing can occur on the same vehicle. After testing, the MAthematical and DYnamic MOdels (MADYMO) software package will be used to create a model.

Keywords: low-speed car collisions, responses, live crash testing

Table of Contents

Team 2   **iv**

2018

List of Tables

List of Figures

Chapter One: EML 4551C

1.1 Project Scope

The primary objective of the project is to develop an empirical model of occupant and vehicle responses in a low speed, rear-end vehicular crash with an emphasis on the effect of bumper structure on the two responses. In order to develop this model, live crash testing will be performed. As such, a secondary objective of the project is to design a mount that allows multiple bumper to be interchangeably mounted to the same vehicle. This will enable the testing of multiple bumper structures for the evaluation of the effect of without the purchase of multiple vehicles for testing.

As the sponsor of this project, the primary stakeholder on this project is Cummings Scientific, LLC (Cummings Scientific). Therefore, Cummings Scientific will primarily benefit from the empirical models of occupant and vehicular responses. In turn, this will benefit the plaintiffs and defendants they represent. Furthermore, as the empirical model is adopted in the traffic accident reconstruction industry other forensic consulting firms could benefit from this model for vehicle and passenger response. In addition, designing and validating the crash test device will offer a proof of concept to the accident reconstruction industry for repeated crash testing with a single vehicle. Finally, another beneficiary of this model and device is the automotive design industry. A crucial facet of the automotive design industry is the safety of passengers. Having a clear idea of the occupant and vehicular responses to a low speed rear-end collision and the effect of bumper structure on these responses can enable them to design vehicles that perform in a safer manner during these kind of collisions.

Due to the time constraints placed on the project, the initial results of this research will be applicable only to vehicles that are able to withstand very low speed impacts with negligible structural damage after multiple tests. Additionally, this project will consider bumper structures that are primarily marketed in the United States, not world markets.

1.2 Customer Needs

In order to accurately assess the needs of the customer, Team 2 held multiple meetings with the project sponsor to determine the sponsor's desired outcome of the project. In these meetings, the sponsor was asked the questions that are detailed in the left column of

Table 1.

Table 1. The sponsor's responses were documented, as shown in the middle column of

Table 1.

Table 1. Following the conclusion of the meeting, Team 2, revised the customer's responses to represent engineering need statements as shown in the right column of

Table 1.

Table 1

Customer Needs Analysis

Question/Prompt	Customer Statement	Interpreted Need
What is the end goal of the project?	Customer wants to build a model that shows occupant and vehicular responses with low speed, rear-end collisions instead of extrapolating from the existing high speed models	Customer needs a method to collect data on low speed collisions to allow building of model
What models are currently used?	Customer and industry currently extrapolates these responses from high speed models	Customer needs a model based on empirical data

What are the current crash test standards?	Single cars are not currently crash tested multiple times	Customer needs a crash test that can be performed on the same vehicle multiple times
How will the crash test results be applied?	Customer would like to integrate results with dynamic simulation software	Customer needs high fidelity models of occupant and vehicular response
Why do you need a low-speed model?	Customer takes many cases where injury results from low speed collision	Customer needs a way to validate injury criterion for low-speed rear-end collisions through occupant responses
What is the physical deliverable of the project?	Customer wants a structure that mounts to the rear of a vehicle and allows multiple styles bumpers to be tested using the same vehicle	Customer needs a device that allows for repeatable testing of multiple bumper structures

1.3 Functional Decomposition

A functional decomposition was performed for the two main components of the project. These components are the interchangeable bumper mounting device and the mathematical model that will be created. Each functional decomposition is listed and justified below.

Interchangeable Bumper Mounting Device.

The interchangeable bumper mounting device must:

- Attach multiple bumper types to test vehicle for rear-end impact testing

- Transfer dynamic response of impact to vehicle and passenger

- Withstand multiple crash tests

- Allow sensor integration for measurement of crash parameters

A primary customer need is the ability to test multiple bumper structures on the same vehicle. In order to accomplish this, the various types of bumpers must be attached to the test vehicle. This device will accomplish this, while allowing an accurate transfer of the dynamic response through the vehicle and to the passenger. It is necessary to test multiple bumper structures to

Team 2 **5**

determine the impact of the bumper structure type on the empirical model created from the crash tests performed. In order to record live crash test data for use in creating the empirical model, the device will need to be able to accurately gather and transmit sensor data. Furthermore, the repetitive testing of the same vehicle with various bumper structures is more cost effective than crash testing multiple vehicles.

Low Speed Rear-End Crash Model.

The model of the low speed rear-end crash must:
- Characterize vehicle response to low-speed impulse

- Transfer the input signal to a passenger response

- Output measures (i.e. force, acceleration, etc.) that are contained in the MADYMO output

A chief goal of this project is to define impulse responses to low speed rear-end crashes. Given an input of crash data, the model must give an accurate output of vehicle and passenger responses. Since the MAthematical DYnamical MOdeling (MADYMO) software suite will be used for crash modeling by the sponsor and team 2, the output from the model must be compatible with the MADYMO model data. Any data output from the empirical model should also be output from the MADYMO model for validation and integration purposes.

1.4 Target Summary

In order to effectively develop targets for the project, the targets were classified into two main categories that correspond to the main components of the project. The first category contains targets for the interchangeable bumper mount and the second category contains targets for instrumentation and test. This section summarizes the key targets in each category. A

complete list of targets can be found in Appendix B: Target Catalog. The master list of targets will be appended to as the project progresses. In general, targets were generated to correspond to the functions listed in the previous section on functional decomposition.

Interchangeable Bumper Mount Targets.

The general purpose of the bumper mount is to allow multiple collisions for data collection to occur using the same vehicle, while also being able to swap bumper styles between tests. To fit this purpose, targets were established for the number of crashes that it can withstand, the different style bumpers it can hold, and the different vehicles that can be used. After conferring with Cummings Scientific, a target of 15 collisions was set. Furthermore, following background research on the main types of bumper structures and discussion with Cummings Scientific, a target of mounting different four bumper structures (piston-isolator, crumple zone matrix, foam core, and solid frame mount) was established. To define the degree of universality of the bumper mount, a target of four vehicles was set for the number of vehicles that it should be able to mount to. This target was generated based on the number of different types of bumpers that will be tested. This redundancy in mounting will allow for another test vehicle to be used in the case that unanticipated structural damage to the pickup truck frame is incurred.

While those are the most obvious tasks the mount must be able to complete, it is also important to consider the physical impact of the test. The bumpers' size, weight, and overall design need to be taken into consideration to minimize the impact of the mount on the data collected when compared to baseline tests where the mount is not included. Potential target categories for these parameters are yield strength and stiffness of the current vehicle frame, as

well as size and weight parameters for the mount. These targets will be established in the coming weeks as background research continues to progress.

Test and Instrumentation Targets.

Cummings Scientific recommended performing a minimum of 15 live crash tests, at an average delta-v of less than 4 mph, in order to accurately gauge the response of the occupant. The target values for the number of tests conducted and delta-v were set accordingly. Crashes that occur at a delta-v less than 7.5 mph are assumed to cause no permanent deformation to the vehicle and is Team 2's definition of a low-speed crash (Wang & Gabler, 2007) (Brach, 2003). Due to this definition, the structural integrity of the test vehicle should not be compromised at the planned test runs with a delta-v less than 4 mph. This assumption will be validated through regular inspections after each test, in addition to a high-speed, final validation test.

At least three accelerometers will be used to measure the acceleration of the test vehicle during impact. The accelerometers will have a sampling frequency greater than 100 Hz and a range of $\pm$ 10g. Each target value was chosen upon the recommendation of Cummings Scientific. Further background research is needed to refine and verify these targets. As the project progresses it is expected that more targets will arise. These may include, but are not limited to: high-speed camera usage, different impact methods for live crash testing, occupant instrumentation, targets regarding an enclosure for the instrumentation if sufficiently close to the excitation point, etc.

1.5 Initial Concept Generation

Since the interchangeable bumper mount is the physical deliverable of the project, concepts for this device were generated. Cummings Scientific has provided a 1999 Mazda B3000 pick-up truck as an initial test vehicle. Before generating concepts, Team 2 inspected this vehicle by removing the existing bumper and examining the vehicle structure. This process was documented through notes and pictures. From this inspection, Team 2 gained an understanding of the bumper mounting system and formed a foundation to generate concepts. For the reader's sake, a picture of the bumper mounting system that exists on the vehicle is shown in Figure 1 and Figure 2.

Figure 1. The rear end of the Mazda B3000 pickup truck with the factory bumper removed. The vehicle structure where the interchangable bumper mount will be attached has been boxed.

Figure 2. The primary attachment points to the frame are highlighted in this figure. This is an isometric view of the structure shown above.

Concepts were generated on both a system and sub-system level. These concepts will be refined and expanded upon to generate a feasible design solution. A sketch of each concept and a description of each concept is presented in this section. The concepts are grouped in terms of system and sub-system concepts.

Concept generation was driven by function and target identification. Background research continues to be conducted on bumper and mounting structure. Therefore, concepts continue to be generated. This implies that functions primarily drive the concepts presented below. As background research continues and targets are refined, the targets will influence the concepts generated and ultimately guide concept selection. One facet of background research

that remains to be completed is physical inspection, measurement, and selection of bumpers for testing. This will occur in the the following week and will allow for further refinement of targets.

Overall System Concepts.

Concept 1.
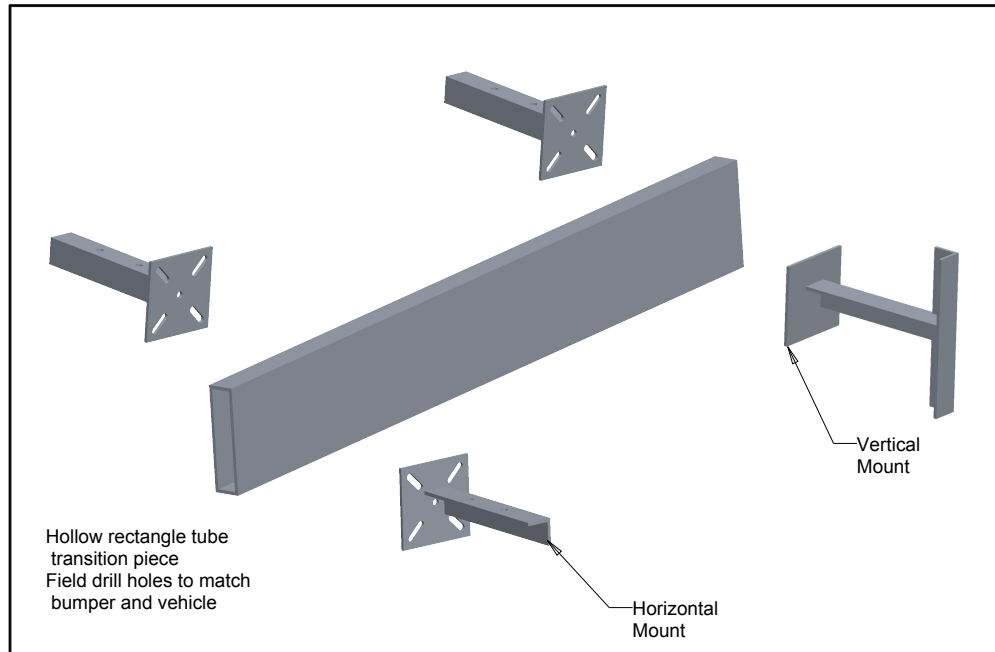
Figure 3. This concept for overall system design incorporates a hollow rectangular tube and horizontal mounts. It can accommodate multiple bumpers.

The design uses a large piece of rectangular tubing to hold adapters that will be fitted to each bumper and vehicle. This piece will have holes drilled in the field and through bolted with a spacer in the middle of the tubing to prevent buckling as the bolt is tightened. The pieces that attach to each side will be made from piece of angle iron with a plate on one side. This place would have a hole centered to allow rotations and slots at different angles to allow adjustment with the least number of new holes. The plate would also help to distribute the force. These pieces would come in two options, on that has a vertical piece to mount to and the other a

horizontal. After several tests it may be necessary to replace the middle tubing if the increasing

number of holes affects the piece's rigidity. This concept meets the functions of attaching

multiple bumper types, integrating sensors for parameter measurements because of its

modularity, and appears to have the ability to withstand multiple crash tests.

Concept 2.
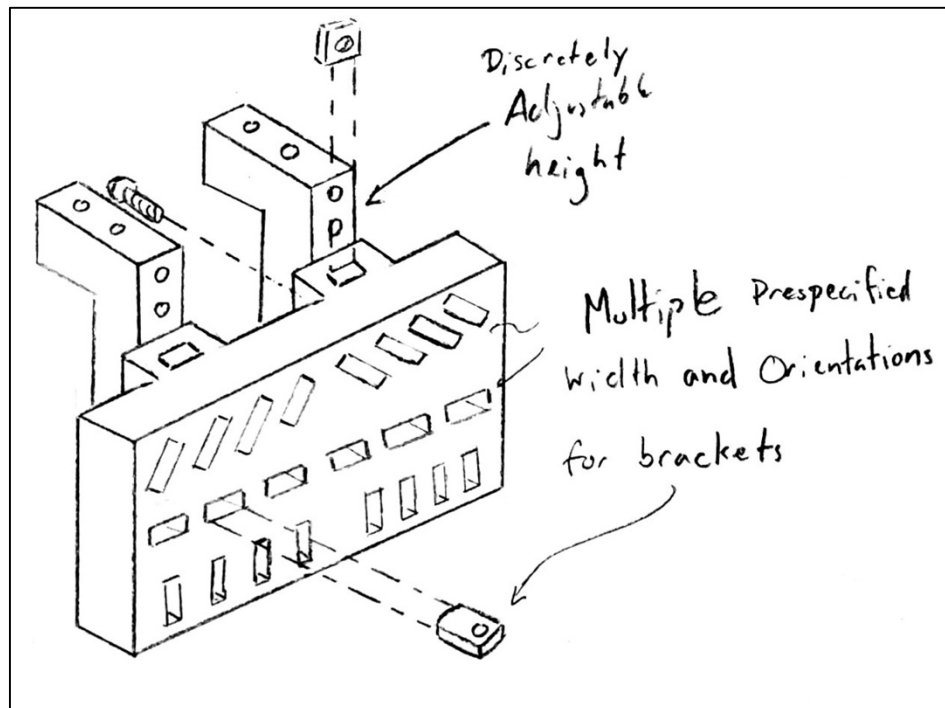
Figure 4. A concept for the overall bumper mount that allows for multiple bumper

configurations.

The next overall system concept is similar to the first, but has distinct features. These

features include pre-specified, not field-drilled holes, and adjustable mounting features on the

side that connects to the vehicle. This will allow for a change in bumper height. The adjustable

rails are attached to the front mounting plate attached by bolts that pass through the back of the

large plate into a square nut that rests inside of the rear of the large plate. In a similar manner to

the first concept presented this concept has many attachment points that use hand tools to mount the bumpers to the mount. This concept allows for the testing of multiple bumpers and for the integration of sensors for parameter measures.

Concept 3.
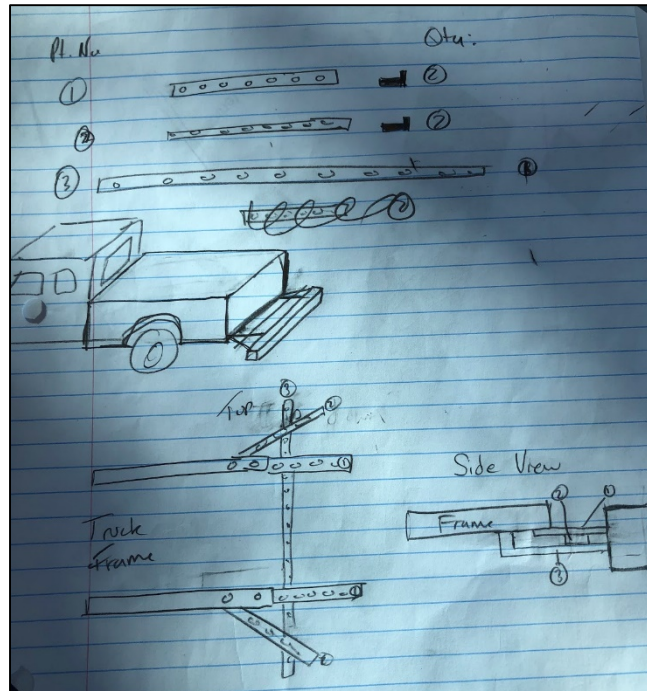
Figure 5. A concept for the overall mount that involves flat bar and spacers.

The third overall concept consists of several pieces of flat bar and spacers. Each mounting point on the frame would be directly fashioned to a mounting point on the bumper. They would be offset from each other with the use of the spacers. This is demonstrated in the side view on the sketch. To add strength and rigidity between all the pieces a long flat bar would be bolted across the top to each other piece as seen in the top view on the sketch. Due to its apparent strength and rigidity, it could likely withstand multiple tests. Additionally, it has

enough connection points to allow for sensor integration and could potentially accommodate multiple bumpers.

Concept 4
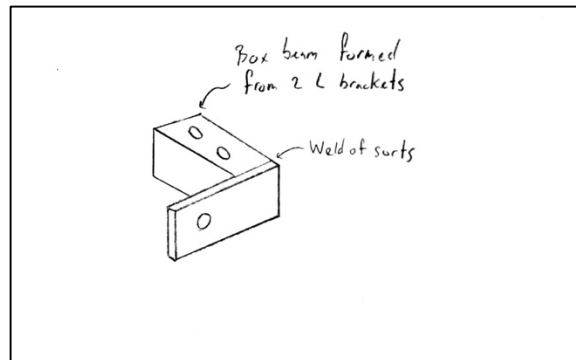
Figure 6. A concept for a simple bumper mounting device.

This concept is small and easily manufactured. Once a variety of bumpers have been chosen and relevant measures are taken, the team would manufacture enough of these mounts for each type of bumper we need. The box beam is written to be made of L brackets, but it could also be made of I-beam if needed or purchased pre-extruded. The interface surface between the box and the plate could have different orientations to meet various geometries on the bumper. This component is designed to specific for the bumper type, so it will transfer impact to the occupant in an unaltered fashion. The size and tube geometry make it likely to withstand multiple tests.

Sub-System Concepts.
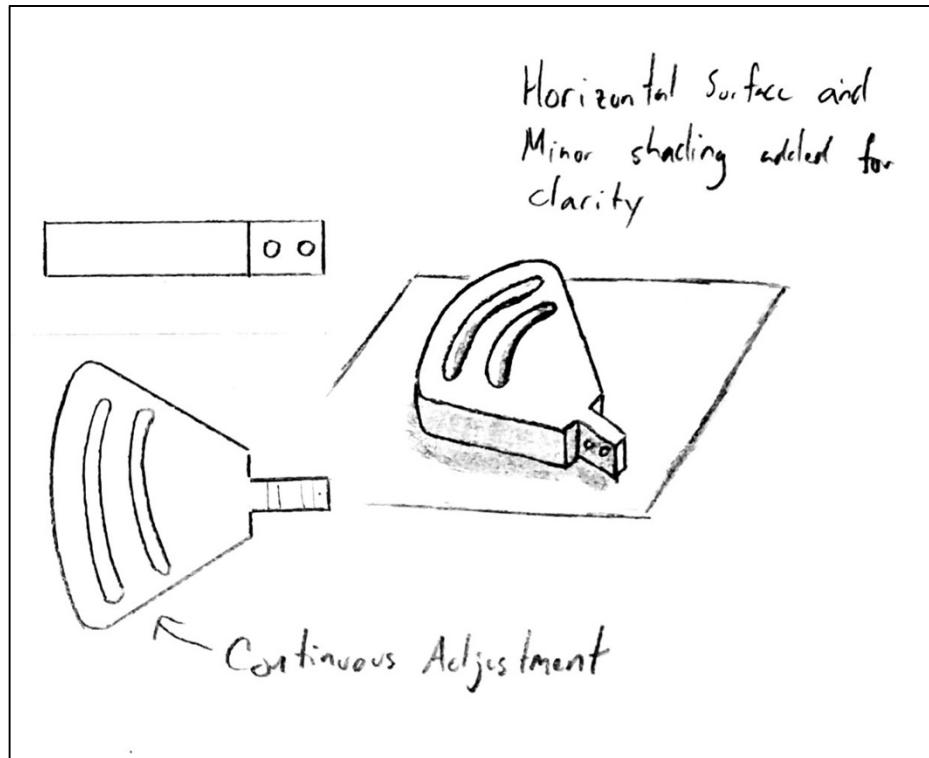
Concept 1.

Figure 7. A concept that allows for variable mounting angle.

This sub-system concept is for a piece that allows for continuous adjustment of mounting angle. This would be useful, as not all mounting points on the bumpers or vehicles are oriented the same way. This concept has slots that can be used to orient the mounting points in any way necessary. These could be mounted in series to allow for two degrees of freedom. Additionally, these pieces have the ability to be set manually with hand tools to specify a position, however, handheld power tools should be used to ensure tightness on the slots. The idea of slots can also be extended to linear slots to allow for linear translations. This piece's modularity allows it to mount to a variety of bumper structures.

Concept 2.
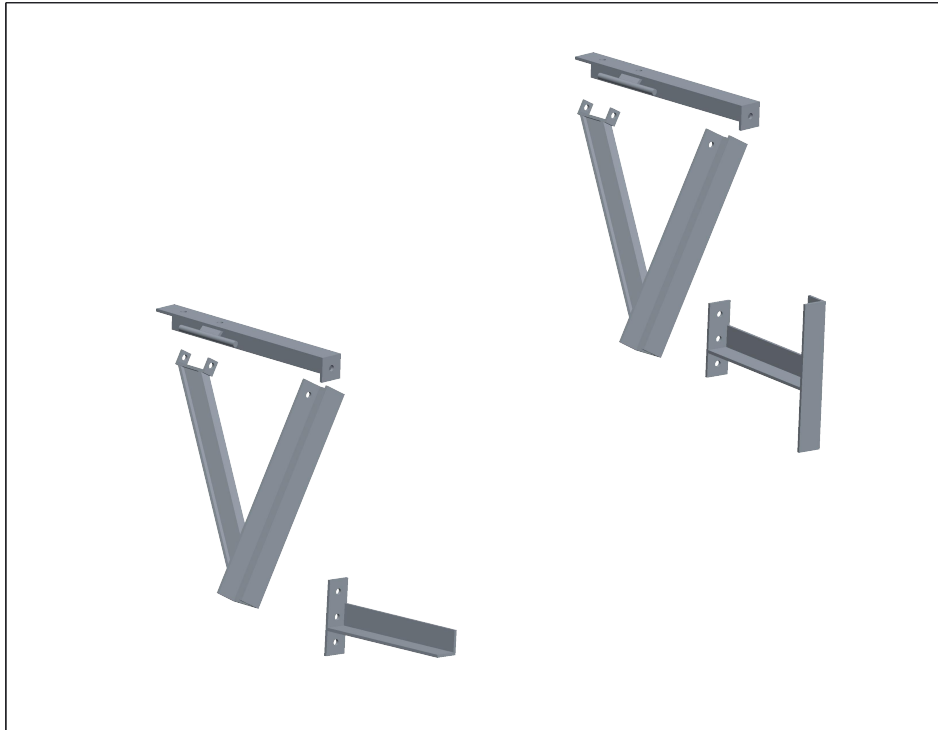
Figure 8. This is a sub-system concept for a swivel mounting feature.

This sub-system concept employs the idea of using swivels as a means of mounting the bumper to the vehicle. The swivels are created using angle iron and the piece that swivels would be a piece of channel. This would allow flush bolting and bolting along the centerline. I-beam would not allow this feature. This would allow the mounting point of the bumper to be moved to any point within the radius of the swivel. There would be two options for attaching the swivel the bumper: a horizontal mount and a vertical mount. This structure also enables multiple bumper structures to be mounted, while providing a rigid base that could withstand multiple crash tests. Furthermore, the design has the space to fit sensors.

Concept 3.
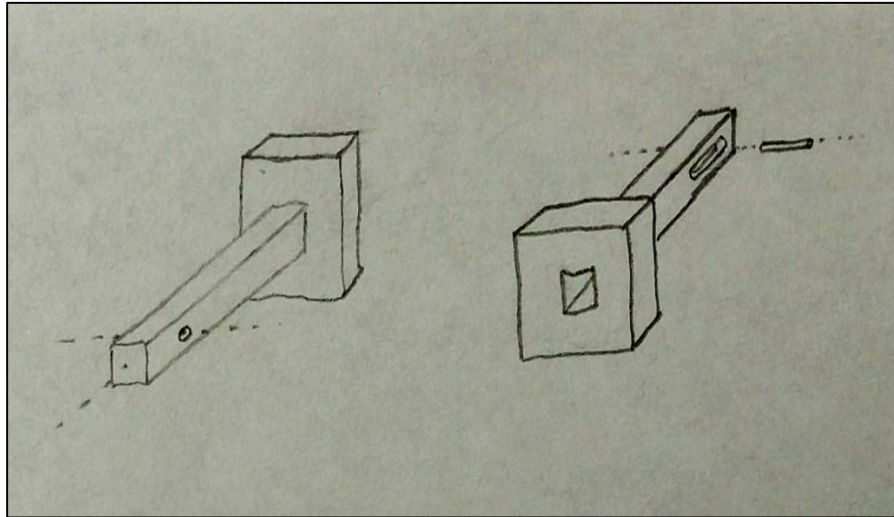
Figure 9. A concept for affixing the interchangeable mount to the pickup truck. This resembles a trailer hitch.

This design resembles a trailer hitch and contains a male-female slot to guide the bumper onto its testing mount. The male joint can be attached to the mounting location on the bumper and the female to the frame. A pin secures the male joint once it is fully inside the female joint while still allowing room for the pin to translate after impact and preventing the bumper from being pulled off. The full impact force will be absorbed by the plates instead of the pin in this way. This piece should withstand multiple crashes due to simple geometry.

Team 2
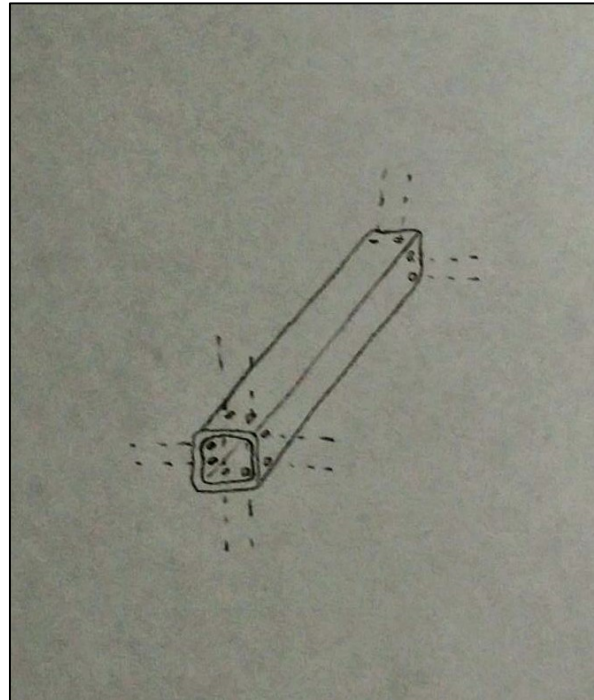
Concept 4.

Figure 10. A concept for the bumper mounting plate.

This is a concept for the front plate of the mount. This design resembles the original mount pulled from the test vehicle, differing in that it omits the altered geometry and mirrors the original L-bracket to form a straight, extruded square bracket. This allows for significant control over the strength of the bracket, given the simplicity of its shape. The hollow square also creates multiple possible mounting points with various orientations. This will accommodate multiple bumper structures because it has many mountable surfaces.

Concept 5.
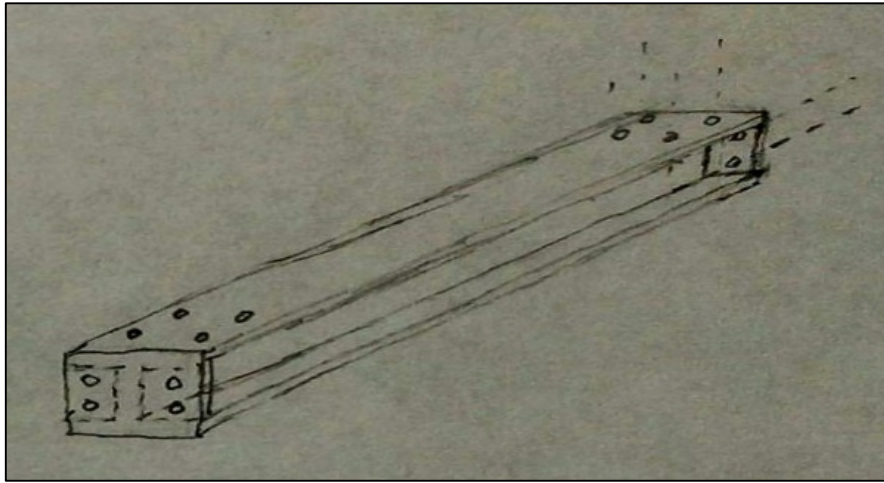
Figure 11. A concept for the mounting plate of the bumper.

This concept is also for the front plate of the mount. The most significant difference from the previous concept is the cross section. The influence is an I-beam configuration, specifically using as short of a bracket as possible while still maintaining a strong geometrical form. The shape of the I-beam allows for multiple mounting locations either along the beam or against a flat square plate extruded from the end of the beam. This produces possible mounting configurations for varying bumper styles in various dimensions. The I-beam cross section it should be able to withstand multiple crashes and the web should accommodate sensor integration.

1.6 Revised Concept Generation

Motivation

Upon the assessment of the concepts, many of the previous ideas were critiqued for not being able to sufficiently meet all of the functions and targets. However, many of them appeared to have the ability to attach to a variety of structures. These aspects in the designs were inversely

related. The team could not find a design aspect to modify a design to make it both stronger without reducing its capability to attach to a variety of surfaces. Prior to the initial concept generation, the only structure that had been thoroughly inspected was the test vehicle with the solid frame mount bumper. As a result, the amount of modularity needed in a design was not clear. At the time, team members could not clearly answer the question, "What two bumper mounting structures vary the most, and in what aspects?" Since the initial concept generation, the team has inspected additional bumpers with different structures and a few were chosen for early testing. From seeing these other types of structures, the team realized that much of the modularity in the original concepts exceeds the amount of variety in the bumpers used for testing. From here, team members were able to reduce the amount of motion required in each design and this significantly increased the expected strengths of the concepts.

For the second attempt at concept generation, the team started off by looking at the original concepts and ranking them with a quick check against the functions. Concepts were given a score, 1, 3 or 5, in each function. On this scale a score of 1 indicates that the design performs poorly for that function, while a 5 indicates that the design meets the function superbly. From this initial assessment, design #1 and #3 scored the highest. When looking at the rest of the scores, the team realized the lower scoring concepts scored low because they were too modular, which led to not being able to withstand as many tests. Additionally, the low scoring designs were not stiff enough to transfer the dynamic impact sufficiently.

Original concepts were assessed to see what was desirable and what direction the team wanted to think about or keep during the second pass of concept generation. Design #1 was identified as most promising by our sponsor's assessment as it seemed relatively strong and

capable to hold multiple bumper. Design #3 performs all tasks quite well except for a total lack

of modularity. The team decided to generate concepts related to the ideas that these two systems

were based upon. From design #1: a large surface to attach mounts in a variety of ways, where

placement can be modified over time and from design #3: tubes and brackets should be small for

structural purposes and simple to manufacture in case they need to be replaced. The new

concepts are detailed subsequently.

Additional Concepts
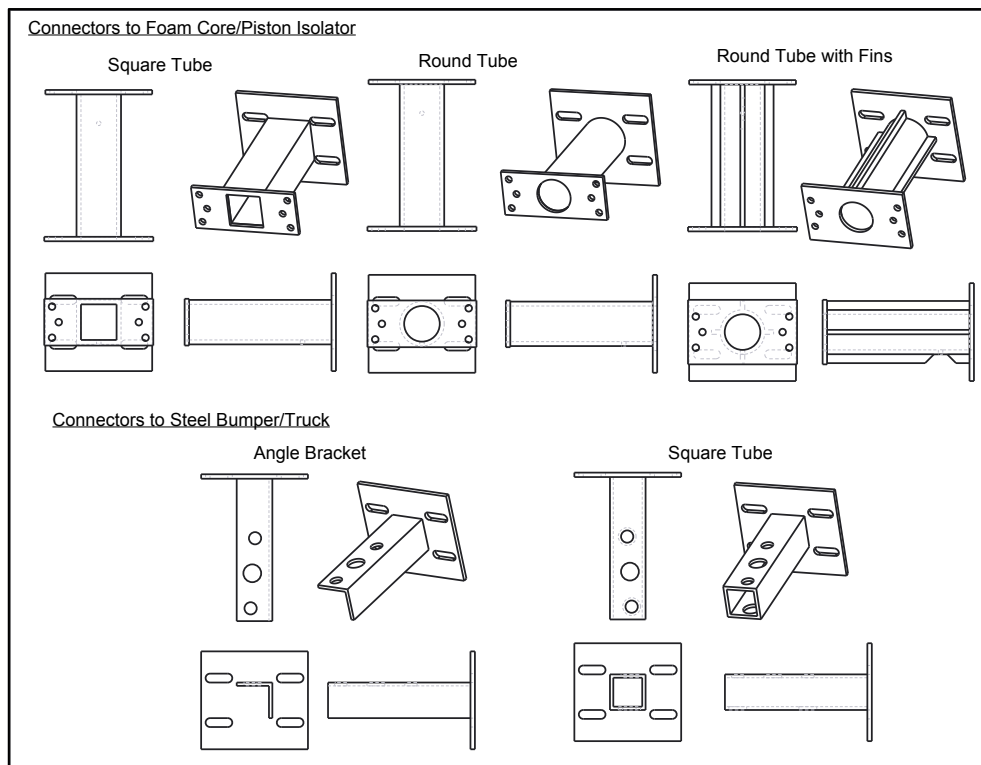
Figure 12. Concepts for interchangeable bumper mount connectors.
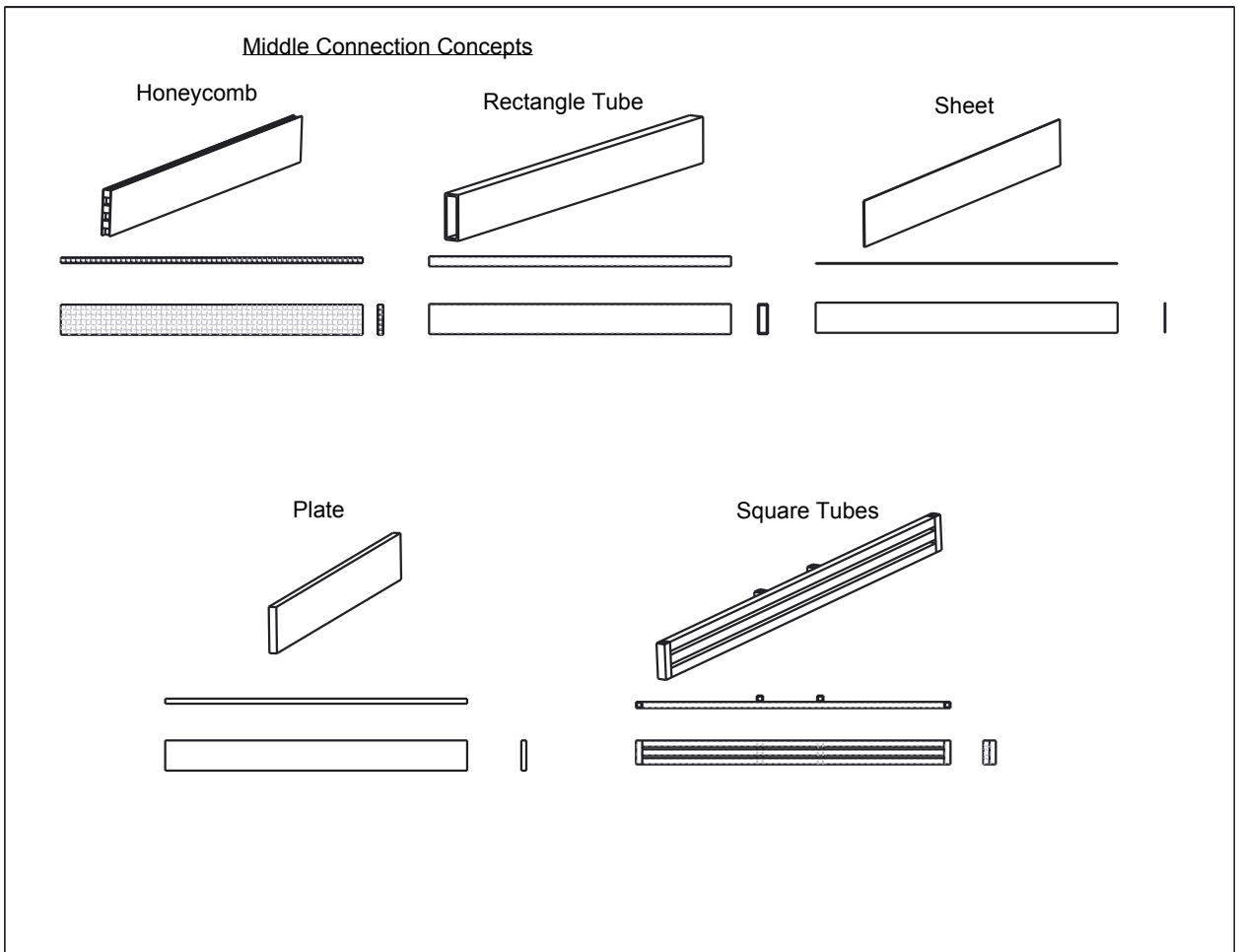
Figure 13. Concepts for the middle connection piece.

After picking the general concept from the first set of concepts the team worked on

finalizing a version of this idea. The concept includes adapters or connectors of different

versions (shown in Figure 12) to allow changing the bolting pattern of the vehicle to a general

flat plate This plate has holes that allow bolting to a center piece which would have similar

adapters bolted to the other side to allow adapting to the bumper of choice at the time. The team

decided we would need two sets of adapters, one for steel bumpers and one for foam core or

piston isolator bumpers. This is because the steel bumper mounts to holes horizontally oriented

and the other bumper's holes are vertically oriented. The same adapters could be used whether mounting to a vehicle or a bumper as they are mirrors of each other. The middle piece (shown in Figure 13) allows the width between mounting points to vary based on the vehicle and bumper being tested. Having this piece span the full width of the vehicle helps negate the effect of the moment being applied from a change in width. Different concepts were developed to address the previously mentioned considerations.

To start different methods for connecting to a foam core or piston isolator were generated. All concepts possess a flat plate on one side with holes to allow bolting to the middle piece. On the opposite side of this plate there is a plate with mirrored holes drilled in it to allow the bolting of the foam core or piston isolator bumper without the need to worry about the orientation of the bolt holes. Once the plate geometry had been established, ideas for the geometry between the plates were formulated. As seen in Figure 12, three potential ideas are a square tube, a round tube, or a round tube with fins placed around it. All would have an opening in the middle where a piston could be placed and would still be sufficiently sturdy to transfer the forces from the collision.

The next type of connector to decide on was one to steel bumpers, such as the one that came off of the test pickup truck. Both designs formulated had a plate just like the previous adapters that allow bolting to the middle width adapter. The two ways we decided we could mount to the steel bumper or the truck were by using a piece of angle, which is how the stock bumper mounts to the truck, or with a piece of square tubing. The latter essentially mirrors the existing angle mount. Both would have holes drilled in the same pattern but the square tubing

has more material to help transfer any loading without deformation or changing the dynamics applied to the vehicle.

The last part, and the part that could most affect the transfer of the dynamic load, is the middle piece. The middle piece must be wide enough to span from one frame rail to the other on most vehicles and allow the different connection pieces selected to be mounted. Five options were generated for this piece. The three simpler ideas were to purchase a piece of metal that could fit the needs. This could be a solid thick plate, a piece of sheet metal, or a long, rectangular tube. An additional option is to fabricate and build a honeycombed middle section similar to techniques used in aircraft to lower weights while keeping the strength high. The final option generated uses a frame of square tubing with with gaps left between the tubes that travel the width of the vehicle. These gaps would create slots for bolts where the width could be changed without adding holes to the structure. All of these concepts are shown in Figure 13.

Each concept generated satisfies the overall functions desired from the mount. The most basic function they allow is the mounting of different style bumpers to a test vehicle. Additionally, each design could intuitively stand up to repeated impacts, while still transferring the dynamic load to the vehicle in an unaltered fashion. Finally, for data recording during live crash testing, each concept possesses a large area to mount accelerometers.

1.7 Concept Selection

Moving from the concepts generated in the second phase of the concept generation stage, a concept selection process was employed. In order to select a concept, Pugh charts were used to compare designs. This method of concept selection was chosen due to the ease with which the

existing target and functional parameters could be contrasted between designs. In order to avoid bias in the concept selection phase, all team members assisted with the assignment of relative ranks and weights for the selection criteria and each value was discussed thoroughly. Relative ranks on performance are scored against a datum design. The datum designs were chosen to be the design in each case that was the simplest or most closely resembled the existing mounting assembly on the bumpers found during the team's bumper inspections. Relative ranks for the connectors are assigned on an integer scale from -1 to 1, where a -1 indicates the design performs worse than the datum for the selection criteria, a 1 indicates that the design performs better than the datum, and a 0 indicates that the design performs as well as the datum.

Two Pugh charts were made for the selection of the middle connection piece, due to the larger number of concepts generated. The initial Pugh chart can be found in Appendix C: Concept Selection. The final Pugh chart is shown Table 4**.** The initial Pugh chart included all five of the generated middle connections, while the final Pugh Chart compares the three highest scoring designs from the initial Pugh chart. The final Pugh chart follows a different relative ranking scale than the Pugh charts for the connectors and the first Pugh chart for the middle connection piece in order to achieve a higher resolution and hone in on the optimal design. This scale ranges from -3 to 3, where a -3 indicates the design performs worse than the datum design, a 0 indicates the design performs as well as the datum design, and a 3 indicates the design performs in a superior manner to the datum.

The selection criteria were generated from the previously discussed functions and targets. The functions and targets were combined in certain cases to create more general selection criteria. Additionally, functions and targets may correlate to more than one selection criteria. For

instance, impact strength correlates to the delta-v of the crash test runs and the transfer of the dynamic load, while fatigue strength relates to the number of tests the device can withstand, as well as the delta-v of the crash test runs.

Additionally, weights were assigned to the selection criteria to increase the resolution provided by the Pugh chart. A weight of a 1 indicates a low importance, while a weight of 3 indicates a high importance. Higher weights were assigned to the strength values due to the fact they will be subject to repeated impact testing. Additionally, a weight of 3 was assigned to the requirement that the mount must hold multiple bumper types, since this is a fundamental need of the customer. Lower weights were assigned to criteria that did not directly precipitate from the customer needs assessment, functional decomposition, or target generation, as they would enhance the project, but are not critical.

Connectors

Table 2

Piston Isolator/Foam Core Pugh Chart

Selection Criteria	Weights	Square Tube	Round Tube	Round Tube with Fins
Impact Strength	3		1	1
Fatigue Strength	3		0	0
Mounting accelerometers	3		-1	-1
Ease of manufacture	2	Datum	0	-1
Weight	2		1	-1
Ability to accommodate multiple types	3		0	0
Field modification	1		0	0
Buckling strength	3		1	1
Aesthetic Value	1		0	1
Score	**-**	**0**	**5**	**0**

For the piston isolator and foam core bumper mounts, the Pugh chart produced a preferred design of a simple round tube against the square tube datum, as shown in Table 2. Comparatively, round tubes will have advantages over the other alternatives in impact and buckling strength due to the reduction of stress concentrations in the bracket geometry and their ability to transfer a load without structural error. Additionally, they are lower in weight, since less material is being used. The round tube with fins shares advantages only in impact and buckling strength. The fatigue strength for both will be different but only slightly such that the difference is negligible. The ease of manufacturing for the round tube is unaffected since round and square tubes are readily available for purchase. The field modification and accommodation ability stay the same for both since each bracket uses predrilled holes and they all have similar mounting plates.

The only criteria where the round tube becomes less desirable is in meeting the function regarding sensor placement, since a round surface would require special mounting points to properly situate a sensor. For the round tube with fins, three criteria, including the mounting area for accelerometers, produce lower scores when compared to the square tube. Adding the fins will require more material, and it is likely to surpass the weight of the other tubes because of this. Fins will also complicate the geometry and thus the manufacturing process of the resulting bracket.

Table 3

Solid Frame Mount Pugh Chart

Selection Criteria	Weights	Angle Bracket	Square Tube
Impact Strength	3		1
Fatigue Strength	3		1
Mounting accelerometers	3		-1
Ease of manufacture	2	Datum	-1
Weight	2		-1
Ability to accommodate multiple types	3		0
Field modification	1		0
Buckling strength	3		1
Aesthetic Value	1		1
Score	**-**	**0**	**3**

For the solid frame mount, the angle bracket was chosen as a datum since it matches the type of mount pulled from our test vehicle. This was compared to the designed square tube mount using the Pugh chart shown in Table 3. In terms of impact strength, fatigue strength, and buckling strength, the square tube produces more desirable results, due to the larger cross-sectional area

that experiences a load, as well as the inherent symmetry in the geometry. This will subsequently require more material and increases the required effort in manufacturing and sensor placement, thus it scores lower than the other alternatives in these categories. The ability to both accommodate multiple types of bumpers and modify readily in the field remain unchanged since holes will be predrilled and mounting plates are all the same.

Middle Connections

Table 4

Middle Connecting Piece Pugh Chart

Selection Criteria	Weights	Plate	Honey Comb	Square Tube
Impact Strength	3		-1	-1
Fatigue Strength	3		-1	-1
Mounting Accelerometers	3		1	2
Ease of Manufacture	2	Datum	-3	-1
Weight	2		1	2
Ability to Accommodate Multiple Types	3		0	0
Field Modification	1		1	3
Buckling Strength	3		-1	0
Aesthetic Value	1		3	1
Score	**-**	**0**	**-6**	**6**

The second component of the interchangeable bumper mount design was the middle mounting section. After an initial Pugh chart analysis, three different members were compared in the final Pugh Chart. These are: a square plate, honeycomb members, and square tubes. Both strength criteria, impact and fatigue, are directly correlated with a specimen's volume and because of this the square plate mounting assembly would be more optimal for this category. Holes will need to be drilled in the mounting assembly to secure accelerometers for data collection. The honeycomb and the square tube concepts are thinner structures and would allow

for easier drilling. Fin structures on the inside of the honeycomb members would cause greater resistance to the drilling, so the square tubes were considered to have a greater area for accelerometer attachment. Unsurprisingly, the square plate comes in last in the weight division due to its greater density. All considered bumper mounting assemblies can accommodate each bumper type that will be tested so they receive the same score for this criteria. During testing the mounting assembly may need to be modified to allow for the attachment of the various bumper types that will be examined. With the square tube assembly, no additional holes would need to be drilled; therefore ease of adaptability places this particular mounting concept at the top of the field use category. Finally, buckling strength was a major category that was considered in the mounting selection process. The buckling strength for the plate would prove greater than the other considerations due to it being a single solid piece.

Justification of Selected Design

As shown in the Pugh charts above, the selected concepts were the round tubing for the piston isolator and foam core bumper structures, the square tubing for the solid frame mount bumper structure, and the square tubing middle connection. Due to the appropriate choice of weights and the proper assignment of relative ranks for a given selection criterion, the results output from the Pugh Chart are accurate. A summary of the justification for each selection is detailed subsequently.

Over the course of live crash testing, each bumper structure will be tested. Therefore, it is imperative to have connecting pieces that accommodate each type of bumper. The round tube connector was selected for the foam core and piston isolator structures due to the readily available components necessary to construct the connector, the lack of stress concentrations

present in a circular cross section as opposed to a square cross section, and its geometrical ability to handle compressive loads without buckling. For the solid frame mount bumpers the square tube was selected primarily due to its symmetry as opposed to the piece of angle that was pulled off of the exemplar solid frame mount bumper. This symmetry allows for enhanced load distribution capabilities and provides a large surface for mounting of accelerometers, while being a readily available component that can be purchased.

A concept was also selected for the center mounting piece of the interchangeable bumper mount. From the final Pugh chart for this design, the square tube design was selected. This design can be constructed from readily available materials. Though the manufacturing process is not as easy as the rectangular tube, solid plate, or sheet metal, it is easier to construct than the honeycomb option and can still be fabricated relatively easily. Additionally, this allows for the easy interchange of connector types without field modification due to the slots between the square tubes as shown in Figure 13**.** Care will need to be exercised when selecting accelerometers and mounting them to the center mounting piece. This is due to the spacing between the square plates, as well as difficulty in using standard fasteners (i.e. not using blind fasteners) on the square tubing. Team 2 has investigated mounting methods for accelerometers and has asserted that it is possible to mount them using either adhesives or stud mounting. This concept is superior to the other concepts due to its lighter weight and lack of necessary field modification, while still maintaining its ability to be constructed from readily available materials. Additionally, due to geometric considerations, this design has sufficient resistance to impact, fatigue, and bucking.

The generated concept for the interchangeable bumper mount meets the previously

outlined needs of Cummings Scientific. This is detailed in

Table 5, where the left column repeats customer needs statements from

Table 1 and the right column describes features of the design that enable this need to be met.

Table 5

Customer Needs and Concept Correlation

Customer Needs Statement	Relevant Features of the Selected Concept
Customer needs a method to collect data on low speed collisions to allow building of model	Allows for mounting of bumpers and sensors for data collection
Customer needs a model based on empirical data	Allows for mounting of bumpers and sensors for data collection

Customer needs a crash test that can be performed on the same vehicle multiple times	Varied connectors allow for multiple types of bumpers to be connected to the mount, which is affixed to a single vehicle
Customer needs high fidelity models of occupant and vehicular response	Geometries of components allow for accurate transfer of dynamic load; Proposed size and weight of components should not affect vehicle dynamics
Customer needs a way to validate injury criterion for low-speed rear-end collisions through occupant responses	Geometries of components allow for effective transfer of dynamic load to occupant; Allows for mounting of sensors for collection of crash test data
Customer needs a device that allows for repeatable testing of multiple bumper structures	Varied connectors allow for multiple types of bumpers to be connected to the mount

1.8 Project Plan

At the conclusion of the Fall 2017 semester, team two had completed a conceptual design of the Interchangeable Bumper Mounting device. This section details the tasks remaining to be completed, major milestones in the project and course and proposes a timeline spring semester. The first two major tasks remaining for the spring semester are to produce a detailed design of the Interchangeable Bumper Mounting device and fabricate a prototype. Subsequent to this, Team 2 can move forward with live crash testing and the generation of the empirical models of the occupant and vehicular responses to the low speed rear-end crash. A timeline of these tasks is shown in Figure 14. Below Figure 14 a description of each task is provided, as well as a justification for its inclusion and the time allotted.
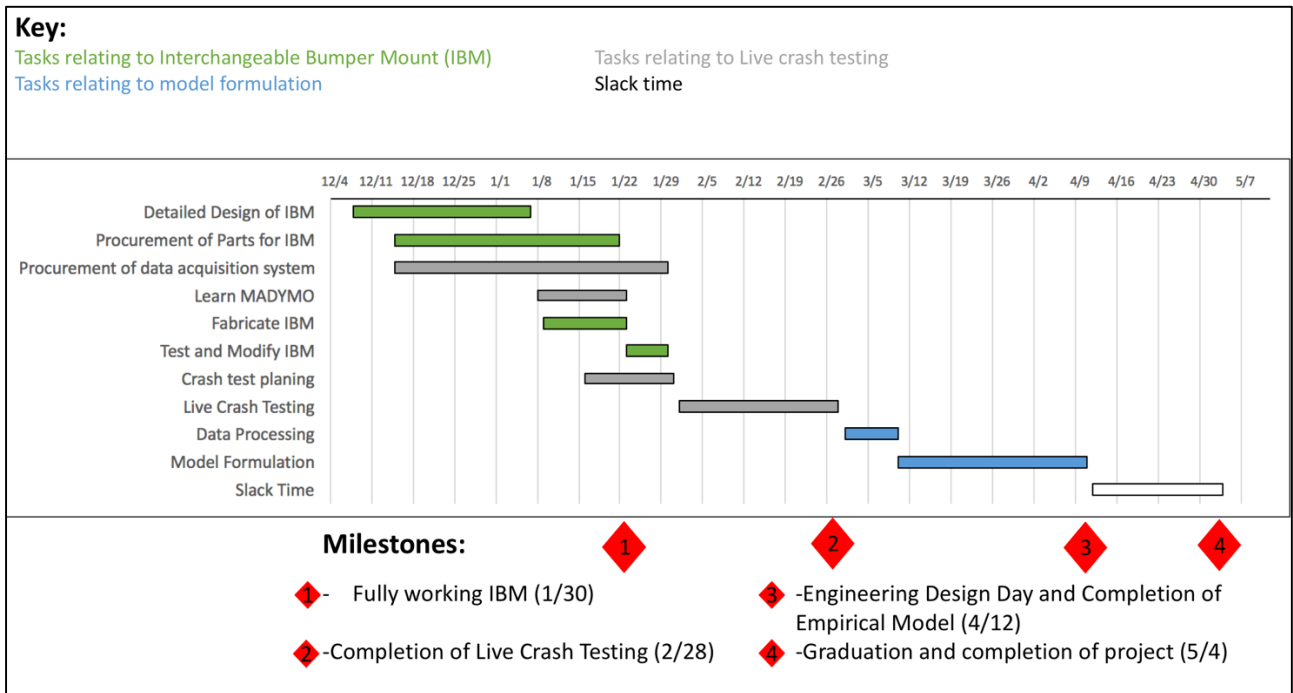
Figure 14. A proposed Gantt chart for the spring semester.

The tasks remaining to be completed are grouped into three major categories: tasks relating to the Interchangeable Bumper Mounting Device, tasks relating to live crash testing, and tasks relating to the development of the empirical model. Times for completion of each of the tasks were established based on discussions with the project sponsor. Milestones are shown as red diamonds with a description of each milestone below the Gantt chart. Milestones will be appended to as the schedule for course deliverables becomes available. The project and all documentation must be completed by 4 May 2018, the last day of the spring semester. Team 2 aims to have models for the occupant and vehicular responses formulated by 12 April 2018, which is Engineering Design Day. The remaining time between 12 April and 4 May will be

devoted to final documentation, as well as refinement of the models where necessary. This is the built-in slack time to the project plan.

As shown in Figure 14, the Interchangeable Bumper Mounting Device will be fabricated and tested for compatibility with the test vehicle and selected test bumpers by the end of January. Due to the simplicity of the design, the fabrication will be done in house. Although members of the team have welding experience, there is no one certified to create welds that are likely to pass inspection and transfer a load correctly. In the tests performed, the load will be transferred linearly through the bumper mount. Each piece in the design between the vehicle and bumper are sandwiched together meaning no load will be transferred through a weld on the design. In the event the width of the bumper and vehicle frame are dramatically different, the moment created would be transferred through sections of the pipe that would remain unmodified from the factory. Without having any critical load bearing welds, having the team building the interchangeable bumper mount would save money that could be reallocated for data acquisition systems and testable bumpers. This would also provide, valuable machine shop practice for the team members.

The January completion deadline for the construction Interchangeable Bumper Mounting Device will allow the team ample time to conduct live crash tests and process the data necessary to complete the empirical models of the occupant and vehicular responses, which is the end goal of the project. This constraint also implies that Team 2 will need to begin to purchase components in December (after the completion of the majority of the detailed design) and January for the Interchangeable Bumper Mounting Device.

Live crash testing will occupy the month of February. This implies that the data acquisition components will need to be obtained during the months of December and January. Outside of the accelerometers necessary for crash test data, all equipment will be borrowed from Cummings Scientific. Therefore, the previously mentioned time is appropriate for acquisition of the components is sufficient. Following the conclusion of live crash testing, Team 2 is left with approximately a month-and-a-half to formulate the occupant and vehicular empirical response models before Engineering Design Day. This should be possible, due to the fact that Team 2 has scheduled learning the MADYMO software program prior to the completion of live crash testing.

In conclusion, the Gantt chart was constructed after consultation with the Cummings Scientific liaison engineer and the course instructor. In order to conduct live crash testing, the Interchangeable Bumper Mount must be completed and test-fit with the test vehicle and test bumpers first. Therefore, all of the tasks concerning the creation of this component must be accomplished first. Once this is complete, live crash testing and modeling will commence. As far as component acquisition, the longest component to acquire will likely be the necessary components for data acquisition, since all of the parts for the Interchangeable Bumper Mount are standard, readily available parts.

Chapter Two: EML 4552C

2.1 Revised Project Scope

The primary objective of the project is to develop an empirical model of occupant and vehicle responses in a low speed, rear-end vehicular crash with an emphasis on the effect of bumper structure on the two responses. In order to develop this model, live crash testing will be performed. As such, a secondary objective of the project is to design a mount that allows multiple bumper to be interchangeably mounted to the same vehicle. This will enable the testing of multiple bumper structures for the evaluation of the effect that different bumper structures have on the response the vehicle and passenger without the purchase of multiple vehicles for testing.

Project Stakeholders

As the sponsor of this project, the primary stakeholder on this project is Cummings Scientific, LLC (Cummings Scientific). Cummings Scientific estimates that they take hundreds of cases each year where occupants claim catastrophic injury from a low-speed collision. Once the occupant and vehicular responses are characterized, the Cummings Scientific biomechanician will use the model to look at potential occupant injuries. Therefore, Cummings Scientific will primarily benefit from the empirical models of occupant and vehicular responses. This will also benefit the plaintiffs and defendants they represent. Furthermore, as the empirical model is adopted in the traffic accident reconstruction industry other forensic consulting firms could benefit from this model for vehicle and passenger response. In addition, designing and validating the crash test device will offer a proof of concept to the accident reconstruction industry for repeated crash testing with a single vehicle. Finally, another beneficiary of this model and device

is the automotive design industry. A crucial facet of the automotive design industry is the safety of passengers. Having a clear idea of the occupant and vehicular responses to a low speed rear-end collision and the effect of bumper structure on these responses can enable them to design vehicles that perform in a safer manner during these kind of collisions.

Project Assumptions

Due to the time constraints placed on the project, the initial results of this research will be applicable only to vehicles that are able to withstand very low speed impacts with negligible structural damage after multiple tests. Additionally, this project will consider bumper structures that are primarily marketed in the United States, not world markets.
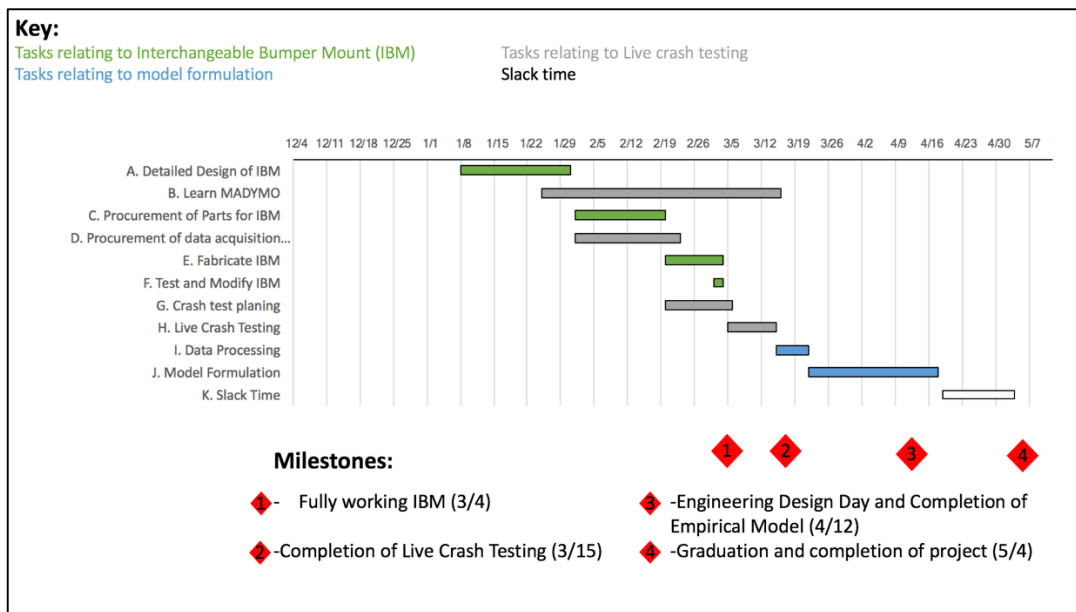
2.2 Spring Project Plan

Figure 15. Proposed Project Plan for Spring 2018

The proposed plan for project completion is shown in Figure 15. Tasks remaining for the spring semester involve finishing the detailed design of the Interchangeable Bumper Mount

(IBM), procuring stock to construct the IBM and sensors for test, fabrication of the IBM, live crash testing, processing the data from the live crash tests, and formulating the empirical model of the occupant and vehicular responses to the collision. In addition to these tasks is learning to use the MADYMO program for model generation and standard project documentation. The dates in Figure 15 were established through team member discussions with the project sponsor. Table 6 shows the owner for each task listed in the Gantt Chart. Ownership was assigned based on the team member roles established at the start of the project.

Anticipated bottlenecks are purchasing components and instrumentation, as well as fabrication of the IBM. This was accounted for with the longer duration given to the timelines for these tasks. Regarding the fabrication of the IBM, fabrication will not occur in-house, as stated in the Fall semester. This was due to the skill sets possessed by the team members, and advisement of the project sponsor.

At of the beginning of the Spring 2018 semester Team 2 had all $2,000 of their budget remaining. It is estimated that $1000 of the budget will be allotted for materials for the IBM and its fabrication. The remainder of the budget will be used to purchase instrumentation for the data acquisition system for the live crash testing.

Table 6

Owners of each task

Task	Owner
A. Detailed Design of IBM	William
B. Learn MADYMO	Orion
C. Procurement of parts for IBM	Dylan
D. Procurement of data acquisition components	Jacob
E. Fabricate IBM	William
F. Test and Modify IBM	Caroline
G. Crash test planning	Jacob
H. Live crash testing	Caroline
I. Data processing	Dylan
J. Model Formulation	Orion
K. Slack Time	Caroline

References

Brach, R. M. (2003). Modeling of Low-Speed, Front-to-Rear Vehicle Impacts.

Wang, Q., & Gabler, H. C. (2007). ACCURACY OF VEHICLE FRONTAL STIFFNESS ESTIMATES FOR CRASH RECONSTRUCTION. *20th International Technical Conference on the Enhanced Safety of Vehicles (ESV).* Washington, DC: National Highway Traffic Safety Administration.

Appendices

Appendix A: Code of Conduct

The code of conduct contained in this appendix represents the guiding principles and policies of team 2.

Mission Statement

Team 2 is committed to creating a professional, positive environment that fosters integrity, innovation, personal growth, and cohesiveness. Through this environment the members of Team 2 will be enabled to devise solutions to the unique engineering challenge set forth by Cummings Scientific, LLC (henceforth referred to as "sponsor") by applying the knowledge gained from their academic studies and professional experiences as mechanical engineering undergraduates.

Team Member Roles and Responsibilities

Team member roles and responsibilities were assigned based on consensus of the entire team. In general, team members were assigned to a specific role based on their individual skill-sets, interests, and experiences. All roles are summarized in the organizational chart shown in Figure 16.
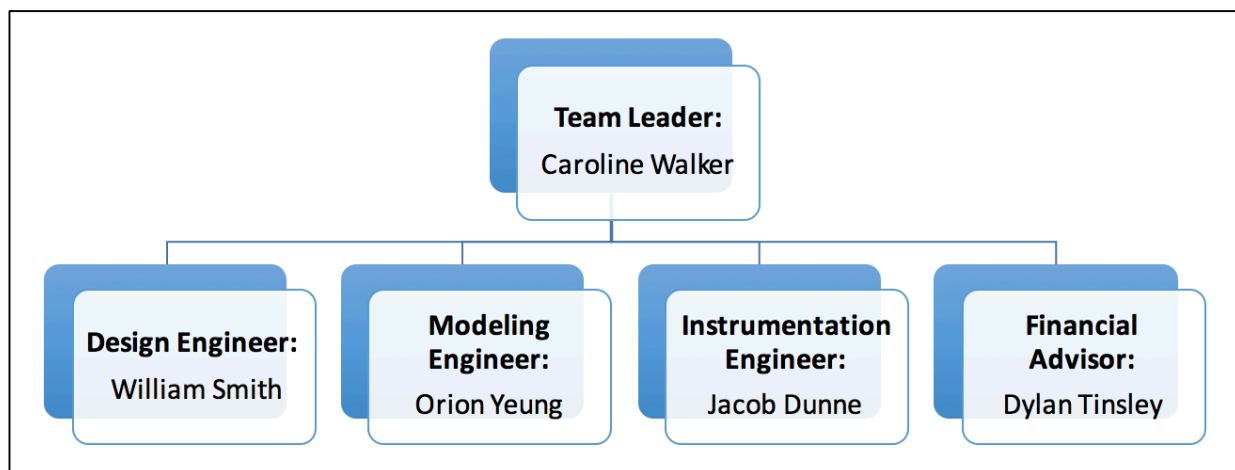
Figure 16. An organizational chart detailing the structure of Team 2.

The primary responsibilities of each role are detailed in the subsequent sections of this document. In general, all team members agree to contribute to the best of their abilities to the overall success of the project; be respectful of other teammates, the sponsor, faculty advisor, and any others they may interact with during the course of this project; and follow through on any commitments they make over the course of the project in a satisfactory manner.

1.1 Team Leader- Caroline Walker

The team leader is responsible for all team management duties, including, but not limited to the following: delegating tasks to team members based on their assigned roles and skills; ensuring the cohesiveness and functionality of the team as a whole; and facilitating, organizing, and planning weekly team meetings, as well as sponsor and advisor meetings. The team leader is responsible for making certain that the timeline laid out for project completion is adequate and enables accomplishment of main project goals. Additionally, the team leader oversees any modifications that must be made to the project schedule over the course of the year.
In addition to managerial duties, the team leader reviews and submits all deliverables and team based coursework. During the review process, the team leader must ensure the technical accuracy of the work and that all requirements set forth by the sponsor or professor are addressed. These aforementioned tasks arise out of the team leader's obligation to facilitate communication between the team, sponsor, faculty advisor, and course professor. This role also implies that the team leader will oversee all presentations, even when not actively presenting.

1.2 Design Engineer- William Smith

This team member supervises the design and fabrication of any physical test components that are required to complete the project. The design engineer is responsible for documenting all possible design alternatives, as well as justifying the selected design of the physical test components. The design engineer will furnish models, graphics, and drawings where necessary to technically communicate the intent of any design to Team 2, the sponsor, faculty advisor, and other parties as the project requires.

1.3 Modeling Engineer- Orion Yeung

The modeling engineer will be primarily responsible for simulation. Simulation consists of employing the Mathematical DYnamic Models (MADYMO) software suite to identify points of interest for sensor location during experimentation. Additionally, the modeling engineer is responsible for generating animations for presentations and reports where necessary to enhance communication of the project's progress and objectives.

1.4 Instrumentation Engineer- Jacob Dunne

The instrumentation engineer acts as a liaison between the design engineer and modeling engineer. As such, the instrumentation engineer should be well-informed about the current status of physical component design and fabrication, as well as the status of any dynamical models for the project. The instrumentation engineer will play a crucial role in selecting the proper sensors and data acquisition items for the test portion of the project.

1.5 Financial Advisor- Dylan Tinsley

The financial advisor is responsible for maintaining and accurate and transparent record of all project funds, debits, and credits. The financial advisor reviews expenditure requests and purchases items for the project. The financial advisor must have approval from the majority of the team (three of five members), including the team leader to make a purchase. The Financial Advisor is responsible for generating content for financial sections of all reports and presentations.

As a summary of how team members' roles relate to the main topics of the project, the network shown in Figure 17 was created. In Figure 17 each team member is represented by an ellipse at the bottom of the network, major components of the project are signified by the squares at the top, and the paths connecting the team members to the components indicate the team members' primary areas of responsibility. Each path is color coded by the team member it corresponds to. The conclusion from this network confirms the purpose of assigning roles to team members, namely that the project workload is effectively divided and team members retain the ability to collaborate on sections of the project.
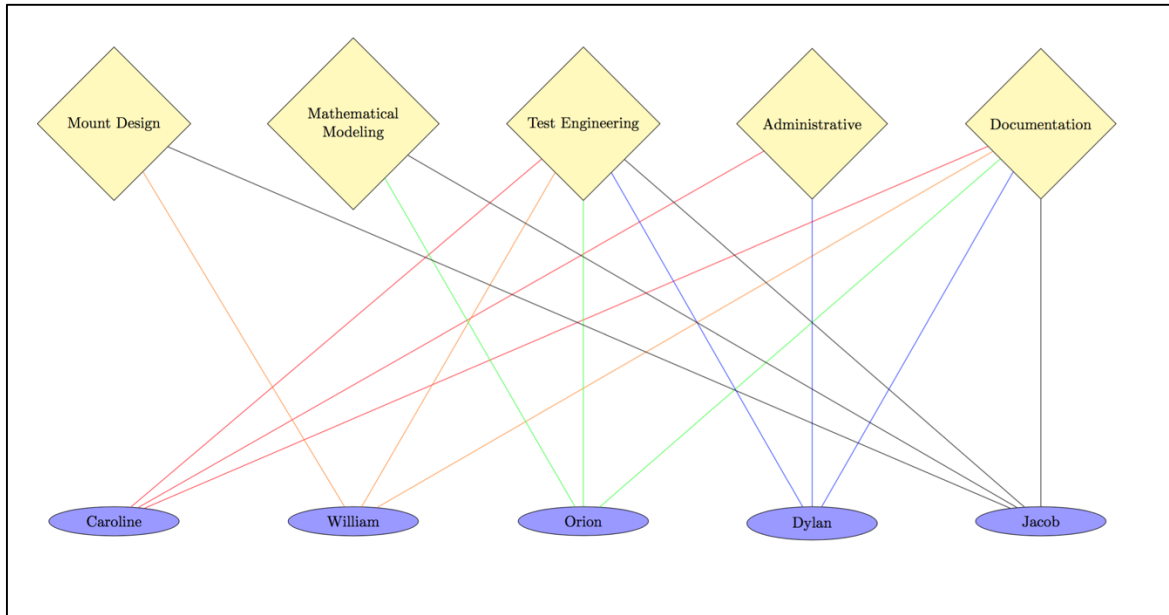
Figure 17. A network detailing the primary areas of responsibility for each team member.

Communication

The primary methods of communication between team members will be through the use of the GroupMe messaging application and phone calls. Secondary methods of communication between team members will be email and standard text messaging. The primary method of communication with the sponsor shall be through email. As such, it is required that all team members have a functional email account. Team members are responsible for checking the GroupMe application and their email at least twice per day to ensure proper dissemination of information. The primary method of file transfer will be through email. If a file is too large to be emailed, Google Drive, Dropbox, or a similar application will be used for file transfer.

Work Schedule

The regularly scheduled senior design class time (Tuesday/Thursday from 1400 to 1815 hours) will be a standard work period for Team 2. Team members are expected to be present

during the time of the regularly scheduled senior design class time, unless the team leader has been notified ahead of the class. Additional work times will occur on Monday afternoon and evening, Tuesdays after senior design class time, Thursdays after senior design class time, and Friday afternoons. Weekends will be utilized as needed.

Meetings

Weekly team meetings will occur each Thursday immediately following the conclusion of the senior design class. If the lecture period ends earlier than scheduled, the meeting will be held directly following the conclusion of the lecture. If no lecture is held, then meetings will occur at 1400 hours. This meeting will serve as an opportunity to gauge the current status of the project, prepare presentations and reports, and ensure all team members are informed of their tasks, as well as other team members' tasks. Additional meetings will be announced via GroupMe or email at least 24 hours in advance of the meeting. All meetings will take place at the College of Engineering unless another location is specified at least 24 hours in advance of the meeting.

It is Team 2's goal to hold bi-weekly meetings with the sponsor, at a time to be agreed upon by the sponsor and Team 2 within the first two weeks of the project. These meetings may be held via teleconference or in person with the sponsor. The mode of communication and the location of the meeting will be announced at least 24 hours in advance of the meeting. Additionally, Team 2 plans to meet regularly with their assigned faculty advisor. Within the first two weeks of the project a time to meet with the faculty advisor will be established and communicated to all team members.

If a team member is unable to attend any meeting, they are responsible for letting the team leader know as soon as reasonably possible (preferably 24 hours before the meeting is scheduled to take place). Repeated absences from meetings without sufficient notice will not be tolerated.

Decision Making Guidelines

When making decisions, each team member pledges to approach the issue at hand from a logical standpoint and act in an ethical manner that is best for the project and team as a whole. Major project decisions (i.e. changes to project schedule, major deviation from a plan or design established by the entire team, significant expenses, etc.) shall be made by consensus of the entire team. In general, major decisions, shall be made during weekly team meetings or in bi-weekly meetings with the sponsor. If a major decision must be made outside of this time consultation with the team may occur during an unscheduled team meeting, via the GroupMe application, email, phone call, or other appropriate means. Decisions that are not considered major can be made by individual team members without prior consultation with the entire team. The team shall then be notified of the decision within a reasonable amount of time. Team members shall make every effort to avoid conflict of interest when making decisions.

Dress Code

Casual attire is acceptable for weekly team meetings, unless otherwise specified 24 hours in advance of the meeting. For sponsor meetings, advisor meetings, as well as presentations that attire will range from business casual to formal. The exact attire will be agreed upon 24 hours in advance of the event.

Conflict Resolution

If there is a dispute between team members, the team members will attempt to solve the conflict between themselves. If a resolution is unable to be reached, the team members will approach the team leader who will intervene and attempt to reach a resolution. If the team leader can not resolve the conflict, the course professor will be approached for reconciliation purposes.

Ethics

The ethical guidelines specified by the National Society of Professional Engineers (NSPE) Code of Ethics shall be the guiding ethical code for Team 2. All team members are expected to be familiar with these standards and carry them out to the best of their abilities.

Revision Policy

If a revision to the aforementioned principles is needed, the following procedure shall be enacted. The need for a revision to the Code of Conduct will be communicated to the entire team and potential modifications proposed by any team member. The majority of team members (three of five) shall approve the modification. The team leader is responsible for updating the Code of Conduct in accordance with the approved modification.

Appendix B: Target Catalog

This appendix contains a comprehensive list of all targets for the project. They are divided into two major categories. The first is an interchangeable bumper mount category and the other is a test and instrumentation target category.

Table 7

Interchangeable Bumper Mount Targets

Target	Value
Number of impacts sustained	Minimum of 15
Number of different bumper styles tested	4
Minimum number of accelerometers	3
Delta-v of crashes	Less than 4 mph
Number of tests	Minimum of 15

Table 8

Test and Instrumentation Targets

Target	Value
Range of accelerometers	$\pm 25g$
Sampling frequency of accelerometers	100 Hz
Minimum number of accelerometers	3
Delta-v of crashes	Less than 4 mph
Number of tests	Minimum of 15

Appendix C: Concept Selection

The Pugh charts for concept selection are found here.

Table 9

Piston Isolator/Foam Core Pugh chart

Selection Criteria	Weights	Square Tube	Round Tube	Round Tube with Fins
Impact Strength	3		1	1
Fatigue Strength	3		0	0
Mounting accelerometers	3		-1	-1
Ease of manufacture	2	Datum	0	-1
Weight	2		1	-1
Ability to accommodate multiple types	3		0	0
Field modification	1		0	0
Buckling strength	3		1	1
Aesthetic Value	1		0	1
Score	**-**	**0**	**5**	**0**

Table 10

Solid Frame Mount Pugh Chart

Selection Criteria	Weights	Angle Bracket	Square Tube
Impact Strength	3		1
Fatigue Strength	3		1
Mounting accelerometers	3		-1
Ease of manufacture	2	Datum	-1
Weight	2		-1
Ability to accommodate multiple types	3		0
Field modification	1		0
Buckling strength	3		1
Aesthetic Value	1		1
Score	**-**	**0**	**3**

Table 11

Initial Middle Connecting Piece Pugh Chart

Selection Criteria	Weights	Rectangular Tube	Honeycomb	Plate	Sheet	Square Tubes
Impact Strength	3		1	1	1	1
Fatigue Strength	3		1	1	-1	1
Mounting Accelerometers	3		-1	-1	0	-1
Ease of Manufacture	2	Datum	-1	0	0	-1
Weight	2		-1	-1	1	-1
Ability to Accommodate Multiple Types	3		0	0	0	0
Field Modification	1		0	-1	0	1
Buckling Strength	3		1	1	-1	1
Aesthetic Value	1		1	0	0	1
Score	**-**	**0**	**3**	**3**	**-1**	**4**

Table 12

Final Middle Connecting Piece Pugh Chart

Selection Criteria	Weights	Plate	Honeycomb	Square Tube
Impact Strength	3		-1	-1
Fatigue Strength	3		-1	-1
Mounting Accelerometers	3		1	2
Ease of Manufacture	2	Datum	-3	-1
Weight	2		1	2

Team 2

47

2018

Ability to Accommodate Multiple Types	3	0	0
Field Modification	1	1	3
Buckling Strength	3	-1	0
Aesthetic Value	1	3	1
Score	**-** **0**	**-6**	**6**