This is to certify that the

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DESIGN AND ANALYSIS
OF A HYBRID ELECTRIC VEHICLE CHASSIS

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Clark Radcliffe
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DESIGN AND ANALYSIS OF A HYBRID ELECTRIC VEHICLE CHASSIS

By

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ABSTRACT

DESIGN AND ANALYSIS OF A HYBRID ELECTRIC VEHICLE CHASSIS

By

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Design of a hybrid electric vehicle chassis for the 1993 and 1994 HEV Challenge is presented. Computer finite element modeling and solid modeling techniques were used in developing the chassis. The main design parameters are presented and described. Final chassis design was tested, using finite element analysis, to ensure overall structural integrity and occupant safety. The chassis proved to be safe and reliable, under the rigors of competition driving, in the 1993 and 1994 HEV Challenges.

Dedicated to my shiny brand new wife, Keli.

ACKNOWLEDGMENTS

I would like to thank each and every Spartan Charge team member who dedicated a significant portion of their lives to building a winner. A special thanks to Dr. Gerrish, Dr. Park, Denny Welch, Dr. Strangas and Dr. Martin for putting in many overtime hours to the project. Thanks to all the companies and organizations, especially Ford, Saturn, U.S. Department of Energy, and the Society of Automotive Engineers, for sponsoring and organizing the HEV Challenge. I would like to thank the numerous faculty members who always found time to answer my questions. I appreciate the support given to me by my family and friends. Thanks also to my then fiancee, now wife, Keli, who put up with my hardships and accepted the long hours working on the project. Finally, I would like to thank my faculty advisor, Dr. Clark Radcliffe, who encouraged me to become involved with the project, lent valuable insight, and helped guide me through the past few years.

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INTRODUCTION

Michigan State University took part in the HEV (hybrid electric vehicle) Challenge competition, sponsored by Saturn, The Society of Automotive Engineers (SAE) and the U.S. Department of Energy (DOE). The 1994 HEV Challenge brings with it the Ground-Up and Escort Conversion classes featured in the 1993 Ford/DOE/SAE HEV Challenge, and it offers a new class, the Saturn Conversion class. The 1994 Challenge allows the Ground-Up and Escort classes, which were range-extender vehicles with significant zero-emission-vehicle (ZEV) range in the 1993 challenge, to optimize their vehicles. The new Saturn Conversion vehicles are power-assist hybrids competing within their own class. Power-assist hybrids have shorter ZEV range with the electric energy storage used to boost the auxiliary power unit (APU) power for short intervals. Vehicles in all three classes compete in a variety of dynamic and static events to evaluate performance and overall engineering design.

Michigan State is one of 12 universities competing in the "ground-up" portion of the Challenge. Student teams must complete 100% of the vehicle, though componentry may be purchased from companies that manufacture the required materials. Michigan State University's entry for the HEV Challenge, "Spartan Charge" (Figure 1), has a series power train configuration, and can operate as a zero-emission vehicle (ZEV) for short commuting distances of less than 50 miles. Low-emissions were obtained with a methanol powered engine carried on board to recharge the batteries to extend the overall range of the vehicle. Charging was accomplished with a three-cylinder four-stroke Geo Metro engine which turns an alternator to produce electricity to power an electric motor and recharge the batteries.

Design and construction of the vehicle's chassis allowed students to gain the most knowledge when a high-technology computer-aided approach was taken in the development of the chassis' structural systems. Computer modeling packages and the role they played in design, development and strength analysis are described. Governing parameters, decisions made concerning the final design, and construction of the chassis are also discussed. Computer finite element modeling analyses, that were used to verify the structural integrity of the vehicle, showed that passenger safety was ensured.

Figure 1. Michigan State University's Hybrid Electric Vehicle, Spartan Charge.

COMPUTER MODELING

Utilizing a computer-aided design software package, I-DEAS (Integrated Design Engineering Analysis Software) by Structural Dynamics Research Corporation, was the most efficient way to develop the HEV chassis. I-DEAS is an integrated package of mechanical engineering software tools that provides a variety of applications for product design. Lawry [5,6] provided useful guides that were helpful in developing and analyzing the finite element and solid models of the chassis. Utilizing the available computational capabilities of I-DEAS aided in the design of the structural systems.

I-DEAS is made up of a number of "Families" of applications, each subdivided further into "Tasks" all executed from a common menu and sharing a common database. Applications include Solid Modeling, Finite Element Modeling & Analysis, System Dynamics, Drafting, and Manufacturing. Our needs included Finite Element Modeling and Solid Modeling.

Finite Element Model

Chassis overall design was first constructed in the Finite Element Modeling package. A monocoque mid-section, straddled by space-frames in the front and rear were roughed out on paper and then translated into a finite element model. Aluminum was used for the monocoque and was modeled using isotropic thin-shell elements, while the steel space frames were conveniently modeled by beam elements. Thicknesses and material properties of the thin shells could easily be governed, in addition to the beam element's cross-sections.

In developing the Finite Element model of the chassis the construction geometry task of the Finite Element Modeling Family was used. Corners of the monocoque and major tube intersections were defined in a global coordinate system and represented by points on the graphic display. All points were then connected by lines which determined the planar intersections of the monocoque and the geometric orientation of the beam sections. Two dimensional surfaces, created from the construction geometry, represented the aluminum monocoque surfaces, while individual lines defined the tubular space frame geometry. An auto-mesh feature was utilized to develop an array of finite elements from the construction geometry. This methodical approach is powerful for the inevitable event of mesh refinement. Old mesh configurations can be deleted and a refined mesh can be obtained from the previously created construction geometry. Construction geometry was a useful task in developing a base geometry from which finite element models could be built.

A series of finite element strength analyses ensued after the creation of the preliminary model. Excessive high local stresses and deflections were reduced and material thicknesses were optimized in an iterative manner which was especially helpful in optimizing the front and rear space frames. A collection of beam cross-sections were created. Larger cross sections were used in high stress areas and tube geometry could be easily relocated and analyzed. Finite element modeling is flexible, in that separate sections, such as space frames, could be loaded and analyzed as separate entities.

Space frames were modified and analyzed easily because they were modeled with one-dimensional beam elements. Torsion and braking loads were chosen to simulate extreme operation conditions. Locations where the space frames bolt on to the monocoque were held fixed. Appropriate forces were applied to the wheel locations which were then transferred to the frame through the suspension geometry that was modeled using rigid members. Figures 2 and 3 show an exaggerated view of the effects of braking and torsion on the front space frame. Dashed lines represent the unloaded frame and solid lines represent the frame under load.

Several different loading cases were used in verifying the structural integrity of the vehicle since the objective of the finite element analysis was to create a structurally sound and safe chassis. These loading schemes will be discussed in more detail in the Finite Element Modeling section.

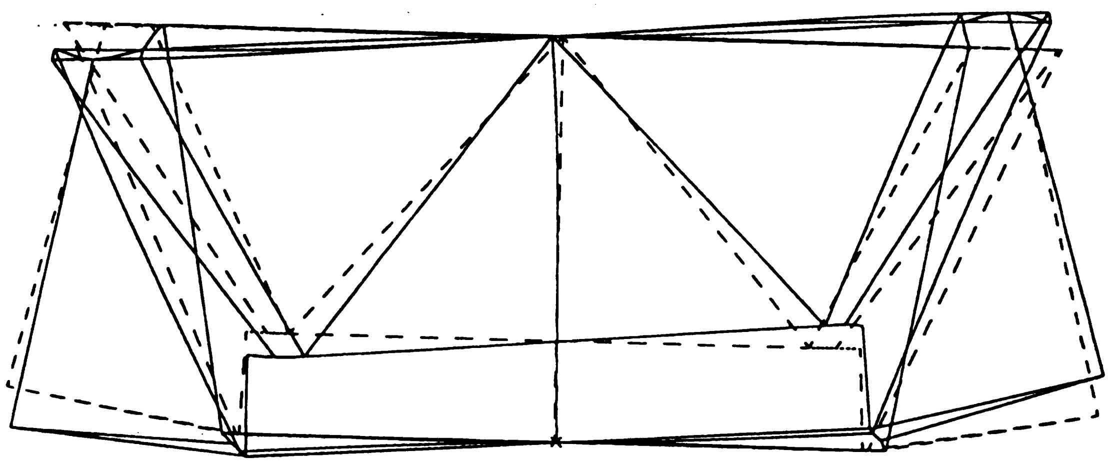

Figure 2. Front Space Frame Under Torsion Load. (Front View)

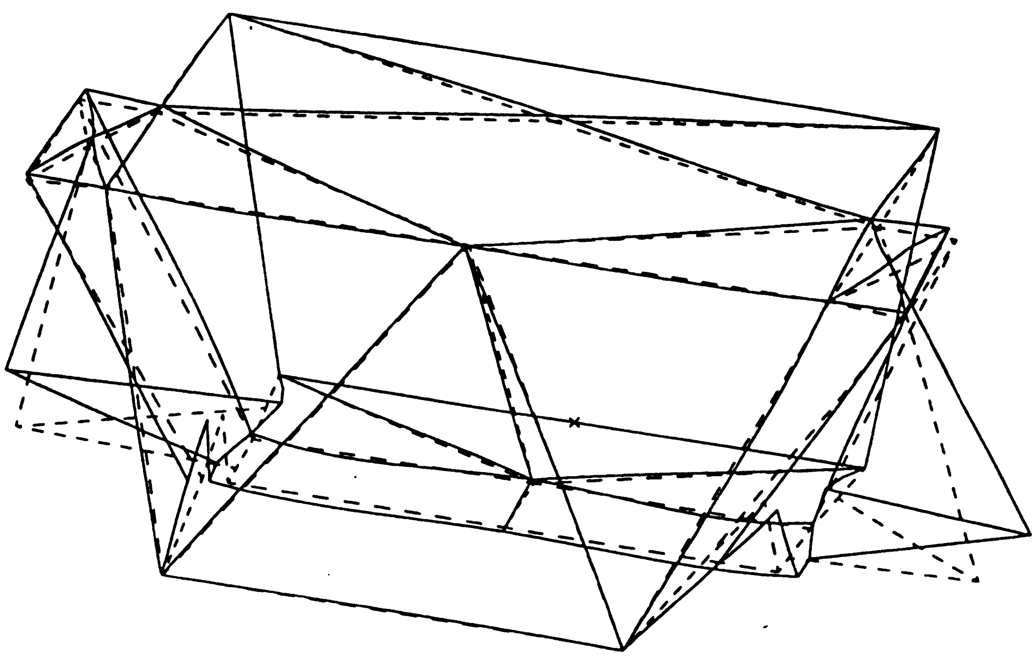

Figure 3. Front Space Frame Under Braking Load. (Front Isometric View)

Solid Model

Final chassis geometry that resulted from the finite element analyses was used to produce a computer solid model that was constructed in the Solid Modeling Family. This solid model exactly replicates what the chassis will look like when it is constructed which was useful for surfacing the body shell, checking component clearances and spacing, verifying vision requirements, and deciding mounting locations. Impressive drawings for presentations and displays were generated from this model. Figure 4 shows the computer solid model of the chassis.

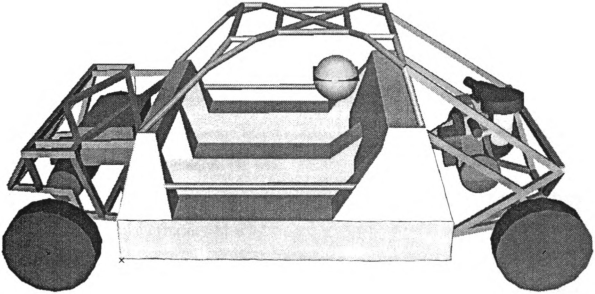

Figure 4. Computer Solid Model of Chassis.

The first entity created in I-DEAS Solid Modeling was the monocoque which was created using blocks representing the sheets of aluminum with the same thickness and geometry. Once the monocoque was created, an aluminum color was created from a color palate and a shiny gloss applied to give the object a natural appearance. This monocoque served as a basic foundation for the remaining components to be built around and attached to.

Front, rear, and roll-cage space frames were created around the monocoque which were composed of square and round tubing with accurate tube sizes and wall thicknesses. Points in space were located in Construction Geometry and used to define vectors around which the tubes were created. A steel tubing color scheme was developed and applied to give a life-like appearance.

All major components to be mounted in the chassis were meticulously created to give an accurate picture of spacing and clearance concerns. These components included the Geo Metro Engine, alternator, electric motor, transmission, inverter, wheels and dash board. They were positioned in the chassis and colored to give an accurate visualization of the final product.

Space for the drivers head was created as a sphere and placed in the passenger compartment. Head placement was oriented at a vertical height the same as a fiftieth percentile male occupant to ensure that the visibility requirements, as stated in the HEV Challenge Rules and Regulations [3], were met.

Computer aided engineering is becoming an everyday practice in the engineering world. Using finite element and solid modeling techniques reduces the need for other costly testing methods. Products can be produced more efficiently and in less time using a computer aided approach. Using the computer to help engineer the structural systems enabled us to become familiar with a powerful tool that is available to today's engineers.

CHASSIS DESIGN

The vehicle chassis links the mounting points for the vehicle's front suspension, steering, engine, transmission, rear suspension, final drive, fuel tank, seats for occupants, and in our case, motor controller, electric motor, and batteries. It requires rigidity to maintain accurate handling, lightness to reduce inertia and rolling resistance, and toughness to sustain punishing fatigue loads from the road, power unit, and driver. This section describes the design decisions made to develop the final hybrid electrical vehicle chassis.

A number of key design parameters were observed during the chassis design phase. These parameters include:

- Passenger Accommodations
- Materials for Fabrication
- Battery Housings
- Packaging

Each of the design parameters played a major role in the design of the chassis and will be described separately.

Passenger Accommodations

Ergonomics play a vital role in the design of interiors for today's auto makers. Automobile operators are becoming more and more demanding for new interiors to be functional as well as comfortable. To accommodate the needs of the passengers the chassis' mid-monocoque was designed to provide ample space for comfort and clear visibility.

Rough passenger compartment dimensions and measurements were taken from a compact car. Seats were positioned in their furthest back position. Figure 5 shows the general dimensions that were taken. These were used as a general layout for the passenger compartment. This helped in deciding the distance from front to rear firewall, height of ceiling, seat accommodations, dash position and passenger placement. Vision requirements, defined in the HEV Challenge rulebook [3], were observed in the design and verified through the computer solid model of the chassis. Spartan Charge's passenger comfort, visibility and accessibility to controls were rewarded with a first place in Ergonomics award.

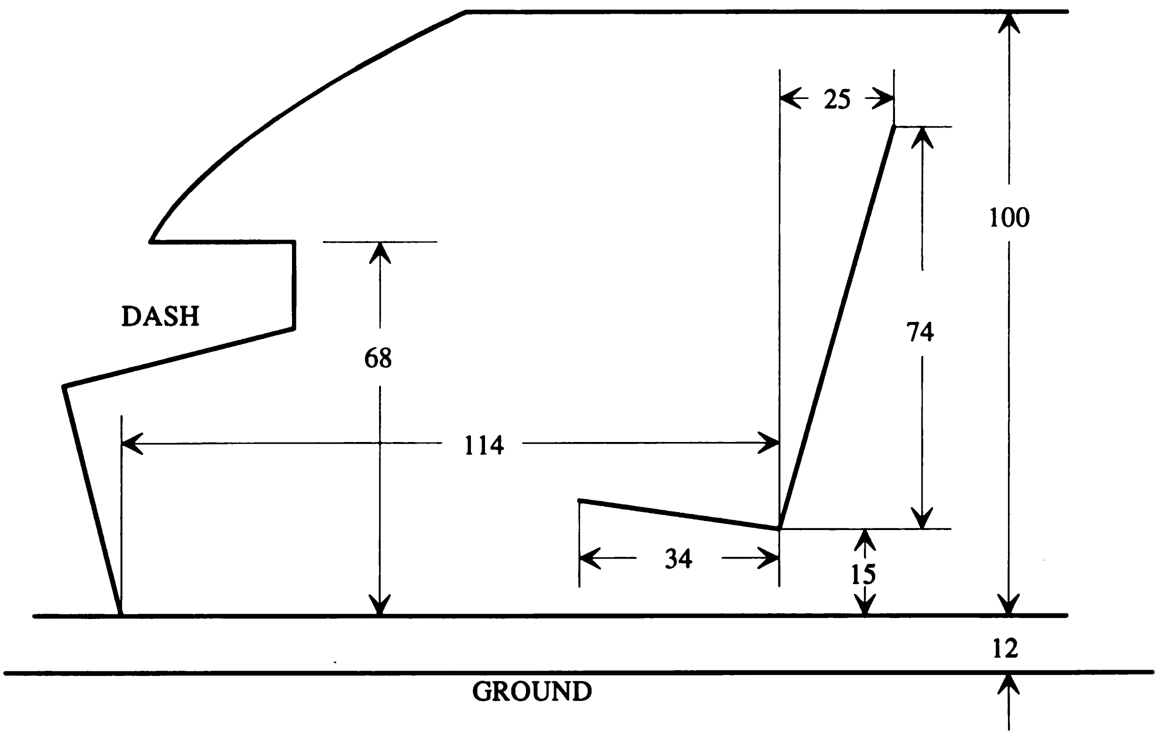

Figure 5. Passenger Compartment General Dimensions in Centimeters.

Materials for Fabrication

Choice of materials was decided upon considering manufacturability, recyclability, material properties, safety, and ability to model accurately using finite element analysis. Composite materials and conventional metals were considered for use in the chassis. Composite materials are very attractive because of their material properties, but a composite chassis would have been difficult to manufacture. Plus, the anisotropic material properties of composite plies are more difficult to model on the computer.

Basic chassis design was planned while considering the tools available for it's construction. Some of the advantages of composite materials become less appealing when considering the more difficult manufacture methods associated with these materials. The Farrell Hall machine shop, which is part of the Agricultural Engineering Department where the vehicle was constructed, had a large variety of machines and experienced mentors to aid in conventional metal construction. Therefore, basic metal construction techniques, such as welding, bonding, and riveting, were used in manufacturing the chassis.

Though composite structures have a low density, which is crucial to reduce excess weight, an equally important property to consider is toughness. Toughness is a measure of the combination of strength and ductility. Toughness is the area under the material's stress-strain curve which represents the amount of energy a material can absorb before failure. This property has to be considered to ensure the long term reliability of the vehicle. Although composite structures are generally lighter and stiffer they also are unforgiving and more susceptible to design flaws. Also, local high stress areas or manufacturing defects in a composite structure can easily develop a crack that can go undetected which can then propagate and eventually result in a sudden catastrophic failure. According to Smith [7], the energy-absorbing qualities of a well-designed and well-fabricated aluminum monocoque outweigh the weight saving and stiffness of a composite monocoque. Composite structures must absorb impact by controlled fracture rather than by plastic deformation. Designing controlled fracture is very difficult and requires many crash tests. Conventional metals provide the added security of local plastic deformation in a high stress area which will reduce the strain energy in that small location thus allowing the surrounding material to absorb the added loading.

Tubular steel and sheet aluminum were chosen to be used to construct the chassis because of their toughness and simpler computer modeling advantages. These metals are both recyclable and easy to manufacture with the available shop tools and machinery. Smith [7,8] and Fournier [4] provided helpful manuals for design and manufacturing techniques of aluminum and steel. 5052 sheet aluminum was chosen because of it's excellent resistance to corrosion and workability properties, Bray [1]. Lightweight sheet aluminum was easy to bend and the joints were bonded and riveted to construct the passenger monocoque. Square tubular steel was chosen for building the space frames. The flat sides made it easier to cut and weld joints and attach component mounts.

Battery Housing

Battery selection had not been made prior to the chassis design phase. So in designing the chassis, two types of batteries, lead-acid and nickel-metal-hydride, had to be applicable which were of different sizes and weighed 750 and 875 pounds respectively. This meant that battery housings had to be designed to accommodate both battery types. Also these battery housings had to be completely sealed from the passengers, able to support the heavy battery weight, provide proper battery ventilation, be serviceable, and positioned low and close to the middle of the vehicle so as not to hamper the dynamic performance of the vehicle. Figure 6 shows the battery configuration in the mid-monocoque section.

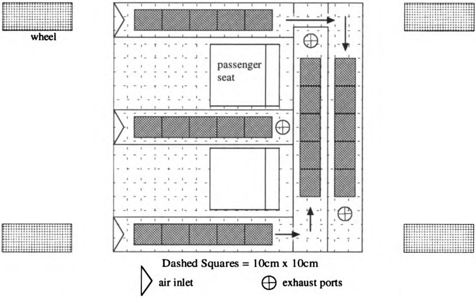

Figure 6. Battery Pack Placement and Ventilation in the Mid-Monocoque.

Five identical battery packs were chosen to aid in serviceability. Because the packs are identical they are interchangeable, and any pack could be put into any housing. Each battery pack's electrical characteristics could be monitored. If one of the five battery packs was malfunctioning it could easily be replaced. Housings were designed so that the batteries are loaded into the vehicle from underneath the chassis. This ensured that the batteries would be completely sealed off and inaccessible to the passengers. Figure 7 shows the ribs and battery placement within the aluminum housings.

Box sections were utilized in the aluminum monocoque to house the batteries and to lend structural rigidity to the chassis. Therefore, chassis stiffness was increased by strategically placing the box sections around the perimeter of the monocoque. All box sections were constructed with four internal stiffening ribs for the extra strength needed to hold the heavy batteries (Figure 7).

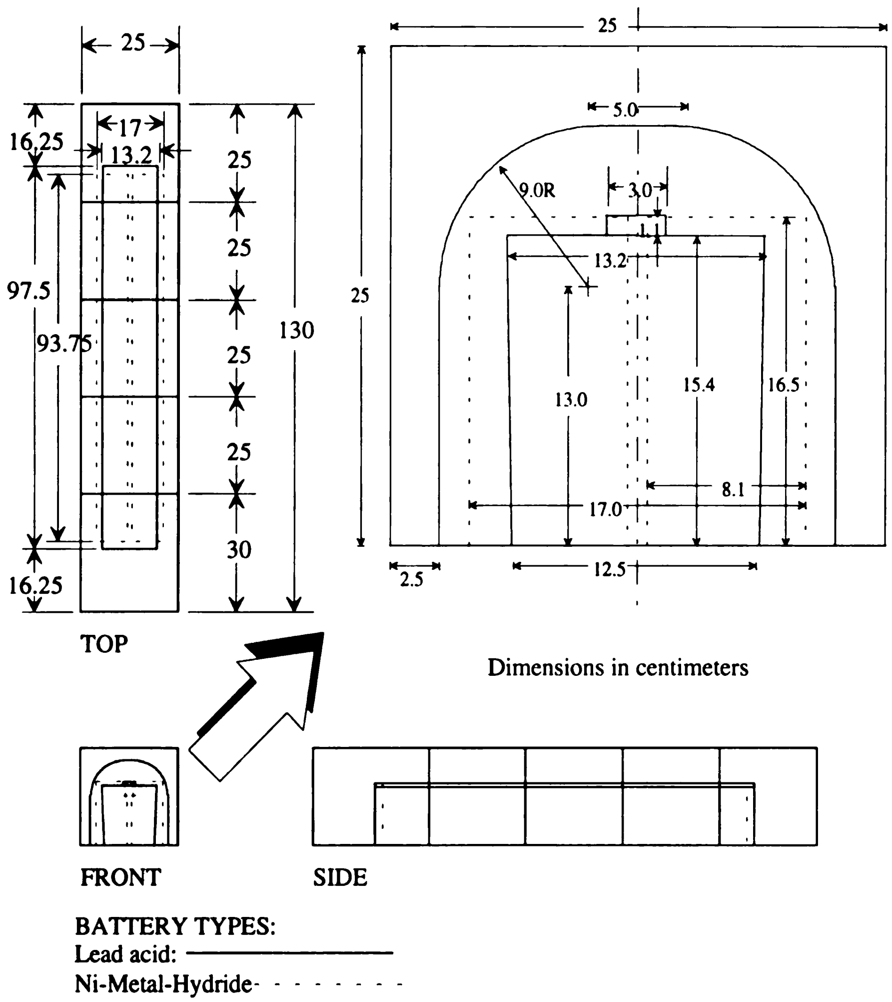

Figure 7. Battery Housing Details.

Packaging

Major components were packaged into the chassis using the I-DEAS computer model. Chassis space frames were designed to accommodate the Geo Metro suspension while the overall size of the space frames were adjusted in the model to provide the needed space for the major components. A front wheel drive vehicle was decided upon with the electric motor and its controller (inverter) in the front space frame. This electric motor was fitted to a Geo Metro transmission, also conveniently located in the front, which was directly coupled to the front wheels. The Geo engine and alternator were placed in the rear space frame behind the storage compartment. Figure 4 shows the solid model and its use in component packaging.

Final Chassis Design

Final MSU Spartan Charge chassis configuration was specified from the previously described design parameters. After considerable research and thought, a mid-chassis aluminum monocoque passenger compartment and front and rear steel bolt-on space frames were decided upon. This modular space frame/monocoque design can prove to be very convenient for small collision repairs. In the event of a small crash, the space frame will deform to absorb the crash energy leaving the monocoque unharmed which would enable the damaged space frame to be removed and a new space frame installed with relative ease.

The monocoque was made of recyclable sheet aluminum and was reinforced around the perimeter with an internal space-frame. Large box sections along the sides dramatically improve the torsional stiffness of the chassis and double as battery housings. This monocoque will contain five uniform battery packs that are inserted into the monocoque from the bottom. The sides and top of the box sections are then bent from one sheet of aluminum to ensure that the batteries are completely sealed and inaccessible from the passenger compartment.

Both space-frames were constructed of square mild steel tubing that were easy to weld mounts to. The steel bolt on and off space frames contain all of the major propulsion components except the batteries. Figures 8 and 9 show the final chassis design and display the coordinates of major structural member intersections in millimeters.

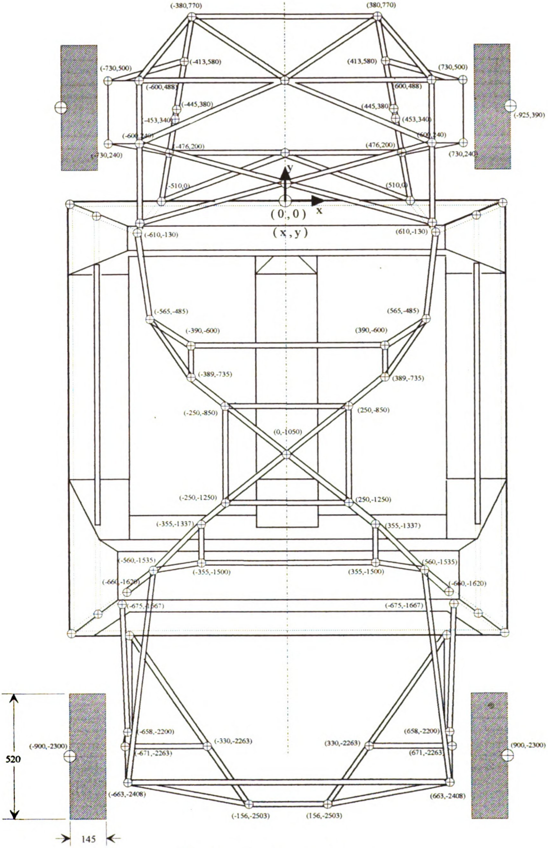

Figure 8. Top View of Chassis.

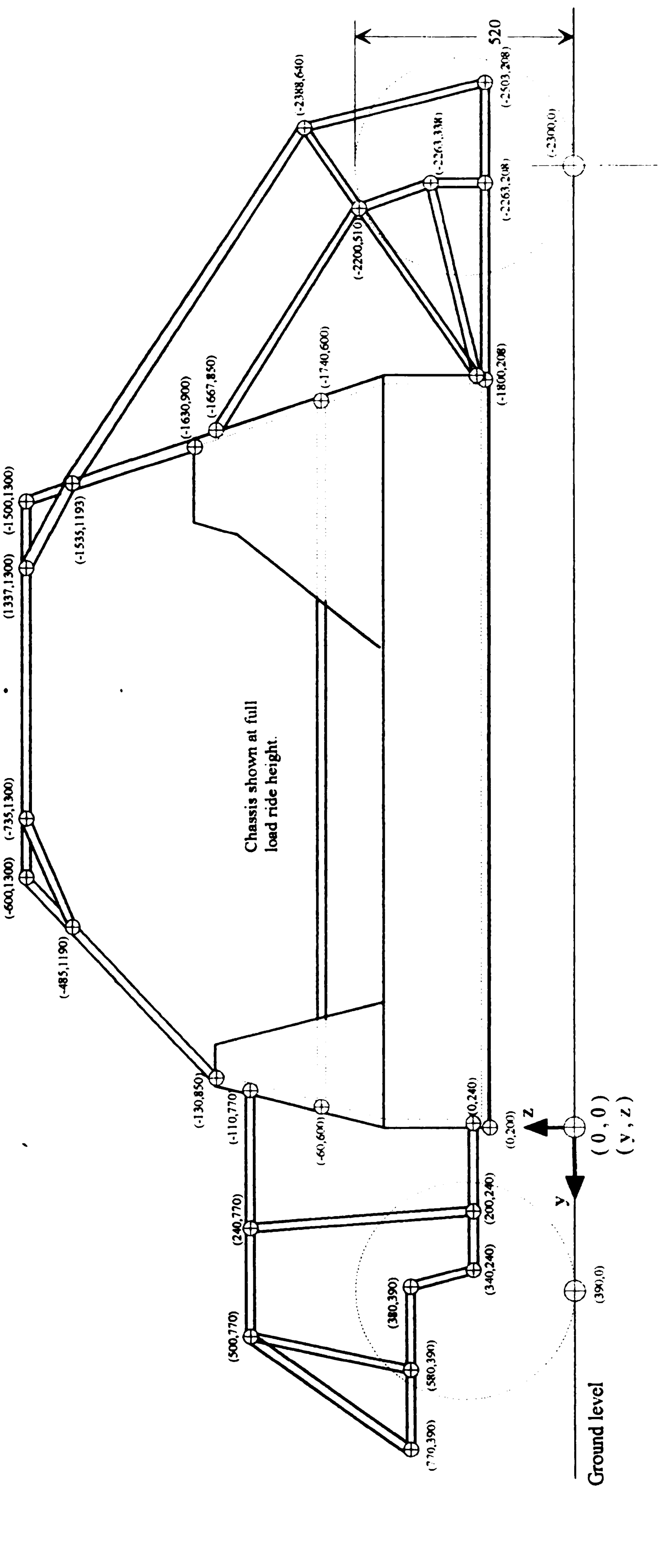

Figure 9. Side View of Chassis.

STRUCTURAL INTEGRITY

Through the use of finite element analysis (FEA) on I-DEAS the structure was proven to be sound and able to stand up to extreme operating conditions. All of the FEA analyses were performed using a linear static analysis. Structural integrity was confirmed with three analyses: *Torsional Stiffness*, *Mid-Span Bending*, and *Hitting a Bump While Braking*. In each analysis the entire chassis was modeled. Analyses verified that the chassis would be adequately stiff and strong to operate safely under extreme operating conditions.

Torsional Stiffness

Torsional stiffness of the entire chassis was determined using rigid beams to conservatively model all suspension geometry while the rear wheels were held fixed. A 100Nm torque was then applied to the front wheels. Figure 10 represents an exaggerated view of the displacement of the front axle with respect to the fixed rear axle. The displacement results were used to calculate the angle difference between the front and rear axles. To determine the torsional stiffness in Nm/degree, the 100Nm torque load was divided by the angle difference between axles.

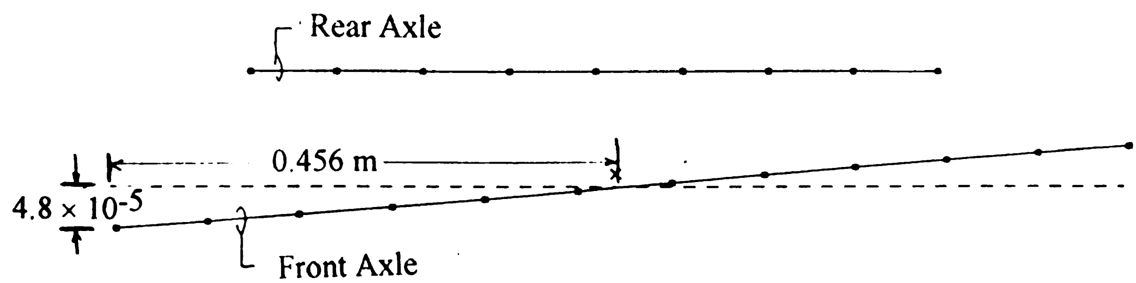

Figure 10. Front and Rear Axle Relationship to Calculate Torsional Stiffness.

Fenton [2] states that the torsional stiffness of a vehicle chassis should be a minimum of 6500Nm/degree to prevent unsafe handling due to excessive dynamic deflection. Calculations indicated an angle difference between the front and rear axles of 6.03×10^{-3} degrees. Dividing this number into the 100Nm torque gave a torsional stiffness of 16,580 Nm/degree which is well above the published requirement for safe operation. It should be noted that a number well above the minimum is desirable to account for common 'over stiff' computer results from a finite element model of just over 5000 elements. Considering the amount of material used in the chassis it is hard to accept the large number obtained for torsional stiffness. Thus, we went with our design on the premises that an over designed chassis is acceptable but an under design could be devastating.

Mid Span Bending

Deflections at the middle of the chassis were made using component weights as indicated in Table 1. Component weights were placed in their appropriate position on the chassis, and wheel locations were held fixed. Fenton [2] states that mid span bending should not exceed 1.27mm. Analysis on the MSU Spartan Charge chassis indicated the mid span bending was 0.45mm. Considering compensation for common 'over stiff' computer results for our model, this result indicated that the vehicle was within acceptable deflection levels.

Table 1. Approximate Vehicle Component Weights used to Calculate Mid-Span Bending.

Component	Weight in pounds	Weight in Newtons
I. C. Engine	130	580
Inverter	80	355
Electric Motor	160	710
Transmission	50	220
Dash	75	335
Batteries	800	3560
Passengers	400	1780
Seats	50	220
Fire System	10	45
Electrical, Fuses, Wiring	50	220
Fans	10	45
Fuel System	60	265
Body	150	670
Alum. Monocoque	250	1110
Top Roll Cage	35	155
Alternator	40	180
Steering	50	220
Doors	60	265

Hitting a Bump While Braking

This simulation shows the effect of both front wheels of the vehicle hitting a bump or curb while braking. Loads were calculated based on equations in Ref. [2]. Dynamic measurements on small passenger automobiles have shown peak accelerations of 3g recorded in the vertical direction. Longitudinal braking forces are limited by the adhesion of the tire to the road, thus a limiting figure of 1g is acceptable. It is suggested to multiply these accelerations by a 1.5 factor of safety to arrive at the corresponding maximum accelerations of 4.5g vertical and 1.5g horizontal. Then, as the driver applies the brakes while hitting a bump, the resulting forces will be

$$\text{Vertical load due to bump} = R \times 4.5$$

$$\text{Rearward load due to bump} = R \times 4.5 \times \tan \Theta$$

$$\text{Load transfer due to bump} = R \times 4.5 \tan \Theta \times y/2B$$

Load transfer due to braking = 1.5 Wy/2B

Rearward load due to braking = 1.5R + 1.5 Wy/2B

These add up to give the reaction at each of the front wheels

$$\text{Vertical component} = 1.5\left\{3R\left(1+\frac{y}{2B}\tan\Theta\right)+\frac{Wy}{2B}\right\} = 22.5\text{kN}$$

$$\text{Rearward component} = 1.5\left\{R(3\tan\Theta+1)+\frac{Wy}{2B}\right\} = 28.0\text{kN}$$

where

W = weight of vehicle (3000 lb, 13360 N)

B = wheel base of vehicle (275 cm)

y = height of center of gravity above ground (35 cm)

R = single wheel reaction force, assuming under breaking 2/3 of the vehicle weight shifts to the front wheels (1000 lb, 4450 N)

Θ = angle between vertical and the line between impacting bump and axle, typical for hitting roadside curb (45°)

The breaking while hitting a bump force components were 22.5 kN vertical and 28.0 kN in the rearward direction. These forces were applied to the front wheels, while the rear was held fixed.

Figure 11 is a color plot of the stress distribution (in Pascals) throughout the aluminum monocoque due to this loading condition. The front space frame, constructed of a steel with a 340MPa yield stress, was well below yielding stress levels, thus it is not included in the results. The results of this extreme loading condition show that the maximum stress (136MPa) in the aluminum monocoque is below the yield stress for the aluminum (145MPa) that we are using. This analysis confirms that under the most extreme driving conditions, hitting a curb while braking, the chassis will not plastically deform.

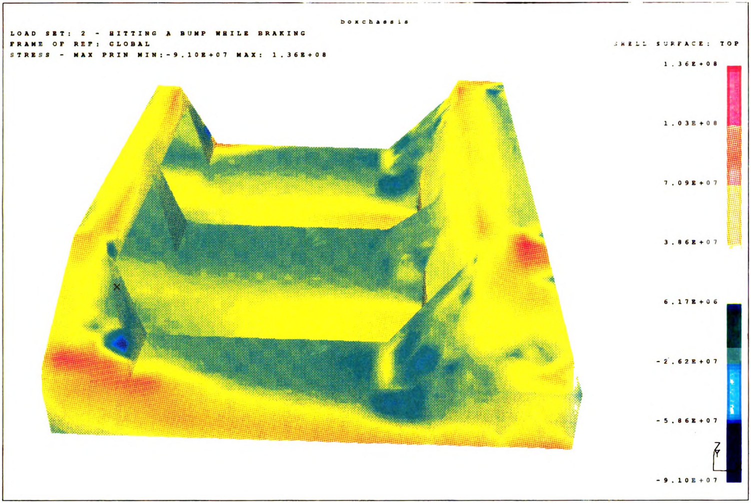

Figure 11. Stress Plot for Hitting A Bump While Braking.

OCCUPANT PROTECTION

The ground-up MSU Spartan Charge vehicle is designed for occupant protection under the HEV Challenge Rules and Regulations document. Essential safety features of concern include protection in the event of frontal impact, side impact, and rollover. Containment of the batteries is addressed which is a very important issue in electric vehicles. In addition to previously mentioned vehicle structure design, I-DEAS contributed significantly to safety verification. Occupant protection FEA analyses were performed using the maximum reasonable loads, plus safety factors, to simulate the vehicle behavior in the event of a rollover or crash situation.

As specified in the Sports Car Club of America (SCCA) vehicle regulations, all the bars or safety structures that an occupant can come in contact with are padded with a minimum of 2.5cm of foam. There are no sharp exposed corners or edges where an occupant could be injured, plus five point seat belt harnesses are installed for the driver's and passenger's protection.

Rollover Protection

Occupants must be protected from contact with the ground in any rollover attitude. A roll bar near the occupants and a forward roll hoop are in place to protect against roof crushing. The roll bar is braced with braces of identical tubing attached at the top of the roll bar at 57 degrees from vertical and room is allocated so that the helmet of the tallest occupant of the vehicle is at least five (5) centimeters below the surface defined by the roll bar and the front roll hoop. Continuous closed sections of steel tubing welded to the internal steel space frame, around which the monocoque is constructed, make up the roll bar and roll hoop. Seamless SAE 4130 medium-carbon chromium-molybdenum steel tubing had an outside diameter of 1.5 inches and a nominal thickness of 0.095 inches.

The rollover finite element design was analyzed on I-DEAS with a relevant rollover load set. Required loading according to the United Nations Standard for rollover stated in Fenton [2] was 0.6 times the vehicle weight placed at each of the windscreen pillars. To give a higher factor of safety, a load of two times the vehicle weight was directed at 30^{o} from vertical on the front drivers side A-pillar to determine the local stress in this critical area. Nodes representing the bottom of the vehicle were fixed. The highest stress in the rollover cage (650 MPa) is below the yield stress (820 MPa) for the alloy steel that was used and was located at the bottom of the drivers side front roll hoop.

Side Collision Protection

Frame members extending from the roll bar to the roll hoop at a height above lap level protect vehicle occupants from a side collision. Steel side bars constructed from SAE 4130 medium-carbon Chromium-molybdenum steel tubing with an outer diameter of 1.5 inches and a wall thickness of 0.095 inches were incorporated in the door so as not to hamper vehicle egress. These bars were integrated into the doors of the vehicle, and were secured with a mechanical coupling at each end that served as the door latch. The sliding lock collar which is operated by a door handle was also constructed from SAE 4130 round stock. As an integrated whole, the bar and the coupling transmit impact forces from a side collision to the rest of the frame. Occupant safety is significantly enhanced with this feature.

The aluminum battery box structure is an energy absorbing crush zone also offering side collision protection. Each battery box is reinforced with one inch square steel tubing around the bottom outside face. Battery box openings along the bottom are reinforced with one half inch square solid 5454 aluminum bar stock. Four vertical stiffeners reinforce each battery box compartment against lateral forces.

For conducting a linear static stress analysis, a load of two times the vehicle weight was directed horizontally into the side of the car in an area corresponding to the middle of the passenger door. A node set representing the side of the vehicle opposite the intended impact area was restrained against movement in any direction. Maximum stresses on the side of the car were 140 MPa, below the 145 MPa yield stress for aluminum. Figure 12 shows the stress contours, the smallest closed contours having the maximum stress. Maximums occur at the interface where the loaded steel side impact bar comes in contact with the thinner wall aluminum sheet.

Frontal Impact Protection

Occupants are protected from frontal impact from a minimum 300 mm crush zone, as specified in the rules, which is located between the plane defined by the nose of the vehicle and the vertical plane defined by the brake pedal hinge. However, the space needed for the electric motor, transmission, and motor controller was not to be included in the minimum crush zone dimension. The side bar door coupling, the roll bar/cage arrangement, and the monocoque all contribute to the overall stiffness and strength of the passenger compartment. These features are very important to the prevention of significant passenger compartment deformation in the event of a head on impact.

Fenton [2] states that in a frontal impact, the passenger compartment should retain its shape after a 30 mph solid barrier impact. An FEA analysis on I-DEAS involved forces based on the required 30mph (13.4 meters per second) impact velocity. The force was calculated by using

$$F = m \times dV/dt = m \times \Delta V/\Delta t$$

m = Vehicle mass (1360 kg)

ΔV = Change in velocity from 13.4 meters per second to 0 (13.4 m/s)

Δt = The average time it takes for a vehicle to completely stop upon hitting a barrier at 13.4 m/s (0.15 s)

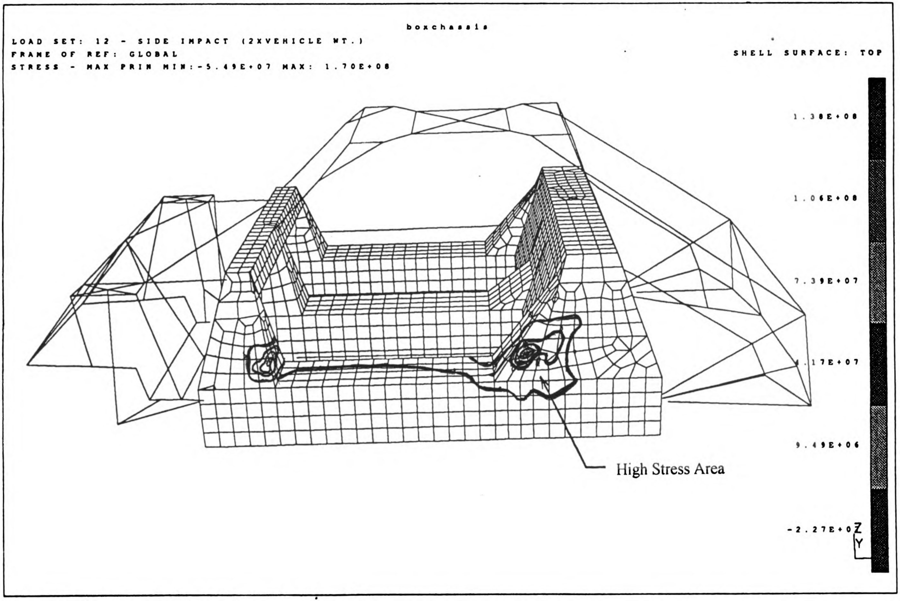

Figure 12. Stress Plot for Side Impact Test.

A force of 121 kN was directed horizontally into the front of the car and a node set representing the rear of the monocoque was restrained against movement. As expected, stresses in the front space frame of the chassis, where the crush zone is located, were well above yield stress, so significant plastic deformation would take place as kinetic energy dissipates. However, the passenger compartment was stressed at yield stress, which complies with Fenton's statement that no significant plastic deformation should occur in the passenger compartment. The maximum stresses in the passenger compartment were around 145 MPa at the space frame/monocoque interface, just reaching the 145 MPa yield stress for aluminum.

Battery Containment

Physical isolation of the batteries from the passengers involves several levels of protection, the primary of which involves the separation of the batteries from the driver and passenger by the 0.062 inch thick walls of the fully enclosed battery box structure. Battery tray openings are reinforced with one half inch square solid 5454 aluminum bar stock to prevent local deformation. Four vertical stiffening ribs reinforce each battery box compartment against lateral forces. Figures 6 and 7 show schematics of the battery boxes. These physical isolation and strengthening features stiffen up the structure in addition to offering passenger and driver protection from the batteries and side impacts.

CONCLUSION

The HEV Challenge provided a unique opportunity to design and construct a hybrid electric vehicle chassis. Chassis design parameters were identified as: passenger accommodations, materials for fabrication, battery housings, and packaging. These were discussed and appropriate decisions were made which resulted in a structurally sound HEV chassis. The design was constructed for the 1993 and 1994 Hybrid Electric Vehicle Challenge. The HEV Challenge gives students the chance to apply their design and analytical skills to real world problems.

A high-technology computer-aided approach was utilized in the chassis' structural system development. Computer solid modeling and finite element modeling were used extensively in the chassis design. Solid modeling was especially helpful in packaging the components, deciding mount locations, verifying vision requirements, surfacing the body, and provided an accurate visual aid. Finite element analyses were instrumental in determining structural member locations and cross-sections. Structural integrity finite element analyses were performed to ensure that the chassis would be safe and able to withstand the excessive rigors of competition. I-DEAS proved to be a valuable tool in the development of the chassis.

LIST OF REFERENCES

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1. Bray, Jack. Aluminum Mill and Engineered Wrought Products, Reynolds Metals Company.

2. Fenton, J. Vehicle Body Layout and Analysis, Mechanical Engineering Publications, London.

3. Ford Motor Company. HEV Challenge Rules and Regulations, 1992.

4. Fournier, Ron & Sue. Metal Fabricator's Handbook, Price Stern Sloan, Inc. 1990.

5. Lawry, Mark. I-DEAS Student Guide, Structural Dynamics Research Corporation, 1990.

6. Lawry, Mark. I-DEAS Finite Element Modeling, Structural Dynamics Research Corporation, 1990.

7. Smith, Carroll. Engineer to Win, Motorbooks International. 1984.

8. Smith, Carroll. Prepare to Win, Aero Publishers, Inc. 1975.