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**ANALYSIS AND DESIGN OF
A HYBRID ELECTRIC VEHICLE BRAKING SYSTEM**

By

Michael James Twork

A THESIS

**Submitted to
Michigan State University
in partial fulfillment of the requirements
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ABSTRACT

ANALYSIS AND DESIGN OF A HYBRID ELECTRIC VEHICLE BRAKING SYSTEM

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The design, development and testing of the braking system of a hybrid electric vehicle for the 1993 Ford/SAE/DOE competition are described. The main objective was to design a system that would provide safe and reliable braking for the vehicle. This was accomplished by modifying a braking system from a 1993 Geo Metro as well as by adding an ABS unit. Regenerative braking effects are discussed. The system requirements are presented and motivation is established for system modifications. The system provided safe and reliable braking and was recognized by the competition organizers as the Most Innovative Design in Mechanical Systems.

Dedicated to my wife, Kristi, and my daughter, Kali.

ACKNOWLEDGEMENTS

I would like to thank the Spartan Charge Team for all the blood, sweat and tears that we shared on this project. I would like to thank Dr. John Gerrish and Dr. Gerald Park for their tireless and fully committed support. I would like to thank the Mechanical Systems Team for their efforts. Thanks to Denny Welch for his commitment to the project and to the team. I would like to thank the College of Engineering for pursuing such an outstanding opportunity for the students to learn through application. I would like to thank Ford Motor Company, The Society of Automotive Engineers, The United States Department of Energy, and all other event sponsors. Thank you to my family and friends for 15 months of understanding and acceptance. Finally, I would like to thank my academic and thesis advisor, Dr. Clark Radcliffe, for patience, encouragement, and guidance.

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THE HEV COMPETITION

Hybrid electric vehicles (HEV) need to be proven as practical low emissions vehicles. The goal of the 1993 Ford/SAE/DOE HEV Challenge was to encourage development of HEV's and to demonstrate their practicality. The competition determined the most practical and efficient student designed vehicle entry. Thirty schools were chosen to compete from a field of 67 applicants. Michigan State University was one of twelve schools that built a hybrid electric vehicle in the Ground-up Class. The remaining 18 schools chose to convert Ford Escorts to hybrid electric vehicles. The schools competed in static and dynamic events to evaluate design and performance. Descriptions of the events are contained in Appendix A.

A practical, low emissions vehicle is needed in North America to break dependence on foreign oil and to reduce pollutants that are harmful to the environment. Electric vehicles have long been considered the next step in the automotive evolution because of their environmental friendliness, however, they are not yet feasible for general use because present battery technology limits vehicle range to 40 miles or less. California has recently passed legislation mandating that in 1998 at least two percent of all vehicles sold in that state must be emission free or have emission free capabilities (Kobe 1993). This percentage increases to five percent in 2001 and ten percent in 2003. Major metropolitan areas will eventually be zoned as emission free zones, where only vehicles with emission free capabilities may travel. Hybrid Electric Vehicles combine electric vehicle operation with an auxiliary internal combustion power source to give both emission free capabilities over a limited range and vehicle ranges of about 400 miles using auxiliary power.

The Hybrid Electric Vehicle is a compromise between pure electric and pure internal combustion powered vehicles as it incorporates the benefits of both. Figure 1 shows a typical series power train configuration for a hybrid electric vehicle. The vehicle can operate in pure electric mode while in emission free zones. In hybrid mode, in outlying areas, the APU can be used to extend vehicle range. The internal combustion engine, which is not directly coupled to the wheels, can be run at its optimal rate for efficiency and emissions because it is used to generate electricity. This electricity is either used to power the electric motor or to recharge the batteries, extending the range of the vehicle.

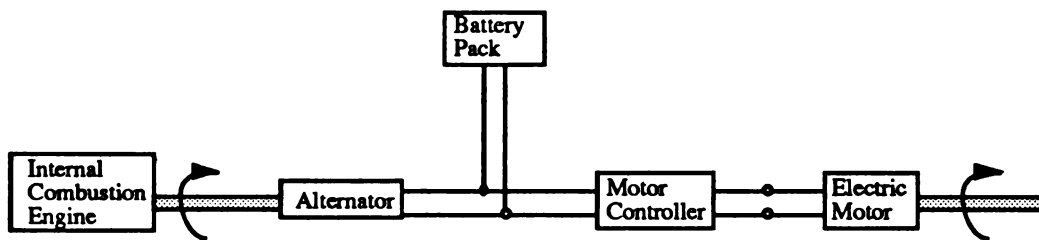


Figure 1. A Typical Series Power Train Configuration for a Hybrid Electric Vehicle

Michigan State University's entry to the HEV Challenge, "Spartan Charge" (Fig. 2), provided a unique opportunity to design and implement the vehicle's braking system. The braking system design objectives are presented. The design constraints and preliminary decisions regarding the braking system are examined. The three major elements of the system are discussed. After a general model of each element is presented, the modifications and implementation of each is detailed. The final, fully integrated system is then reviewed. Finally, the competition performance of the vehicle braking is presented followed by Challenge results.

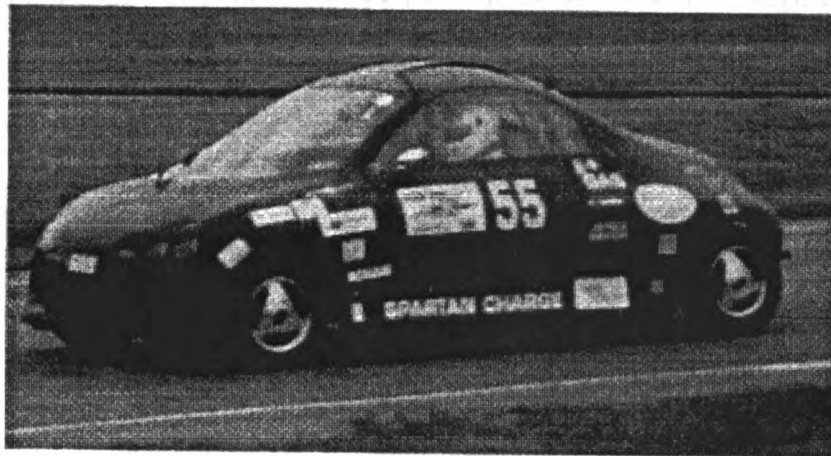


Figure 2. The Spartan Charge Hybrid Electric Vehicle

BRAKING SYSTEM SPECIFICATIONS AND OBJECTIVES

The braking system design objective was safe and reliable braking for the vehicle. Within the scope of the competition, the vehicle was expected to have similar braking performance to present production vehicles, which require a maximum pedal effort in the range of 300 to 550 Newtons (Posa, 1993) to generate 0.7g. HEV Challenge rules required the vehicle to brake at a rate of at least 0.425g. The HEV Challenge vehicles would be tested during vehicle qualifying on a pass/fail basis (Figure 3) to establish their ability to meet the deceleration specification.

Regenerative braking in electric and hybrid electric vehicles converts the inertia of the moving vehicle, through rotational inertia at the drive axle, to electric power by operating the electric motor as a generator. This energy is routed into the vehicles' batteries, slows the vehicle, and conserves some of the energy normally lost to coulomb friction upon braking. Regenerative braking increases the available braking effort of the entire system and the efficiency of the vehicle. Regenerative braking

increases the range of the Chrysler TEVan by 8 percent on the SAE C-cycle (Riezenman, 1992). The more energy that can be recovered through regenerative braking, the less that needs to be generated from the internal combustion engine, which means lower emissions and increased efficiency. It also means increased range and better acceleration. A design goal for the Spartan Charge power train was to realize regenerative braking and to test its effects on the overall braking system performance.

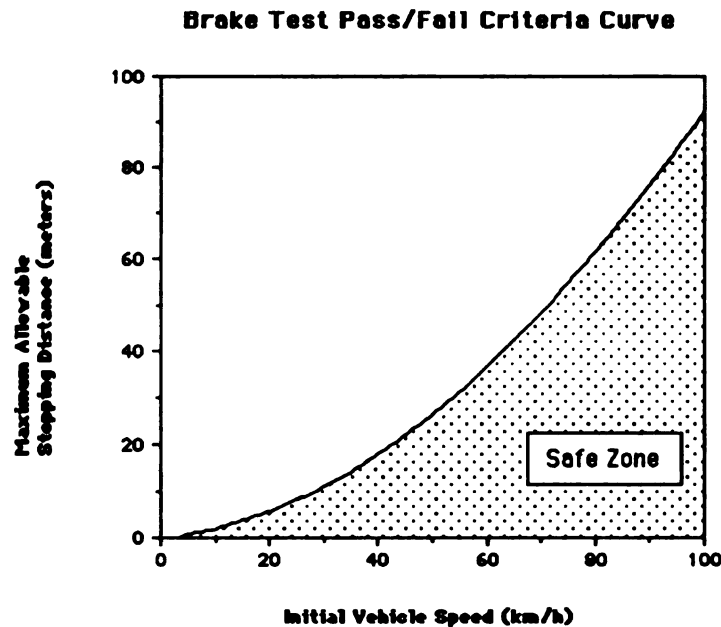


Figure 3. Pass/Fail Criteria for Vehicle Qualifying Brake Test. The Line Corresponds to 0.425g Average Deceleration.

An Anti Lock Braking System (ABS) increases safety and maneuverability during braking by regulating the hydraulic pressure to the wheel(s) which prevents skidding. It would also improve the merit of the braking system design. The goal was to integrate an ABS unit into the braking system to increase the safety of the vehicle.

The design constraints of the project were the timing, financial, and reliability. The time frame of the project at Michigan State University encompassed 15 months

from student organization to the competition. Off-the-shelf components could significantly reduce design and manufacture time of some of the hardware. The financial constraints on the project were severe. Every component on the vehicle needed to be bought with donated funds or donated directly as a gift-in-kind. The braking system reliability was critical. Custom components could seriously compromise the reliability of the system. Ideally, an existing braking system could be transplanted onto the Spartan Charge vehicle. A 1993 Geo Metro was purchased for its California Emissions engine. It was more economical to purchase the entire vehicle than to buy the engine, instrumentation and controls on individual bases. The braking system from the Metro represented a fully tested and functional system that was available immediately and that would not further deplete funds. The Metro braking system became the foundation for the Spartan Charge braking system.

BRAKING SYSTEM DESIGN

The Spartan Charge braking system consisted of three major elements. Conventional hydro / mechanical brakes represented the foundation of the entire system and were assembled predominantly from Geo Metro components. The regenerative braking system included the drive motor, inverter, transmission and battery pack. The Anti Lock Braking System (ABS) included a hydraulic pump unit, electronic control module, and wheel speed sensors.

The Hydro / Mechanical System

The Metro system represented a typical hydro / mechanical system. A generic hydro / mechanical system model will be presented to establish a foundation for further

discussion. Optimal effort bias will be defined for the Spartan Charge vehicle. Finally, the modifications to the Metro system will be detailed.

A hydro / mechanical braking system operates by allowing the driver to control braking force through a pedal control. The driver applies a force to the brake pedal, which creates a pressure in the hydraulic lines. This pressure forces brake pads against a brake rotor which is part of the wheel hub. The friction created slows down the vehicle. Figure 4 shows a hydro / mechanical system with disc brakes in the front and drum brakes in the rear.

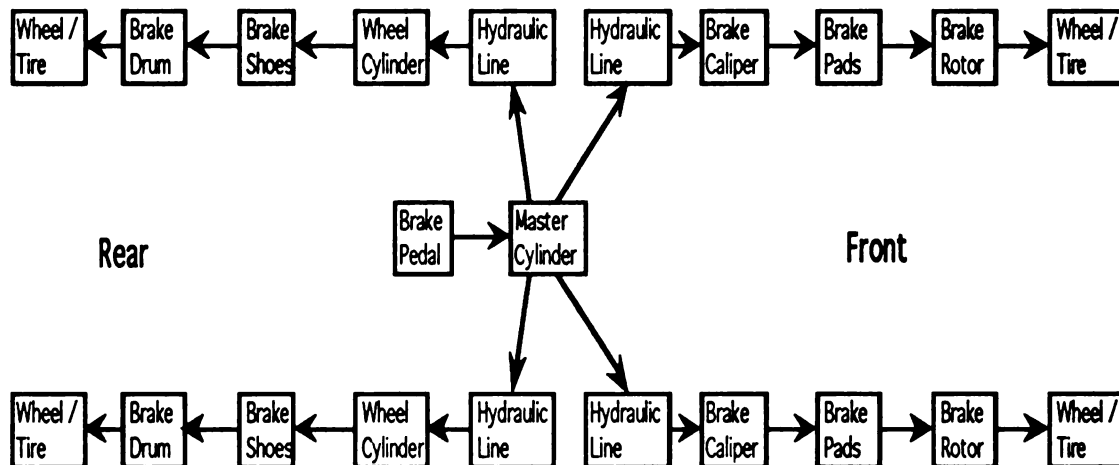


Figure 4. A Generic Hydro / Mechanical Braking System

The deceleration rate a vehicle with adequate braking is clearly limited by the adhesion of the tires to the road surface. The maximum vehicle deceleration obtainable occurs when all four wheels are on the verge of locking up or skidding. While it is difficult to obtain simultaneous lock up of all four wheels, this theoretical condition can be used to establish the maximum braking efforts. The forces required to create wheel lock up are defined as the braking capacities and represent the maximum force that the

system can use, while the optimal effort bias is defined as the ratio of the front brake capacity to the rear brake capacity. The optimal ratio is described by;

$$Effort_Bias = \frac{F_{f_{opt}}}{F_{r_{opt}}} = \frac{\mu_r mg(b + c\mu_r)/WB}{\mu_r mg(a - c\mu_r)/WB} = \frac{5.8kN}{3.6kN} = \frac{62\%}{38\%} \quad (1)$$

where

- $F_{f_{opt}}$ = optimal braking force at the front axle;
- $F_{r_{opt}}$ = optimal braking force at the rear axle;
- m = mass of the vehicle (1360 kg);
- g = gravity (9.81 m / s²);
- WB = wheel base of vehicle (272 cm);
- μ_r = coefficient of friction between the tire and the road (0.7 - wet asphalt);
- a = the distance from the front axle to the vertical projection of the center of gravity (130.5 cm);
- b = the distance from the rear axle to the vertical projection of the center of gravity (141.5 cm);
- c = the height of the center of gravity (37.6 cm).

The optimal braking effort that could be applied to the front wheels of Spartan Charge is 5.8kN. The vehicle braking can not be optimized if the system can not create 5.8kN at the front wheels. A similar analysis for the Metro yielded an effort bias of 77/23 with the front braking capacity at 4.8kN. Effort bias ratios are usually in the range of 65/35 to 75/25 because most vehicles are front heavy (Newcomb, 1975). Spartan Charge was slightly rear heavy and had a low center of gravity, which caused the optimal effort bias to fall below the normal range.

The hydro / mechanical system required some modifications to compensate for the 450kg increase in mass and a 21% increase in front braking capacity from the Metro to the Spartan Charge. To maintain system reliability, simple changes were preferred. The four modifications to the hydro / mechanical system were: the elimination of the vacuum powered brake booster; increasing the brake pedal mechanical advantage;

increasing the friction coefficient of the brake pads; and adding an adjustable bias bar. The net result of these modifications along with change in mass, wheel base and center of gravity from the Metro to Spartan Charge yielded a predicted pedal effort of 533N.

Vacuum powered brake boosters use vacuum from an internal combustion engine to reduce pedal efforts. Since hybrid electric vehicles have the capability to run in a pure electric mode, the internal combustion engine would not always be available as a source of vacuum. Alternate sources of vacuum and other types of boosters were investigated, however, each would have hampered the vehicle efficiency. As a result, the vacuum powered brake booster was eliminated from the system.

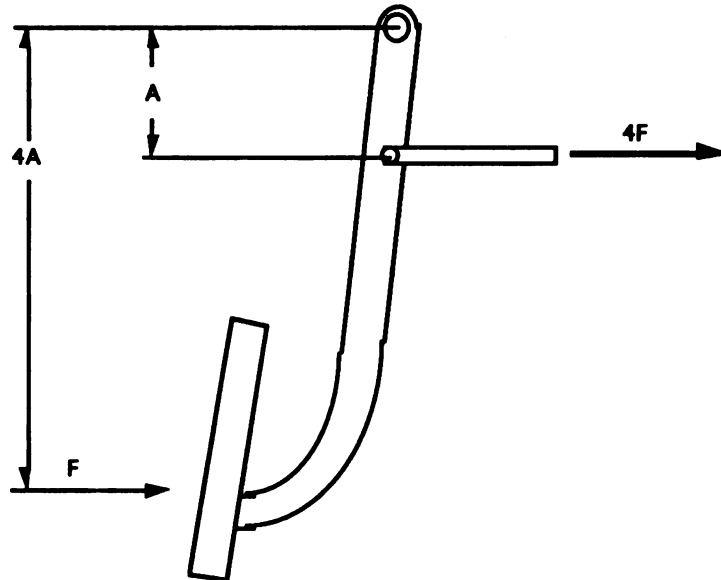


Figure 5. Brake Pedal Mechanical Advantage

The brake pedal mechanical advantage is the ratio of the pedal lever arm to the master cylinder push rod lever arm (Figure 5).. The mechanical advantage of the brake pedal could be altered to increase the brake effort available while keeping the pedal force constant. The mechanical advantage of the Metro brake pedal was 4.1:1. The input force at the brake pedal is multiplied by the mechanical advantage, and the resulting force acts on the master cylinder push rod. Increasing the mechanical

advantage, however also increases the pedal travel, which is generally undesirable. A Tilton pedal assembly, with a mechanical advantage of 6.2:1, was identified to replace the Metro pedal which increased the braking effort available by 51 percent.

The friction coefficients could be increased on the pads and shoes and would result in increased braking performance. The relationship between the hydro / mechanical braking effort available at the front wheels and the friction coefficient of the brake pads is described by (2).

$$F_{front} = \frac{F_{act} \mu R_s}{R_{roll}} \quad (2)$$

where

- F_{front} = the effort available from the front hydro / mechanical brakes;
- F_{act} = the actuating force of the caliper piston;
- μ = the coefficient of friction between the disc brake rotor and the brake pad;
- R_s = the effective radius of the brake pads;
- R_{roll} = the rolling radius of the tires.

Table 1 summarizes the SAE method of labeling friction materials. A two digit code is stamped on the pad or shoe with the first digit representing the normal, or cold, coefficient of friction, and the second digit representing the hot coefficient of friction.

TABLE 1. SAE Friction Coefficient Classifications of Materials

CLASS	FRICTION COEFFICIENT
D	$0.15 < \mu < 0.25$
E	$0.25 < \mu < 0.35$
F	$0.35 < \mu < 0.45$
G	$0.45 < \mu < 0.55$
H	$0.55 < \mu$

The Metro stock pads were classified EE, with both cold and hot coefficients of friction between 0.25 and 0.35. A classification of FG would correspond to a cold friction

coefficient between 0.35 and 0.45 and a hot friction coefficient between 0.45 and 0.55. Ferodo Automotive Products Incorporated makes after market pads for the Metro that have a friction coefficient that is classified as GG.

The Ferodo pads had a cold friction coefficient of 0.534 and a hot friction coefficient of 0.513. According to (2), these pads would increase the available braking effort at the front wheels by 67 percent. Consultants from Robert Bosch Corporation cautioned against expecting drastically increased performance based solely on friction coefficients because the properties of friction materials can change drastically with rising temperatures (Posa 1993). With this in mind, a conservative interpretation of the Ferodo data was taken and a factor of safety of 1.2 was introduced into all brake performance predictions.

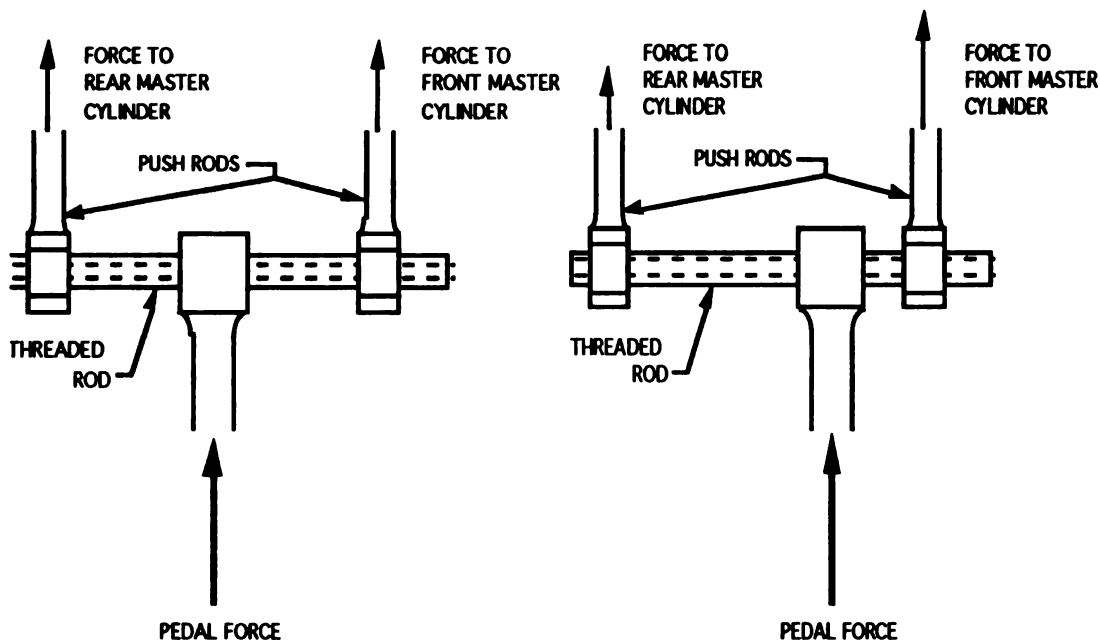


Figure 6. An Adjustable Brake Bias Bar - Neutral Adjusted (left) and Front Biased (right).

An adjustable bias bar is a mechanism that allows the vehicle's hydro / mechanical effort bias to be tuned. A bias bar distributes the pedal force to the front

and rear master cylinder push rods (Fig. 6) for a near neutral adjustment and a front biased adjustment. The bias bar in the Spartan Charge vehicle was set up for dual master cylinders. One master cylinder is dedicated to the front brakes and one to the rear brakes. This type of a split system has the added advantage that the front and rear master cylinder bores can be chosen independently to complement the needed line pressures to achieve the braking capacities at each axle. Finally, the adjustable bias bar was instrumental in tuning the hydro / mechanical system correctly to support and utilize regenerative braking.

Regenerative Braking

Regenerative braking operates the electric portion of the power train in reverse (Fig. 7). The torque from the wheels is transferred through the transmission to create electrical power at the electric motor, used as a generator during regenerative braking mode. This electrical power is routed to the batteries by the inverter, or motor controller. Each of the components in Figure 7 already exists within the power train of the vehicle, so no additional components needed to be purchased.

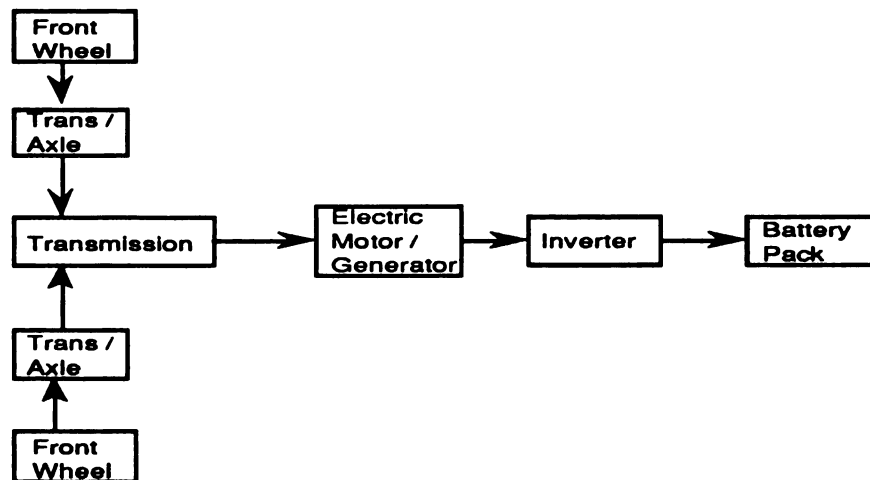


Figure 7. A Typical Regenerative Braking System

Regenerative braking increased the range of the Spartan Charge by 6 to 15% on individual tests, depending on the driving environment. These tests were run

approximately one month before the competition and include urban and highway driving environments. Table 2 summarizes the regenerative braking test results.

Table 2. Summary of Spartan Charge Regenerative Testing

Drive Cycle	Total Kilometers	Total KWH	Regenerated KWH	Average Range Increase
Urban Drives	44	4.352	0.667	15.3 %
Highway Drives	83	7.082	0.430	6.1 %
Total	127	11.434	1.097	9.6 %

The optimal or maximum regenerative effort that the power train could create depends on the breakdown (maximum) torque of the electric motor. This maximum torque for the Spartan Charge was 54.6 Nm. First gear of the transmission is 3.42 and the rolling radius of the tires is 0.28m. This results in a maximum regenerative effort of 662.4N, or 11.5% of the front braking capacity. Regenerative braking will make vehicles more efficient, so auto makers will try to recapture as much energy through regenerative braking as they can. Coupled with the modifications to the hydro / mechanical system, the addition of regenerative effort could produce forces large enough to result in wheel lock up. ABS will be necessary on hybrid electric vehicles that employ regenerative braking to prevent brake lock up and to compensate for the changing front / rear brake effort encountered with regenerative braking.

The Anti-lock Braking System

An Anti-lock Braking System prevents wheel lock up by sensing the wheel speeds and appropriately regulating hydraulic pressure. The elements shown inside the shaded region of Figure 8 are components of the ABS system, while those outside are

part of a hydro / mechanical system. The four wheel speed sensors continuously monitor the wheel speeds. If the speed of any wheel is 5% lower than another wheel during braking, then the pump unit regulates the pressure in the hydraulic line leading to that wheel's brake hardware to prevent that wheel from locking up. If the ABS electronic control module senses a wheel or wheels skidding during braking, then it pulsates the pressure in the hydraulic lines. Pulsating the pressure alternately reduces braking to prevent wheel lock up, and then quickly increases the braking effort near capacity again to optimize braking.

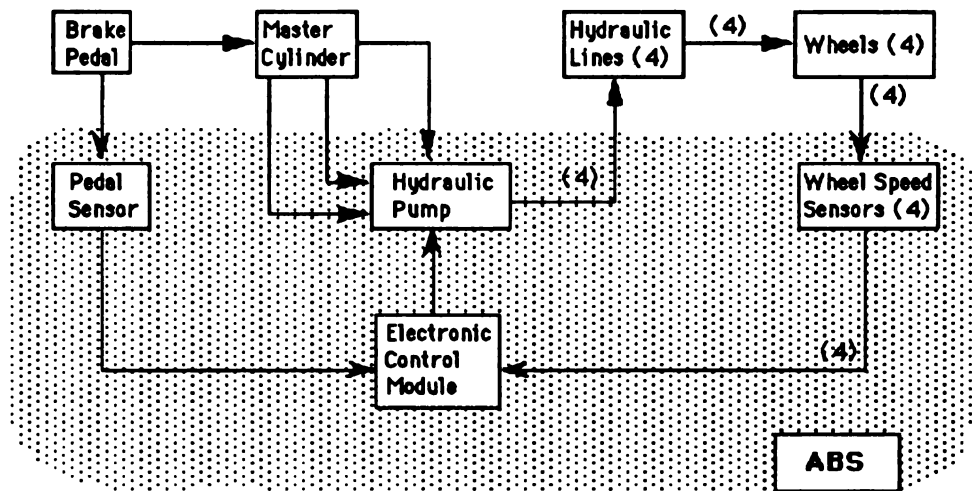


Figure 8. A Typical Anti-lock Braking System

An Anti-lock Braking System (ABS) was desirable because it could increase safety and performance. Figure 9 compares the braking performance of two vehicles. The first vehicle has ABS and the second vehicle, which does not have ABS, is assumed to be in a skid. Both vehicles had an initial speed of 100 km/h. The skidding vehicle takes 25% more distance to stop compared to the vehicle with an ABS system (Emig, 1992). It is important to note that the vehicle without ABS is still traveling at

over 45km/h at the same point where the vehicle with ABS has stopped. The vehicle with ABS decelerated 25% faster than the skidding vehicle.

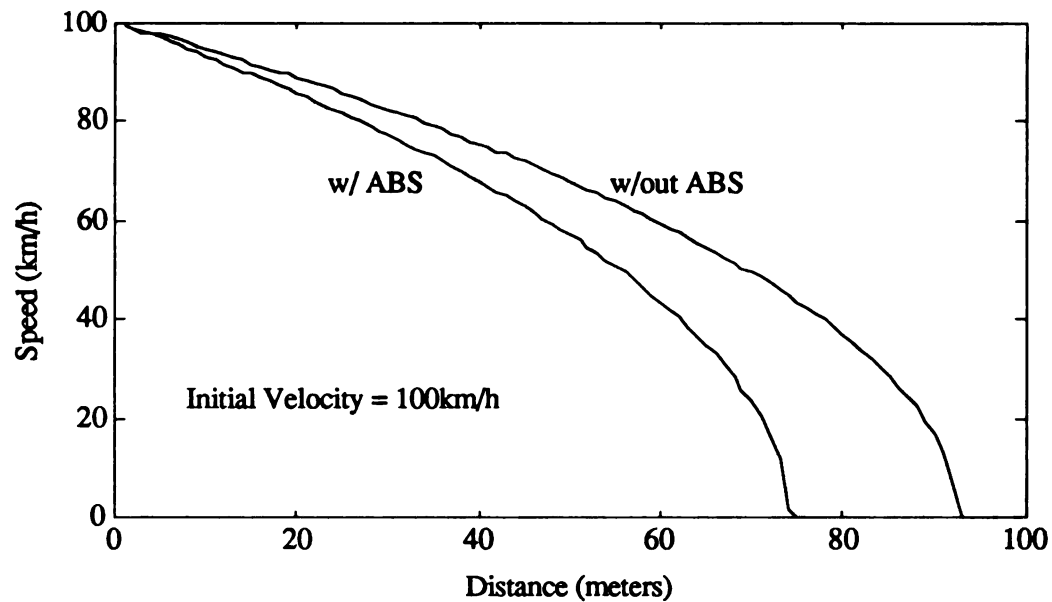


Figure 9. Comparison of an ABS Stop and a Skidding Stop

The ABS system for the 1991 Chevrolet Corvette, manufactured by Bosch, closely matched the weight, track width, and wheel base of the Spartan Charge vehicle. Table 3 compares the key parameters of the two vehicles. A unit was donated by Bosch and consisted of a hydraulic pump unit and electronic control module. Bosch did not manufacture the wheel speed sensors for the system, consequently an alternate source had to be located.

Table 3. Comparison of Mass, Wheel Base, and Track Width Between the 1991 Corvette and the Spartan Charge

	1991 Corvette	Spartan Charge	% Difference
Mass	1465 Kg	1360 Kg	-7 %
Wheel Base	245 cm	272 cm	+10 %
Track Width	153 cm	165 cm	+7 %

The wheel speed sensors from the Corvette were not available and not suitable for the rear drum brakes of the Geo. A search was undertaken to reach the Corvette engineer responsible for the ABS unit to seek advice. The phone conversations led to NDH Integral Bearing Systems, who were experimenting with ABS for smaller cars. NDH had retrofitted a 1991 Geo Metro with ABS. NDH was eager to get involved and donated custom, integral bearing sensors for the rear and the pulse wheels and sensors for the front.

HEV BRAKING DESIGN PERFORMANCE

The braking system underwent a transformation from the fundamental Metro system to the final competition system. Figure 10 shows the fully integrated braking system. All the components from each of the three elements have been included and are functional. The predicted pedal effort of the system is 533N, which falls into the upper end of the 300 to 550N range of the automotive standard.

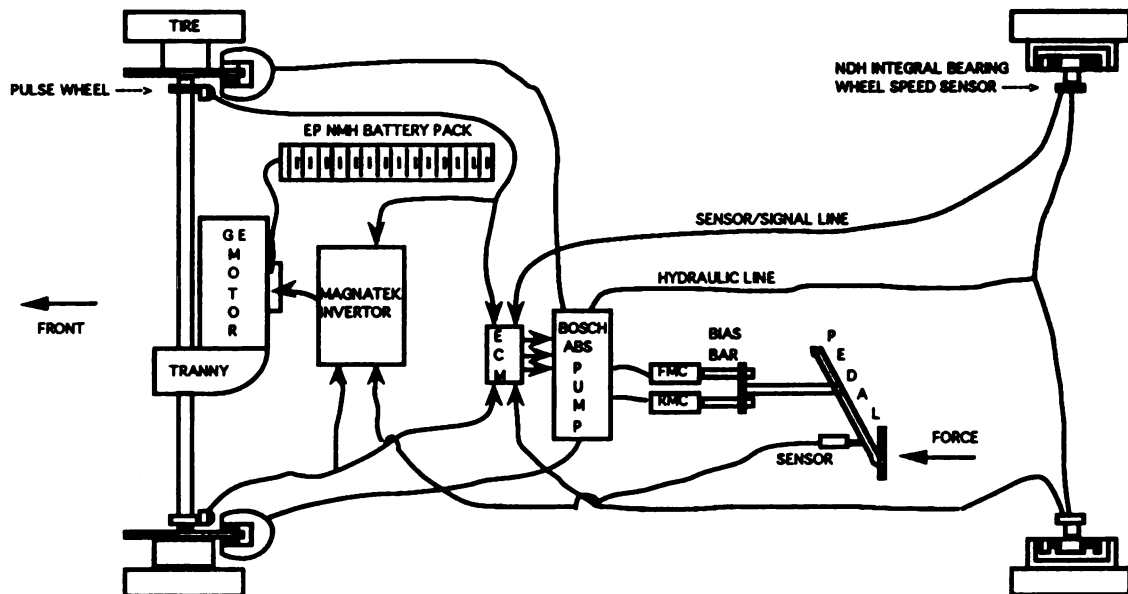


Figure 10. The Spartan Charge Braking System

The braking system achieved and surpassed the required system specifications and objectives. Spartan Charge passed vehicle qualifying, including the pass / fail brake test, on the first attempt. The vehicle stopped from an initial velocity of 72km/h in 41 meters, in a safe and controlled manner, for a deceleration rate of 0.497g. Figure 11 shows the pass / fail curve again with the Spartan Charge braking performance included. The vehicles were allowed to try as many times as necessary to qualify, so the driver did not approach the braking capacities on the first, and only, qualifying attempt.

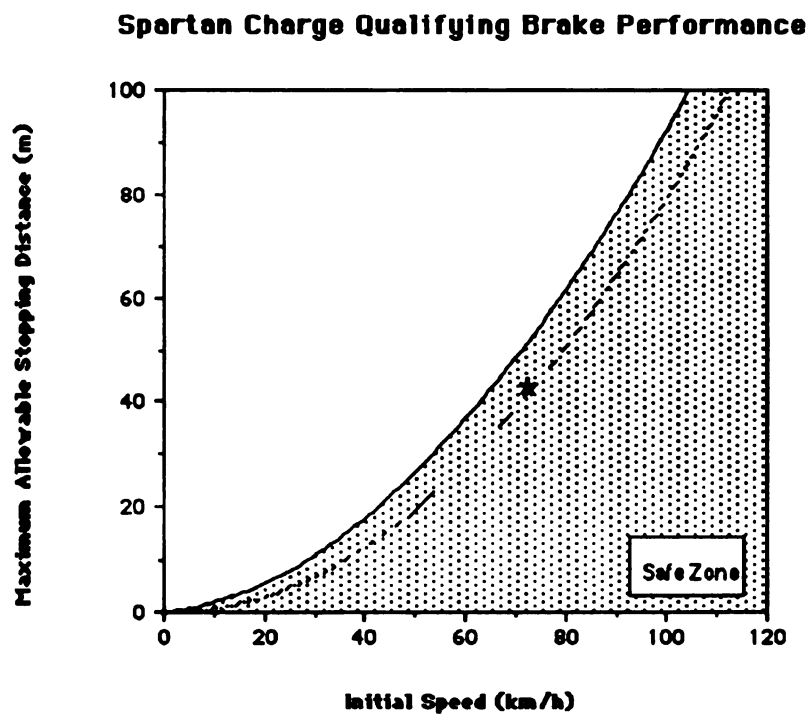


Figure 11. Spartan Charge Brake Test Qualifying

Spartan Charge was one of two vehicles in the Ground-up Class with regenerative braking. Test runs yielded as much as an 18 percent increase in range

during urban driving and an average increase in range of 9.6% for both highway and urban driving. Regenerative braking can account for as much as 11.5% of the front braking capacity and greater percentages under gentler braking conditions.

Spartan Charge was the only vehicle at the competition with an Anti Lock Braking System. The ABS was necessary because of the increase in available braking effort from regenerative braking. It was a testimonial to the team's dedication to safety and engineering.

The braking system clearly fulfilled the main objective of providing safe and reliable braking. The Spartan Charge braking and power train system was recognized by the competition organizers as the Most Innovative Design in Mechanical Systems. Clearly, the ABS (braking) and the regenerative braking (braking and power train) contributed to Spartan Charge receiving this award as it was the only vehicle with both capabilities.

The Spartan Charge hybrid electric vehicle met all of its objectives, including the mission to provide safe and reliable braking. This was accomplished by modifying a Geo Metro braking system to support both regenerative braking and Anti Lock Brakes. The braking system attained each of its objectives which are summarized here.

- Deceleration rate of 0.497g,
- Predicted pedal effort of 533N,
- Functional regenerative braking yielding an average 9.6% increase in range,
- Functional Anti-lock Braking System.

The braking system helped set the Spartan Charge hybrid electric vehicle apart from the other contestants. The braking and power train system was celebrated as the Most Innovative Design in Mechanical Systems.

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APPENDIX A

Description of Events

Description of Events

Emissions Event - This event was designed to measure vehicle exhaust emissions and evaluate its ability to minimize the formation of regulated vehicle emissions.

Commuter Event - The goal of the commuter event was to evaluate the low speed maneuverability and handling of the HEV under typical commuting conditions.

Range Event - The objective of the range event was to test the durability of the vehicles and their overall range.

Acceleration Event - The acceleration event evaluated the ability of the vehicles to accelerate from a standing start over a distance of 100 meters.

Efficiency Event - The efficiency event was designed to determine which vehicle had the best distance per unit energy rating during the commuter, range, and emissions events.

Engineering Design Event - The engineering design event evaluated the amount of engineering effort each school put into constructing their vehicle.

Oral Presentation - The oral presentation event evaluated each team's ability to make an informative and exciting presentation aimed at selling the benefits of their hybrid electric vehicle.

Cost Assessment - The purpose of the cost assessment event was to quantify the market value of each vehicle, including hardware and labor.

Technical Report - The objective technical report event was to evaluate each vehicle design and operation strategy`.

APPENDIX B

Spartan Charge Awards 1993 HEV Challenge

Spartan Charge Awards 1993 HEV Challenge

The competition consisted of not only static and dynamic events, for which points were awarded, but also a series of engineering awards. The points awarded for the events determined which school would win the competition, while the engineering awards were monetary and were intended to recognize individual aspects, elements or systems of the vehicles' designs.

Eight engineering awards were presented during the competition. Spartan Charge was awarded the following;

- Best Styling
- Best Ergonomics
- Best Use of Materials
- Best Use of Electronics
- Most Innovative Design in Mechanical Systems

The citation for Most Innovative Design in Mechanical Systems was awarded based on the braking system and the power train. The remaining three engineering citations were awarded to three different schools.

The competition events were intended to evaluate design and performance of the vehicles. Spartan Charge placed in the following static and dynamic events;

- | | |
|---------------------|-------------|
| - EMISSIONS EVENT | (3rd Prize) |
| - ORAL PRESENTATION | (3rd Prize) |
| - RANGE EVENT | (3rd Prize) |
| - COMMUTER EVENT | (2nd Prize) |
| - TECHNICAL REPORT | (2nd Prize) |
| - DESIGN EVENT | (2nd Prize) |

The top five schools, along with their point totals, are listed below. The total points available was 1000.

- 5th Place, Lawrence Technological University with 507 points,
- 4th Place, University of Tennessee with 550 points,
- 3rd Place, Michigan State University, with 676 points,
- 2nd Place, University of California at Davis, with 700 points,
- 1st Place, Cornell University, with 775 points.

APPENDIX C

Recommendations for Further Work

Recommendations for Further Work

Although the Spartan Charge Braking System performed well and was identified as part of the Most Innovative Design in Mechanical Systems, many improvements can and should be made. The following list contains items under three headings; the minimum or Must Do Items, the Should Do Items, and finally the wishful, or Try To Do Items.

Must Do Items

1) Increase the rear Braking Capacity (BC) to the point where rear lock up is achievable.
This is possible by

- A) Larger Drums
- B) Replace Drums with Appropriate sized Discs (would affect ABS)
- C) Higher Friction Coefficients (heat transfer effects?)
- D) Smaller Rear Master Cylinder Bore (present is 0.625 in. dia.)
- E) Larger Wheel Cylinders

2) Tune for Optimal Effort Bias (when entire system is finalized)

- A) Determine Regenerative Braking Effort Desired (ie 50%)
- B) Adjust Braking Capacity Effort Bias (to incorporate regen effort)
- C) Tune Hydro / Mechanical System with Adjustable Bias Bar

EXAMPLE

NOTE: These are NOT actual Spartan Charge Parameters!

A) Regen Setting (R_{set})= 50%, Gear Ratio (G_{ratio}) = 3.5 (1st gear Transmission), The Breakdown Torque of the Electric Motor (T_{bd}) = 75 Nm, Rolling Radius of the Tires (R_{roll}) = 25Cm

$$Re\ gen_ Effort = \frac{R_{set} T_{bd} G_{ratio}}{R_{roll}} = \frac{0.5 * 75 Nm * 3.5}{0.25m} = 525N \quad (3)$$

B) The Braking Capacity Effort Bias (BCEB) is the Ratio of the Front Braking Capacity (maximum amount of braking effort usable without the tire skidding) to the Rear. If the Front Brake Capacity = 5.25 kN and the Rear = 3.5 kN, then

$$BCEB = \frac{5.25kN}{3.5kN} = \frac{60\%}{40\%} \quad (4)$$

The Hydro / Mechanical System Bias (HMSB) is the ratio of the front effort required from the HMS (brake capacity minus regen effort) to the rear effort required from the HMS

$$HMSB = \frac{5.25kN - 0.525kN}{3.5kN} = \frac{57.5\%}{42.5\%} \quad (5)$$

(This is the bias at the wheels that the HMS should be tuned for.)

The Front HM Effort ($F_{HMeffort}$) = 4.725 kN, The Rear HME = 3.5 kN.

The Force needed (to reach BC) at the Front Master Cylinder (F_{fmc}) is the pressure needed in the hydraulic line times the Master Cylinder Area (A_{fmc}). This pressure is the piston actuating force needed divided by the Piston Area (A_{fp}). The actuating force is the required effort at the tire times the rolling radius divided by four times the Effective Radius (R_{feff}) of the braking material surface. The same equation will work for the rear. Therefore

$$F_{fmc} = \frac{F_{HMeffort} R_{roll} A_{fmc}}{4 A_{fp} R_{feff}} \quad (6)$$

$$R_{feff} = 3.5 \text{ Cm,}$$

$$A_{fp} = 18.09 \text{ cm}^2$$

$$A_{fmc} = 1.96 \text{ cm}^2$$

$$R_{feff} = 9 \text{ Cm}$$

$$A_{rp} = 2.01 \text{ cm}^2$$

$$A_{rmc} = 0.694 \text{ cm}^2$$

As a result, $F_{fmc} = 914.2 \text{ N}$ and $F_{rmc} = 839.2 \text{ N}$

The Adjustable Bias Bar (ABB) distributes the pedal force to the front and rear master cylinders and should be adjusted (Figure 12) to reflect the ratio of the master cylinder forces

$$ABB_Bias = \frac{922.9 \text{ N}}{838.9 \text{ N}} = \frac{52.4\%}{47.6\%} \quad (7)$$

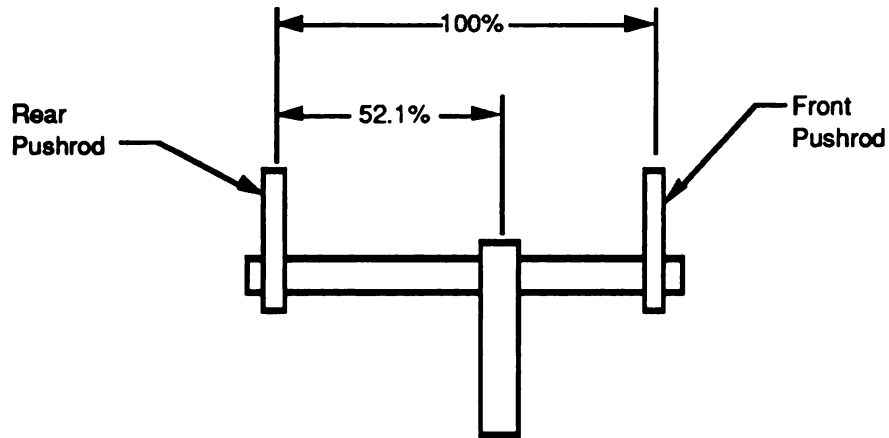


Figure 12. How to Set the Bias Bar

3) Test, measure and document pedal force at maximum and intermediate stopping forces (Table 4). Correlate with deceleration rates and other factors. (Shoot for pedal effort below 100# to create 0.5g or more.)

Table 4. Example Pedal Force Table

Vinitial	Stop Dist	F _{pedal}	R _{set}	g
72km	40m	100#	50%	0.5097g
50km	34m	70#	50%	0.2892g

4) Analyze the Brake Fluid Volume Necessary to Displace to Create the Brake Capacities and Compare to Actual Volumes Displaced.

Should Do Items

- 1) Duct Air to the Front & Rear Brake Hardware.
- 2) Heat Transfer Analysis of All Brake Hardware.
- 3) Replace Front Discs w/ Vented Discs (may require custom calipers).
- 4) Test/Verify that ABS Works Properly.

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