IPRO It takes a team
INTERPROFESSIONAL PROJECTS PROGRAM

IPRO 342

Hybrid Electric School Bus:
Simulation, Design & Implementation

FINAL REPORT / FALL 2006

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Section 1 - Introduction and Background

One of the up and coming concepts in the modern world is the idea of hybrid electric vehicles (HEVs). Conventional vehicles use an internal combustion engine (ICE) to drive the wheels of the vehicle. Although the ICE performs very well at constant speeds, its efficiency at transient speeds is extremely poor. An electric machine, however, can be much more efficient and environmentally friendly at these changing speeds. Unlike conventional vehicles, HEVs utilize a combination of an electric machine and an internal combustion engine (ICE) to propel the vehicle, but in a way that is more fuel efficient and better for the environment. In fact, HEVs attain the highest fuel economies when operated in stop-n-go driving conditions. Since school buses start and stop so frequently, they are an ideal candidate for hybridization.

The primary goal of IPRO 342 was to design a workable test bed for a hybrid electric school bus that can be used to evaluate the suitability of hybridizing a school bus. While there are several types of software programs already in use to look at fuel efficiency in automobiles, most of them are unable to model all of the details and functions of a hybrid electric vehicle. Indeed, previous HEV IPROs have mainly dealt with simulations of HEV systems, which, of course, do not take into account all the practical considerations of building an actual HEV. Thus, the development of a test bed is absolutely necessary to improve and standardize the hybrid electric vehicle, something that many auto manufacturers are looking at as well.

The IPRO team did considerable research toward achieving its goal. From this research, the team compiled a great deal of information for each of the HEV components (both mechanical and electrical) that will be included in the test bed, all of which will be presented shortly. Initially, however, the team had to make several decisions. For example, one of the first things determined was the hybridization factor, or the ratio of electric power to the total (ICE + Motor) power for the test bed, since this parameter affects the size of the electric motor that gets chosen. It was estimated that a hybridization factor of 1/3 would be appropriate for the test bed.

Another equally important design decision made was the type of HEV system that the test bed will model. Previous HEV research has shown that there are some difficulties with the series HEV set up (i.e. the coupling of a generating electric machine and ICE to drive an outputting electric machine). These include the loss of power in multiple conversion locations, the higher cost, and lesser flexibility. One of the major advantages of a parallel HEV system (i.e. the ICE and electric machine output are combined into the drive shaft) is the ability to run on either the internal combustion engine (ICE), the electric machine, or both in various combinations. This is exactly why the team chose to implement the HEV test bed using a parallel configuration.

Note that all of this research done by IPRO 342 this semester has helped in the design of the test bed, which will actually be built in the following semesters. This semester, the team used what it learned from its research to construct a dyno for an HEV, which is really a small-scale model that will help in building the larger test bed.

In what follows, the IPRO team’s research methodologies and obstacles that it encountered are first discussed. Next, the outcome of the team’s research is presented in detail. The first part of the Results section describes the major electrical components of an HEV and the best choices for the test bed as determined by the IPRO team, while the second part focuses on the mechanical components. The report concludes by revisiting the major goals of this IPRO and making recommendations for future work.

Section 2 - Team Assignments and Research Methodology

Since the beginning of the semester when the original project plan was constructed there were a few changes that affected the overall structure of the IPRO 342 team and how it conducted its research. The entire IPRO team was divided into two sub teams to make research more manageable. These two teams were mechanical and electrical. The mechanical team was in charge of everything that involved the mechanical components of the test bed. The electrical team was in charge of all the electronics research, including the electric motor, power electronics, etc. Team assignments did not change over the course of the semester. There were still two teams, electrical and mechanical, consisting of 5 members each. Individual team members conducted their own research based on tasks assigned by the team leaders. Nevertheless, there was a great deal of collaboration amongst the team members as well as across the two sub-teams for integrating the disparate parts of the research.

The team and sub team responsibilities were as follows:

Team	**Name**	**Responsibility**
Electrical	Ali Gowani	-Electrical Team Leader -Electric Motor
	Tyler Inouye	-Power Electronics
	Garrett Nielson	-Power Electronics
	Sonya Colletti	-Electric Motor -Power electronic isolation -Current Detection
	Eric Hope	-Battery -Dspace
Mechanical	Mohammed Khader	-Mechanical Team Leader -Drive Train/Power Coupling and Splitting
	Preeti Abraham	-Drive Shaft
	Aamer Saeed	-Differential
	Jatan Shah	-Drive Train/Power Coupling and Splitting
	Joel Fenner	-Frame Support

Table 1 – Team member responsibilities

The changes from the original project plan as stated were minimal and only occurred for unavoidable reasons. The original plan was to design a test bed that is a 1/8th scale model of a hybrid electrical school bus. After much deliberation, this was changed to a smaller-scale model due to the size and safety concerns of a 1/8th scale model. Since this change the mechanical team had to redirect itself according to the new changes. Another change for the mechanical team was the use of an electric motor to model the internal combustion engine. This was decided due to the ease of controlling an electric motor as compared to that of controlling an internal combustion engine.

Research on the electrical and mechanical components (motor, differential, etc.) for the test bed was done throughout the semester by each member of the IPRO team. As stated in the project plan, the goal was to conduct this research, and based upon the team's findings, offer recommendations for the design of the test bed. The team did just that, and more. Since research would only provide the theoretical background for the team this semester, the team decided to go above and beyond the mere test bed research outlined in the project plan and actually build a dyno, a small-scale prototype for the test bed. Consequently, team members also got involved in direct, hands-on, real-world engineering experience.

Section 3 - Obstacles

In general, the obstacles encountered by the IPRO team this semester can be divided into two categories: the mechanical team obstacles and the electrical team obstacles.

The major obstacles for the mechanical team were:

- Figuring out what to use and how to build the frame of the test bed
- Figuring out what kind of drive shaft to use
- Figuring out what kind of differential gear to use
- Figuring out what kind of power split or coupling to use

The major obstacles for the electrical team were:

- Figuring out what kind of battery to buy
- Figuring out what kind of motor to use as the electric machine
- Figuring out what kind of power electronics were needed

The two teams overcame these obstacles by reviewing previous test bed designs for other scale models and by researching the possible ideas and solutions for each obstacle. The teams picked the best solution for each obstacle, gave reasons why that was the best solution, and also researched sources for buying the supplies and their pricing. All of this research will be presented in the Results section of this report.

Obstacles were also encountered in building the dyno. These included alignment and vibration issues with the motors, building the electrical components, figuring out how to use a computer program (DSPACE) for simulations/demonstrations, and testing the dyno to make sure it works properly. The IPRO team dealt with these obstacles by buying the electrical parts to build the actual electrical components from scratch, spending time aligning and testing to decrease the motor vibrations, and looking at manual and online guides to learn how to use the computer program for the demonstration and testing.

It has been determined that when the test bed is actually implemented by future IPRO teams, they will surely face other obstacles. These include implementation issues such as building the frame and integration issues such as testing the final design to make sure it works properly. Exactly how these obstacles are handled by other IPRO teams in the future will need to be determined by these teams when implementation time comes, as these are implementation-specific issues and not design issues. One thing is for certain, however: if the IPRO 342 team were to make one suggestion to future IPRO teams on overcoming these obstacles, it would be that the best solution is through teamwork.

Section 4.1 - Results

Battery Pack Research
Eric Hope

Section 4.1.1 - Battery Pack Problem

Select a battery pack for the hybrid test bed that is able to adequately power the electric machine.

Section 4.1.2 - Battery Pack Background Information

Hybrid Electric Vehicles (HEVs) use a conventional car battery as well as a rechargeable battery pack. The conventional car battery maintains the same function in a HEV, starting the vehicle's internal combustion engine. The function of the rechargeable battery pack is to provide power to the HEV's electric motor. Currently, three different types of rechargeable batteries are available for use in HEVs, Lead-Acid batteries, Nickel Metal Hydride (NiMH) batteries, and Lithium-Ion (Li-Ion) batteries.

Lead-Acid batteries contain electrodes composed of lead metal (Pb), lead (IV) oxide (PbO_2) and an electrolyte composed of Sulfuric Acid (H_2SO_4) and water (H_2O). When the battery discharges, the electrodes become lead (II) sulfate ($PbSO_4$) and the electrolyte becomes primarily water. Conventional Lead-Acid batteries are not designed for deep discharging. These batteries contain a large number of thin electrode plates in order to maximize the surface area of the electrode, thus maximizing output current. The thin plates are damaged by deep cycling. Deep-Cycle Lead-Acid batteries are specifically designed to withstand frequent discharging. The plates of a deep-cycle battery are generally thicker than a conventional Lead-Acid battery, allowing them to withstand deep discharging. However, the increase in plate thickness also decreases the surface area of the plates, resulting in a lower output current. Lead-Acid batteries are among the worst batteries in terms of their energy-to-weight ratio. Conversely, due to their ability to supply high currents, Lead-Acid batteries maintain a high power-to-weight ratio.

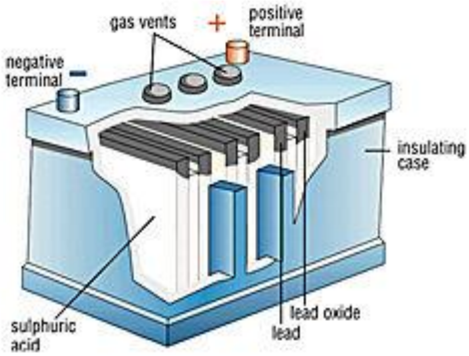


Figure 1 - Lead-Acid Battery

Nickel Metal Hydride batteries are rechargeable batteries that use nickel metal for the cathode and a hydride absorbing alloy for the anode. All commercially available hybrid vehicles currently utilize NiMH battery technology for powering their respective electric machines. For example, the Honda Civic Hybrid currently uses 120 NiMH batteries with a rating of 6 Ah to power its 15kW permanent magnet electric motor. NiMH batteries are highly sensitive to overcharging and temperature changes. Overcharging a NiMH battery will result in decreased charge efficiency. NiMH batteries currently have one of the highest energy-to-weight ratios along with an average power-to-weight ratio.

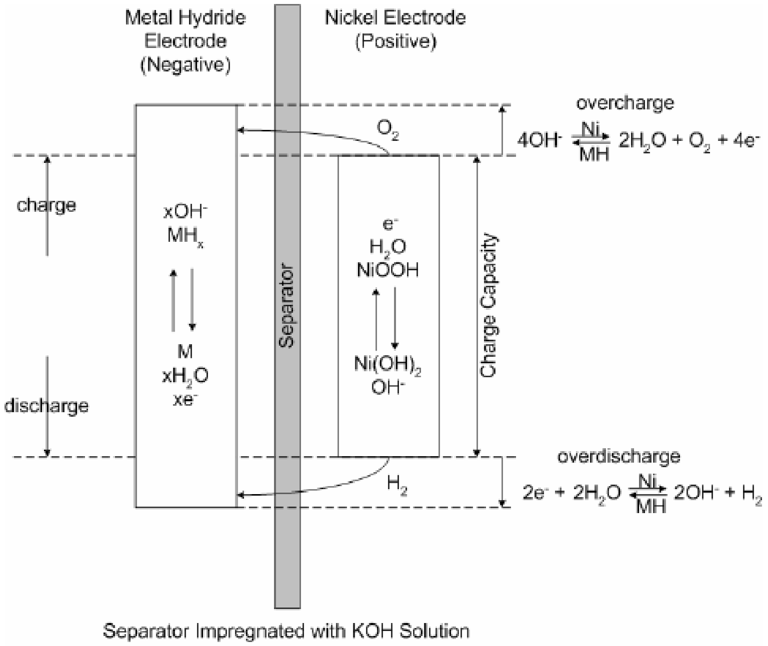


Figure 2 - NiMH Cell

Lithium-Ion batteries are rechargeable batteries that utilize a lithium ion intercalation compound of either graphite or disordered carbon molecules for the anode. This technology deviates from conventional rechargeable batteries that utilize a metal for the anode. For the cathode, the Lithium-Ion battery utilizes lithiated transition metal oxide. In most cases, the transition metal used is cobalt. Finally, a stable combination of linear and cyclic carbonates is used as the electrolyte. This construction provides the ideal combination of a high voltage cathode and a low voltage anode. The result is a rechargeable cell with a very high energy density, larger than that of a NiMH cell. Lithium-ion batteries have become the batteries of choice for small consumer electronic devices. However, Lithium-Ion battery technology is not yet suitable for HEVs. Further improvement is needed in areas such as calendar and cycle life, safety, abuse tolerance, and cost.

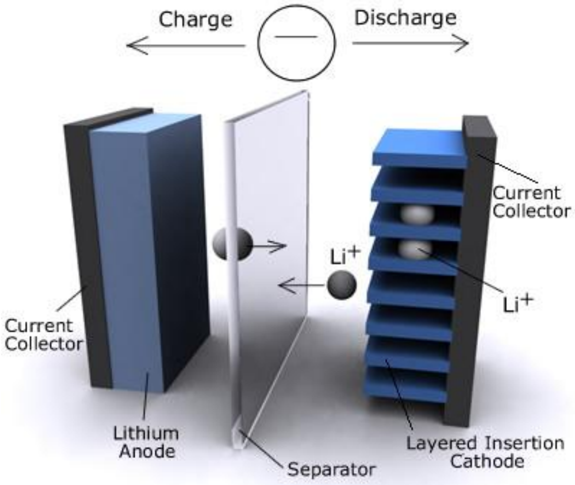


Figure 3 - Lithium-Ion Cell

Section 4.1.3 - Battery Pack Potential Solutions

The first potential solution would be to use a Lead-Acid battery pack to power the electric machine. The battery pack would be composed of several deep-cycle batteries connected in series. The rating and number of batteries contained in the battery pack would highly depend on the size of the electric machine selected. Approximately two to three deep-cycle batteries would be required for this application.

The second potential solution would be to use a NiMH battery pack to power the electric machine. The battery pack would be composed of many NiMH cells. The rating and number of cells contained in the battery pack would highly depend on the size of the electric machine selected. A large number of NiMH batteries would be required for this application.

Section 4.1.4 - Battery Pack Price Information

Deep-Cycle Lead-Acid Batteries

Model	Rating	Price	Source
Haze HZS12-18	12V, 18Ah	$25.00	batteryservice.com
Odyssey PC1200	12V, 44Ah	$165.99	batteriesplus.com
Odyssey PC1700T	12V, 68Ah	$239.99	batteriesplus.com
Odyssey PC2150	12V, 95Ah	$261.00	qualitypowerauto.com
Trojan CB24-AGM	12V, 80Ah	$164.95	ebatteriestogo.com
Trojan CB27-AGM	12V, 100Ah	$184.95	ebatteriestogo.com
Trojan CB31-AGM	12V, 110Ah	$215.95	ebatteriestogo.com
Werker WKA12-33JH	12V, 33Ah	$50.99	batteriesplus.com

Table 2 – Prices for deep cycle lead acid batteries

NiMH Batteries

Model	Rating	Price	Source
Energizer DNH2 D Cell 2-pack	2,500mAh D 1.2V	$8.99	newegg.com
5010B 10 Cell NiMH C Pack	5,000mAh C 12V	$65.00	onlybatterypacks.com
10010F 10 Cell NiMH D Pack	10,000mAh D 12V	$110.00	onlybatterypacks.com
NiMH Battery Pack DV-HF10R2T-MT	13Ah 12V	$129.95	batteryspace.com
NiMH Battery Pack MHP-48V10Ah-4WR	10Ah 48V	$395.95	batteryspace.com

Table 3 – Prices for NiMH Batteries

Section 4.1.5 - Battery Pack Pros and Cons

Lead-Acid Battery Pros	Lead-Acid Battery Cons
• Relatively inexpensive compared to NiMH batteries • High power to weight ratio • Readily Available	• Energy-to-weight ratio (~30Wh/kg) • Energy-to-size ratio (~65Wh/L) • Short Lifespan (3-4 years or about 200 charges) • Slow to charge (~5-10 hours) • Size and Weight (~25-50lbs)

Table 4 – Lead Acid Pros and Cons

NiMH Battery Pros	**NiMH Battery Cons**
• Energy-to-weight ratio (~60Wh/kg) • Energy-to-size ratio (~100Wh/L) • Long Life (~10 years and thousands of charge cycles) • Quick charge capabilities	• Self Discharge Rate (30% per month at 20C) • Requires a “smart” charging device to avoid overcharging • Must be in a temperature controlled environment • Very expensive compared to Lead-Acid batteries (~5-10 times more expensive)

Table 5 – NiMH Pros and Cons

Section 4.1.6 - Battery Pack Practical Considerations

Cell imbalance must be taken into consideration when using multiple batteries in series. This occurs when a battery is at a lower or higher state of charge than the other batteries in the pack, resulting in the battery being driven into an over-discharge or over-charge condition. In extreme situations, the state of charge of the affected battery may reach zero. When this occurs, the battery plates will begin charging to the opposite polarity. The over-discharge or reversal of a Lead-Acid battery can result in extreme gassing and overheating of the affected battery. Ultimately, a cell dry out would occur and the battery would fail. Cell imbalance is responsible for the majority of premature battery pack failures in HEV applications.

In order to combat cell imbalance, a protection scheme must be implemented for each battery contained in the battery pack. This may be accomplished by using an integrated circuit to measure individual cell voltages. The protection circuit would prevent the over-charge or over-discharge of an individual battery by opening the current path to the battery when an out of range voltage is detected. In the case of an over-discharge, the affected battery must be charged. The reverse is true in the case of an over-charge. An effective protection circuit must be designed to protect the hybrid’s battery pack as well as to avoid any additional drain on the battery.

Section 4.1.7 - Battery Pack Conclusions

A Lead-Acid battery would prove to be the best choice for the hybrid school bus test bed. Though they are rather large and heavy as compared to NiMH batteries, Lead-Acid batteries would provide plenty of power to the electric machine. Currently, Lead-Acid batteries are also much more affordable than NiMH batteries. Finally, the purpose of the test bed is to provide a lower bound for the efficiency of a hybrid electric school bus. Since the use of NiMH batteries would provide increased efficiency over Lead-Acid batteries, a lower bound to efficiency would be provided with the use of Lead-Acid batteries.

Electric Motor Report
Ali Gowani

Section 4.2.1 - Electric Motor Problem

Select the best electric motor for the HEV test bed

Section 4.2.2 - Electric Motor Background Information

Electric motors are one of the most important components of Hybrid Electric Vehicle (HEV) drive systems. Indeed, the fundamental idea of an HEV is based on the utilization of both an internal combustion engine and an electric machine to propel the vehicle. In an HEV, the electric motor converts electrical energy from the energy storage unit to mechanical energy that helps drive the wheels of the vehicle. Unlike a conventional vehicle, where the engine must ramp up before full torque can be delivered, an electric motor provides full torque at low speeds, giving the vehicle superior off-the-line acceleration.

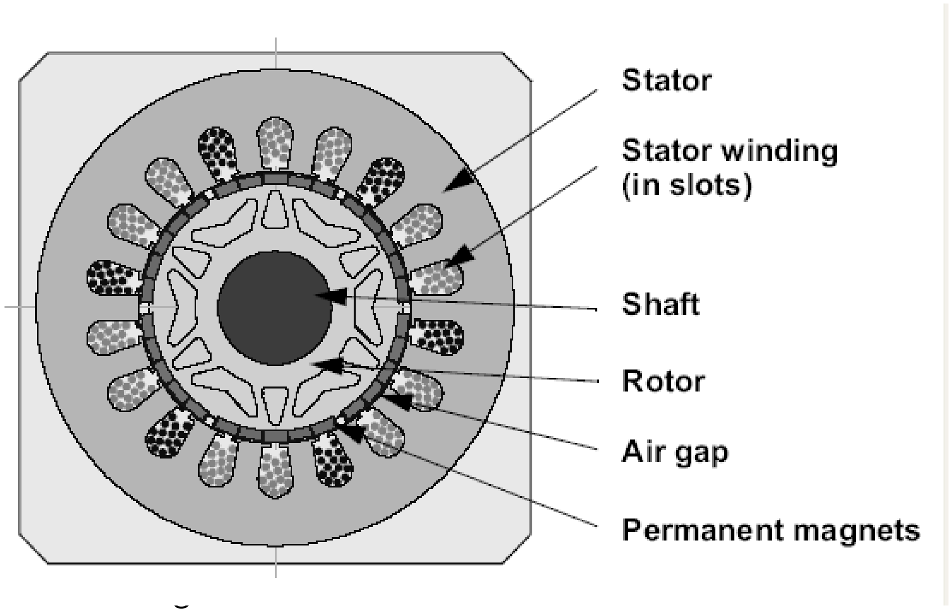
Thus, selecting the proper electric motor is of utmost importance in the design of any HEV test bed. Important characteristics of an HEV motor include good drive control, low noise, and high efficiency, among others. Currently, two types of motor technologies are widely used in HEVs: the permanent magnet motor and the AC induction motor. Of these, the Brushless DC (BLDC) permanent magnet motor seems like the best candidate for the test bed.

Section 4.2.3 - BLDC Motor Fundamentals

In a conventional (brushed) DC-motor, a set of brushes make mechanical contact with a set of electrical contacts on the rotor (called the commutator), forming an electrical circuit between the DC source and the armature coil windings. As the armature rotates on an axis, the stationary brushes come into contact with different sections of the rotating commutator. Essentially, the commutator and brush-system form a set of electrical switches, each firing one after the other, such that electrical power always flows through the armature coil closest to the stator (permanent magnet).

Conventional dc motors can be highly efficient at times, but their major drawback is that they need commutators and brushes, which are subject to wear and require maintenance. When the functions of commutator and brushes are implemented by solid-state switches, maintenance-free motors are realized. These motors are known as Brushless DC (BLDC) motors. In BLDC motors, the mechanical commutator/brush gear rotating assembly is replaced by an external power electronic switch system (an inverter, for example), which is typically implemented by a number of MOSFETs. In other words, commutation – the process which converts the input dc current to ac current and properly distributes it to each armature winding – in a BLDC motor is done by using semiconductor devices such as transistors.

BLDC motors are permanent magnet synchronous motors. They utilize three phases of driving coils that are similar to those in a polyphase synchronous motor and a rotor that is composed of one or more permanent magnets. A cross-section of a BLDC motor is shown in Figure 1 below. The primary difference between the regular, synchronous ac motors and BLDC motors is that the BLDC motors incorporate some means to detect the rotor position (or magnetic poles) to produce signals to control the electronic switches.



Why is this position feedback necessary for a BLDC motor? The answer is simple, if the operation of permanent magnet motors is carefully understood. In a BLDC permanent magnet motor, the permanent magnets are placed on the rotor and the coil of wire (the stator) is inside the housing of the motor. In order to get the rotor to turn, a magnetic field that attracts the poles needs to be created inside the coil. If the magnetic poles of the rotor are not aligned properly with the poles of the magnetic field that is created, then erratic motion will occur. Therefore, it becomes necessary to know where the rotor is with respect to the stator. One way of knowing this is to place sensors inside the motor that detect the position of the rotor with respect to the stator. Once this information is known, the motor controller can place the current in the correct coils of wire (motor phases) and create the desired motion. Once the rotor is in motion, the controller begins switching the current from phase to phase depending on the feedback received from the sensors to create a rotating magnetic field that is always aligned with the rotating permanent magnet rotor.

The most common type of position sensor used with BLDC motors is the Hall effect device. Note, however, sensing where the rotor is can be accomplished with other devices, too – mainly Resolvers and Encoders. For example, a Resolver can determine the rotor position well within a tenth of a degree. Hall effect sensors, on the other hand, can, at best, resolve the rotor position within 30 degrees, but that is all that is needed for accurate position feedback in a BLDC motor. In other words, there is no need for more precision, and consequently, the higher cost. This is exactly why Hall effect sensors are the most popular devices used to monitor BLDC rotor position today.

Section 4.2.4 - Electric Motor Potential Solutions

As mentioned earlier, one of the leading competitors of the BLDC motor today for use in HEVs is the AC induction motor. Generally, the induction motor would require complicated power electronic devices, just as a BLDC motor, if it were to be used in the test bed. However, induction motors are generally cheaper than BLDC motors. So a valid question one might ask at this point is why not just using an induction motor instead of a BLDC motor for the test bed?

Simply put, an induction motor is much more difficult to control than a BLDC motor. Induction motors are older and difficult to optimize for power and efficiency. Still, a great number of hybrid electric vehicles today are driven by induction motors. But, as the U.S. Department of Energy puts it, replacing these induction motors with permanent magnet motors will result in “lighter weight, more cost-effective systems with the higher efficiency and power density needed for HEVs.” This is exactly why a permanent magnet motor such as a BLDC motor would be a better choice for the test bed than an AC induction motor.

Of course, brushless DC motors are only one type of permanent magnet motors; brushed DC permanent magnet motors could also qualify as a good candidate for the test bed. The following table compares the BLDC motor with the brushed DC motor:

	Conventional, brushed motors	Brushless motors
Mechanical structure	Field magnets on the stator	Field magnets on the rotor Similar to AC synchronous motor
Distinctive Features	Quick response and Good controlability	Long-lasting Usually, no maintenance required
Winding Connections	Ring connection The simplest: Delta connection	The highest grade: Delta or Wye, three-phase connection The simplest: Two-phase connection
Commutation method	Mechanical contact between brushes and commutator	Electronic switching using transistors
Detecting method of rotor's position	Automatically detected by brushes	Hall element, Encoder, Resolver, etc.

Table 10 – Motor comparison

Many of the limitations of the classic, brushed DC motor are due to the need for brushes to press against the commutator. This creates friction. At higher speeds, brushes have great difficulty in maintaining contact. Brushes may bounce off the commutator surface, creating sparks. This limits the maximum speed of the motor. The current density per unit area of the brushes limits the output of the motor. Additionally, the imperfect electrical contact causes electrical noise. Brushes eventually wear out and require replacement, and the commutator also is not free from wear and maintenance.

All of these problems are eliminated in the BLDC motor. Of course, the downside of using a BLDC motor versus the classic commutator DC motor is the higher cost, which arises from two main issues. First, BLDC motors require high-power transistors and a more expensive integrated circuit, while brushed DC motors can be controlled by a trivial variable resistor. Second, when comparing manufacturing techniques between BLDC and brushed motors, most BLDC motors require manual labor to hand-wind the stator coils. Brushed motors, on the other hand, use coils that can be inexpensively machine-wound.

The disadvantages of a brushed DC motor, however, far outweigh this cost advantage, particularly for a system such as an HEV, where the electric motor is considered to be the workhorse of the vehicle. Of course, the BLDC motor also has other advantages over the brushed DC motor. The most notable of these is that BLDC motors are considered more efficient than brushed DC motors, meaning that, for the same input power, a BLDC motor will convert more electrical power into mechanical power than a brushed motor. In fact, BLDC motors are the highest performing motors in terms of torque versus weight or efficiency.

The following bullets summarize the outstanding features of a BLDC motor:

- Very high torque to inertia ratio
- Zero out-gassing (no brush dust)
- Very high peak torque
- Very high reliability (no commutator or brush to wear out)
- Potentially higher efficiency (due to no brush friction)

Clearly, this list and the discussion in this section suggests that the opportunity cost of using a BLDC motor is much less than using a brushed DC motor for the test bed.

Section 4.2.5 - Electric Motor Conclusions

Thus, the three-phase, BLDC motor with Hall Effect sensors will be the best choice for the test bed. Even though the BLDC motor is the most expensive, the alternatives, though cheaper, have characteristics that make them seem far more inferior. BLDC motors offer several advantages over brushed DC motors, including higher reliability, reduced noise, longer lifetime, elimination of ionizing sparks from the commutator, and overall reduction of electromagnetic interference. The primary disadvantage of using the AC induction motor is the difficulty of controlling the motor. Simply put, an actual HEV demands an electric motor that is small, lightweight, and provides high output, efficiency, and reliability. The BLDC motor best depicts all of these characteristics and should therefore be the motor used in the test bed, which, of course, is going to be a prototype for an actual HEV system.

Section 4.3.1 - Power Electronic Problem

A battery in a hybrid electric vehicle cannot supply the needed 3-phase voltage to run the brushless DC (BLDC) propulsion motor; a power electronic converter is needed. Therefore, this technical paper addresses the use and construction of this power electronic converter.

Section 4.3.2 - Power Electronic Background Information

A hybrid electric vehicle (HEV) is designed to use an electric motor to assist the internal combustion engine in propelling a vehicle. The best motor for this application is a BLDC motor. For more information concerning a BLDC motor and how it works please see the motor research paper. It is sufficient enough to say that this motor is the best used but contains one major problem for this application. On a vehicle the only power source is that of a battery, which supplies DC power.

At first glance one would think this would be sufficient for the BLDC because the motor contains the term DC in its name. This however is not the case. A BLDC motor needs to have three voltage phases. The reason for this is described in the motor research paper as well. Since the BLDC motor needs three-phase voltage, a DC supply cannot be used directly. One might think that because the motor needs three-phase power, one might use AC voltage, which is available in three-phase voltage of 120V at a frequency of 60Hz. This conclusion is not true for three major reasons.

The first reason that AC power cannot be used is because it is not feasible or possible to always have an AC source. You cannot drive down the road with an extension cord trailing behind that is plugged into an outlet supplying AC voltage. The other major reason is the waveform that is needed at the input of the BLDC motor. A typical AC source contains three phases with each phase having a waveform similar to a sine wave. This waveform can be seen in figure 1 below. The input to a BLDC motor must be a three-phase input with each phase having a waveform similar to the waveform in figure 2 below. One can see that these two waveforms are not the same so another solution must be required. The last reason for not being able to use AC voltage concerns the frequency. As mentioned before AC voltage is a fixed 120V at a frequency of 60Hz. This presents a problem because input voltage wave for a BLDC needs to have a variable frequency. This frequency is directly proportional to the rotor speed, so the fixed 60Hz of AC voltage cannot be used.

The solution to the dilemma of powering a BLDC motor is solved with a 3-Phase DC to AC inverter. This inverter takes the DC voltage supplied by the battery in the vehicle and inverts it to three-phase voltage with each phase having the waveform in figure 2, which is needed to power the BLDC motor.

Section 4.3.3 - Power Electronic Potential Solutions

For this application the solution to the problem of achieving 3-phase voltage is solved by building a DC/AC inverter. The inverter as stated above converts the single-phase voltage supplied from the battery into 3-phase voltage, which is supplied to the motor. In order to build an inverter an understanding of the components and how they fit together is needed.

The first and maybe the most important part of a DC/AC inverter is that of metal-oxide-semiconductor field-effect transistors (MOSFETs). MOSFETs have many uses but in this application they will be used as switches. The typical MOSFET that will be used is shown in figure 3 below. In this figure it can be seen that the MOSFET has three pins. When using a MOSFET as a switch the basic function is that when fifteen volts is applied to the gate pin the MOSFET will turn "on" and in circuit analysis can be viewed as a short circuit in which current can travel through the MOSFET. When the MOSFET is "off" or when no voltage is applied it can be viewed as an open circuit in which no current will travel. To build an inverter it is required to have a setup of 6 MOSFETs. This configuration can be viewed below in figure 4. As can be seen in the figure, the MOSFETs are designed in pairs each pair having a "high" and a "low" MOSFET. The low MOSFETs are connected to their "high" counterparts through the drain and source pins. The "low" MOSFET's source pin in directly connected to the drain pin of the "high" MOSFET. Each pair of MOSFETs signifies a voltage phase. In order to supply power to the motor the MOSFETs are alternately turned on and off according to feedback data from the motor. The motor sends a binary word output that contains the location of the of the motor's rotor. This is done by a sensor called the Hall Sensor that is used to determine rotor position. The hall sensors will then relay that information to the control apparatus which in turn controls the MOSFETs. The stages of which MOSFETs will be on and off can be viewed below in figure 5. As one can see a major point should be made that only one high and one low sensor will ever be on at the same time. One should also note that phase A "high" and "low" will never be on at the same time. This is true also for phase B and C.

The other significant part of the DC/AC inverter is that of a component called a Gate Driver. The main purpose of the gate driver is to take the 5 volts applied to the inputs of the IC chip and amplify it to 15 volts to be applied to certain MOSFETs to turn them on and off. The gate driver that will be used in the application is IR2133. A schematic of this IC chip can be viewed below in figure

6. As one can see there are 28 pins in this chip and in figure 7 below a description of each pin is given. Also provided below is the manufacture's suggested connection, shown in figure 8 below. Figure 7 may be a little difficult to understand so here we will discuss the pins one by one to give a better understanding of what they are used for in this application. Pins 1, 3, 4, 5, 7, and 8 are pins that all are involved in the current protection of the circuit. Pin 1 is the trip that will turn off the chip when high current, that could possibly damage the chip, is sensed. Pins 3, 4, 5, 7, and 8 are all directly tied to an internal operational amplifier of the chip. This operational amplifier is used to detect current to protect the chip from damage. It is sufficient to say that in this particular application, the current and voltage being supplied to the circuit will be regulated so these inputs will not be used and should all be tied to ground. Pin 2 is the pin that is used to clear a fault. If a fault is detected by the chip pin 2 must be held to ground for a few seconds to clear the fault assuming that the problem has been fixed. Pin 6 is used as a type of on/off switch. When 5 volts is applied to the pin the chip is essentially on and vice versa. Pins 9 10 and 11 are the output pins for the three "low" MOSFETs. The chip will output the 15 volts required to turn the MOSFETs on. Pins 13, 16, and 19 are the output pins for the "high" MOSFETs. They output the required 15 volts the turn these MOSFETs on. Pins 14, 17, and 20 are the high side floating supplies they are connected to the outputs going to the motor as shown in figure 8. Pins 12, 15, and 18 are the high side floating supply returns. The connection of these pins can also be viewed in figure 8 below. Pin 21 is Vcc, which is the location in which the chip will be connected to 15 volts for power. Pins 22-27 are the inputs from the controller. These inputs will be 5 volts that will be amplified to be outputted to the MOSFETs. These pins should be connected to an isolation circuit to ensure that digital and analog isolation is provided to the inputs. One note should be made about these pins. These pins are inverted in normal operation and this should be considered when using this chip. The last pin is pin 28 and it is the fault pin. This pin is used to show when a fault has been detected. This pin is also inverted in normal operation, and will output 0 volts when there is a fault in the circuit and 15 volts when there is not. This pin can be connected to a light emitting diode (LED) and designed so that the LED will turn on when there is a fault.

The two aforementioned major elements make up the majority of the circuitry for the inverter and provide a good start for the design process.

Section 4.3.4 - Power Electronic Figures

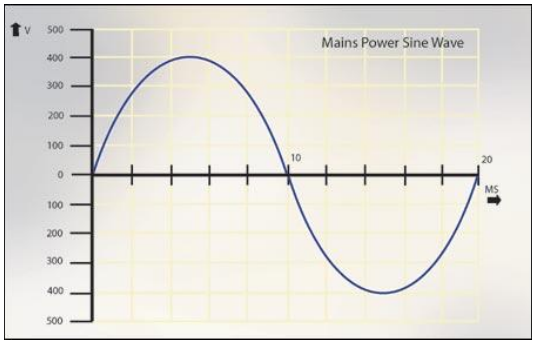


Figure 13 - One Phase of AC power

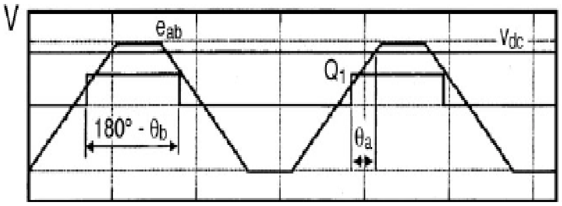


Figure 14 - One Phase BLDC motor input

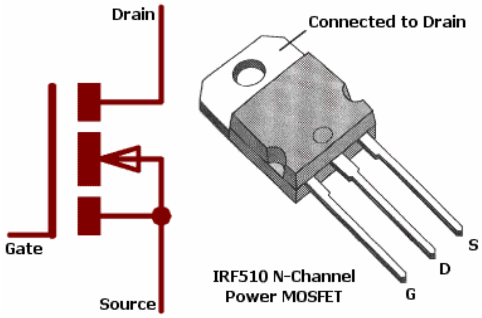


Figure 15 - Typical MOSFET

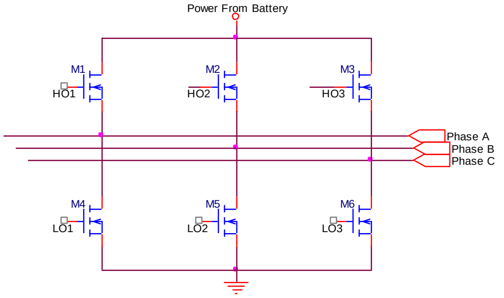


Figure 16 - 6 MOSFET Setup

Stage	**Hall Sensor A**	**Hall Sensor B**	**Hall Sensor C**	**Phase A “high”**	**Phase A “low”**	**Phase B “high’**	**Phase B “low”**	**Phase C “high’**	**Phase C “low”**
1	High	Low	High	Off	On	On	Off	Off	Off
2	High	Low	Low	Off	On	Off	Off	On	Off
3	High	High	Low	Off	Off	Off	On	On	Off
4	Low	High	Low	On	Off	Off	On	Off	Off
5	Low	High	High	On	Off	Off	Off	Off	On
6	Low	Low	High	Off	Off	On	Off	Off	On
-	Low	Low	Low	Off	Off	Off	Off	Off	Off
-	High	High	High	Off	Off	Off	Off	Off	Off

Table 11 - Truth Table for Which MOSFETs will be on or off

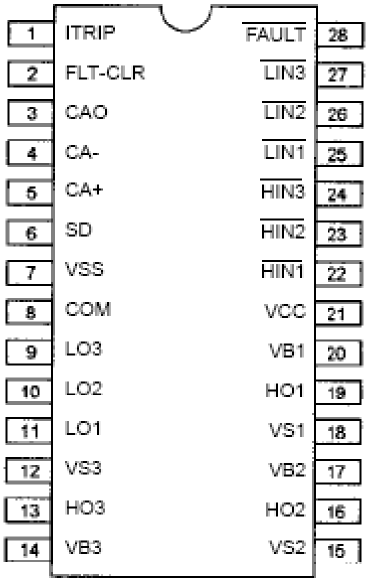


Figure 17 - IR2133 Pin out

Symbol	Lead Description
$\overline{\text{HIN1,2,3}}$	Logic inputs for high side gate driver outputs (HO1,2,3), out of phase.
$\overline{\text{LIN1,2,3}}$	Logic inputs for low side gate driver outputs (LO1,2,3), out of phase.
$\overline{\text{FAULT}}$	Indicates over-current or undervoltage lockout (low side) has occurred, negative logic.
V_{CC}	Logic and low side fixed supply.
ITRIP	Input for over-current shut down.
$\overline{\text{FLT-CLR}}$	Logic input for fault clear, negative logic.
SD	Logic input for shut down.
CAO	Output of current amplifier.
CA-	Negative input of current amplifier.
CA+	Positive input of current amplifier.
V_{SS}	Logic ground.
COM	Low side return.
$V_{B1,2,3}$	High side floating supplies.
HO1,2,3	High side gate drive outputs.
$V_{S1,2,3}$	High side floating supply returns.
LO1,2,3	Low side gate drive outputs

Table 12 - Detail Description of IR2133 Pin Out

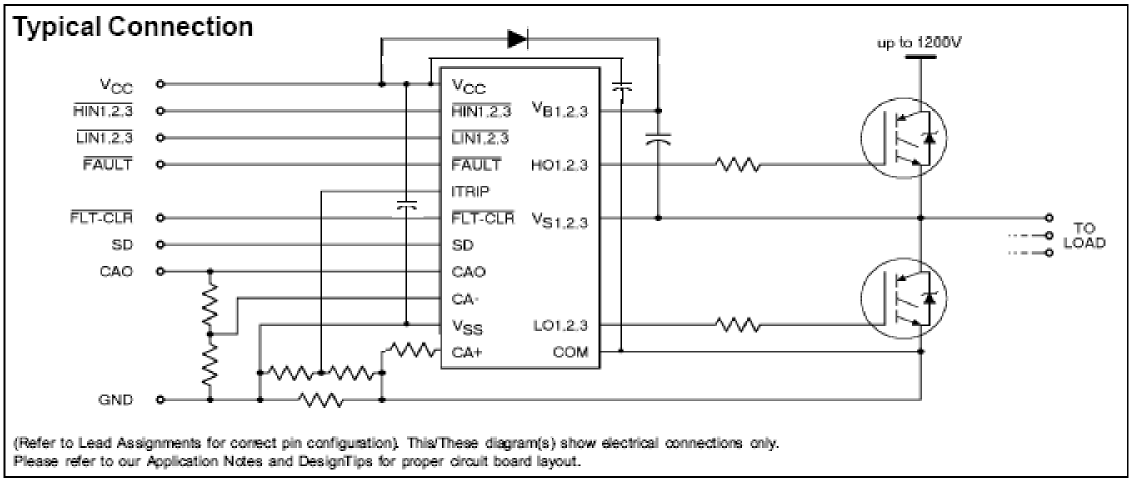
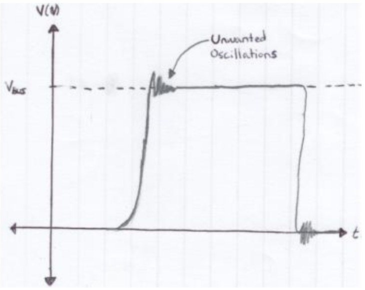


Figure 18 - Suggested Connections of the IR2133



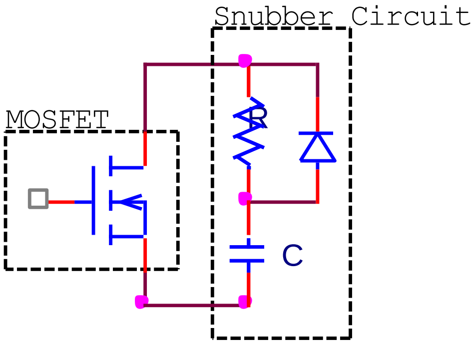


Figure 19 - hysteretic voltage oscillations

Figure 20 - Snubber Circuit

Section 4.3.5 - Power Electronic Practical Considerations

Now that there is an understanding of the major points of the design and background to the inverter there is a key consideration to this circuit. The problem with this circuit is hysteretic voltage. What this means is that the MOSFETs are rated to handle a certain voltage without failure. When the bus voltage is turned on to the MOSFETs, rather than going from zero right to the bus voltage there is a type of oscillation. A general form of this is shown in figure 9 above. Because of this oscillation, the MOSFETs could fail. In order to fix this problem a circuit called a snubber circuit should be added. Simply explained the snubber circuit acts as a filter. Because the oscillations happen in a certain range of frequency, this circuit filters out this frequency range so when the bus voltage is applied to the MOSFET these oscillations are minimized in order to not damage the MOSFET. The snubber circuit for this application is shown in figure 10 above. This circuit was designed using the assumption that if one was to filter out any frequencies above 100 kHz the oscillations would be filtered out. The use of circuit analysis shows that the frequency can be shown by the equation

$f = \frac{1}{2\pi RC}$. Using an arbitrary value of 1000 ohms for the resistor R one could solve for the capacitance C using the equation $C = \frac{1}{2\pi Rf}$.

The other consideration of this circuit was mentioned above as the isolation circuitry. The isolation circuitry is important to ensure that the voltages that are applied to the Gate Driver have no digital or analog noise. This is important to ensure that the chip will not be damaged by the noise and also to ensure that the right values are applied at the right time.

Section 4.3.6 - Power Electronic Price Information

Part #	Quantity	Price	Total	Company	Order #	Description
IR2133	1	$14.25	$14.25	Digikey	IR2133-ND	Gate Driver Chip
N/A	6	$0.63	$3.78	Digikey	568-1160-5-ND	MOSFET N-Ch; 100 Volts; 23A To-220AB
N/A	6	$0.043	$0.258	Newark	33C9490	Polyester Film Capacitor; 100 Volts; 1.5µf
N/A	3	$4.36	$13.08	Newark	07J9347	Ceramic disc and plate; 5 Volts dielectric; 10µf
N/A	6	$0.32	$1.92	Newark	94C2424	5083; 5% Metal Film Resistor; 2 Watt; 1kΩ
N/A	1	$0.126	$0.126	Newark	73K0335	5.1kΩ Resistor
N/A	6	$0.515	$3.09	Newark	41K8853	PR02 Type; 5% Metal Film Fixed Resistor; 2 Watt; 20Ω
IRF510	10	$1.08	$10.80	Digikey	IRF510-ND	100 volt; 5.6 A diode
			$47.304			

Table 13 – Power Electronics parts list

Section 4.3.7 - Power Electronic Conclusions

After background research and design, the final design for the inverter that will be used in this application was designed using OrCAD software and can be viewed on the attached page.

Differential Research
Aamer Saeed

Section 4.4.1 - Differential Problem

The task of this report is to select a differential to properly maneuver the wheels (front or rear) in the vehicle. Depending on the track of the test bed the need for the driving differential(s) will be decided. However for the time being we assume that it is required.

Section 4.4.2 - Differential Background Information

A differential is a device used in automobiles and other four wheeled vehicles to provide equal torque to all the wheels while allowing them to rotate at different speed. The need for equal torque arises from the fact that while turning at a corner each wheel travels a different distance. The inside wheel would travel a shorter distance as opposed to the outer wheel which travels a relatively larger distance. Since the speed is equal to the distance traveled divided by the time required, the wheel traveling a shorter distance has a lower speed. This doesn't affect the front wheels in a rear wheel driven and the rear wheels in a front wheel driven vehicle. This is because the non driven wheels independently rotate. For a four wheel driven vehicle there are usually three differentials. There is a differential each for the front and the rear wheel and one in between them to synchronize the front and the rear wheels.

Nowadays there are many differentials available in the market which has been developed over a period of time. All these differentials perform the basic task required of a differential, but they differ amongst themselves in the way they work and the tractions they provide. Some of the more common differentials available today are limited slip differentials also known as LSD, locking differentials, and the electronic traction control based on the ABS (Anti locking Braking system).

The several options for the differentials will be discussed now and their feasibilities for the HEV's test bed will be evaluated.

Section 4.4.3 - Open Differentials

An open differential is essentially a device attached to the main driving shaft. The open differential always applies the same amount of torque to both the wheels. Its purpose is to supply equal torques to the two wheels attached to it while allowing them to rotate at different speeds. Now consider a vehicle without a differential; the two wheels have the same speed and hence the outer one is dragged over the extra distance and hence the wearing of the tires results. The differential action of open differentials is essential to stop tires scrubbing, to reduce transmission loads, and to reduce under steer* during normal cornering by the vehicle. In a vehicle with a differential, the outer wheel is supplied with a relatively higher speed and hence the dragging is no longer seen. Below are certain figures which give a partial illustration of the differentials.

The equipment and traction are the two major factors that determine the amount of the torque required to be applied to the wheels. In dry conditions where there is a plenty of traction the amount of traction applied to the wheel is limited by the engine and the gearing. In a low traction environment however, the amount of traction is limited by the greatest amount that doesn't cause the wheel to slip. So even thought the car might produce sufficient torque in a low traction environment, there is a need for the minimum traction which will allow the torque generated to be transferred to the ground. When the traction is not enough the wheel simply spins faster but doesn't move ahead, since the other wheel effectively loses all the input torque and is unable to propel the vehicle ahead.

Another unfavorable situation where the open differentials are not of much use is when the vehicle is being driven off road. This can again be explained by the differences in the traction of the two wheels. Assuming if one of the two tires comes off the ground then the will just spin in the air and the vehicle will not move.

The working an open differentials is illustrated by the figures below. In figure 1, the resistance at both the wheels is equal and the pinion in the center does not rotate thereby supplying equal speeds to both the wheels. In figure 2, we see that pinion gear in the center rotates clockwise because of the resistance experienced by the left side gear and thus supplies extra rotation to the right side as well.

- Under steer is the limit when the tires lose grip and can neither steer nor accelerate

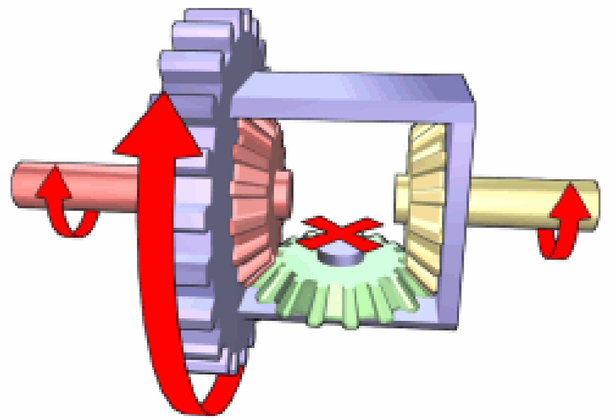


Figure 4 - Equal resistance experienced by both wheels

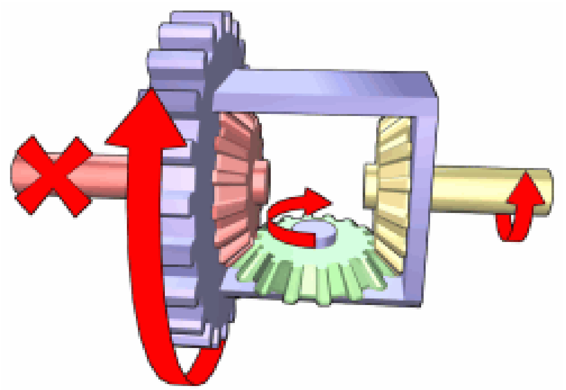


Figure 5 - Higher resistance experienced by the left wheel

Now clearly, the need for a device that adds the extra traction in the vehicles is needed. Such devices are called the traction adding devices. There is several traction adding devices available today namely, Limited Slip Differential (LSD), the locking differentials, electronic traction control based on the ABS (Anti locking Braking system).

Various types of the differentials available in the market are briefly discussed below:

Section 4.4.4 - Limited Slip Differentials

The LSD is the most common of the traction adding devices. As is obvious from the name this type of differential limit wheel slip. It essentially uses a clutch type mechanism. In the LSD, the side gears are coupled to the carrier through a stack of clutch plates. This clutch plate balances the speed differences between the two wheels. It is a device which permits the driving axle to transmit some of the driving force to the wheel with the better traction and prevent the wheel from remaining immobile when one driving wheel loses traction. However when turning on dry pavement they might just slip.

The disadvantage with the limited slip differentials is that they also slip when there is a significant difference in traction between the two wheels in an off–highway situation. It must also be noted that the limited slip differentials don't prevent the wheel slip per se but rather delay it. Therefore traction is lost a little later than without limited slip, and the effect is experienced a little later.
The figure 3 below shows a limited slip differential.

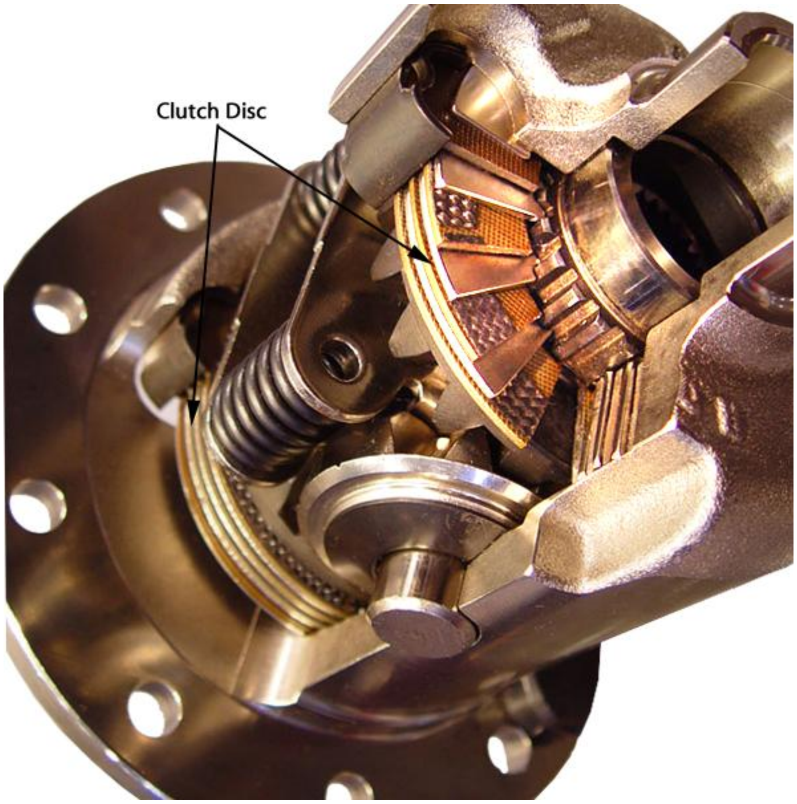


Figure 6 - Limited Slip differential.

Section 4.4.5 - Locking differential

Another solution is the locking differential. This forces both wheels to turn at the same speed irrespective of the traction experienced by the two wheels. This is achieved primarily by locking the planetary gears relative to each other.

These are mostly used for serious off road vehicles and have the same parts as found in an open differential with the addition of electrical, pneumatic or hydraulic mechanisms to lock the two output pinions together. The locking differentials disable the differentials abilities to distribute equal torque and allow the wheel to rotate at different speed. By doing so the wheels rotate at the same speed when engaged a vehicle with locks on all axles has traction if just one wheel does.

This mechanism is usually activated manually by switch, and when activated, both wheels will spin at the same speed. If one wheel ends up off the ground, the other wheel will not be affected. Both wheels will continue to spin at the same speed as if nothing had changed. By disabling (or locking) the differential, steering becomes very difficult and the wheel with the most traction will get the most torque, as much as 100%. This guarantees that any wheel with traction will receive enough torque to move the car.

Locking (disabling) the differential makes it impossible for wheels to roll at different speeds. Therefore, with lockers engaged, on high traction surfaces it becomes very difficult to make turns, and on low traction surfaces the turning radius gets very wide.

Unfortunately the locking differential operates in a manner where it's either on or off. There is nothing intermediate. This can make the vehicle under steer (tend to go straight ahead in corners) or veer suddenly sideways if one side looses traction, like on ice. These serious drawbacks require an experienced driver who knows exactly when to engage the locks which is usually only for a very brief moment and when to unlock it to maintain control on the steering wheel. The figure 4 below shows a limited slip differential

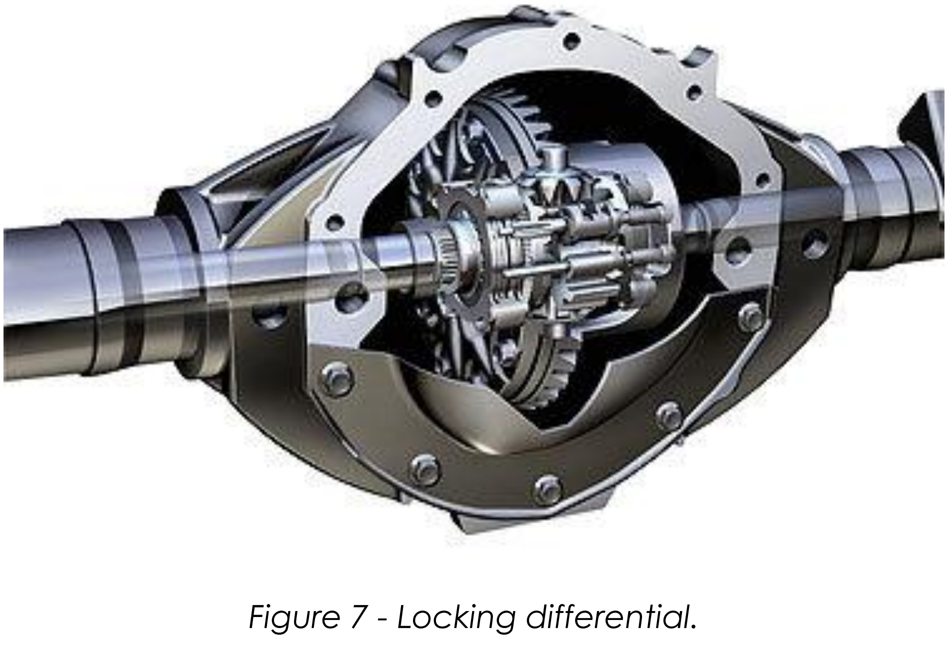


Figure 7 - Locking differential.

Section 4.4.6 - Electronic traction control

The electronic traction control systems usually use the ABS (Anti-Lock Braking System) to detect a spinning wheel and apply the brake to it. Typically, the Traction Control system shares the brake actuator and the wheel speed sensors with the ABS. This progressively raises the reaction torque at that wheel, and the differential compensates by transmitting more torque through the other wheel - the one with better traction.

The detection of the spinning wheel is carried out by a computer system to detect rear wheel spin and modulate engine power to those wheels to provide the most traction. These systems are generally nowadays electro-hydraulic systems designed to prevent loss of traction when excessive throttling over steering is applied by the driver. The loss of traction can be prevented by interventions in the vehicle. These interventions can be retardation of the spark to one of the cylinders, fuel supply reduction or brake one or more wheels

Traction control is not just used for moving a vehicle from a stationary position without slippage. During hard maneuvers in a front wheel drive car there is a point where the wheels cannot both steer and drive the car at the same time without losing traction. With traction control, it's less likely for this loss of control to occur. In some front wheel drive cars, Traction Control can induce steering of the car more tightly into the turn, hence causing over steer, due to its throttle retarding capabilities. This can keep some cars stable in long maneuvers.

Section 4.4.7 - Regenerative Braking & effect of the negative torque at the input

One of the energy efficiency advantages of the HEV over normal ICE vehicles is the concept of the regenerative braking. In a hybrid electrical vehicle an electrical motor is used to create torque to drive its wheel. These motors can be designed to be identical to electrical generators. This means that electrical motors can be designed to use electricity to create torque or reverse the process to create electricity from torque and thus charge the vehicle when it s stationary. Therefore we can now assert that regenerative braking creates negative torque at the input and thus makes the shaft connected to the differential to rotate in the opposite direction.

This causes the differential to rotate in both direction namely clockwise and anticlockwise in any order when the brakes are applied or when the vehicle is moving. This per se is not a very big issue as it just causes impact on the gear tooth because when the gears are made to run in opposite direction they tend to hit the tooth before them because of the clearance (backlash) and the backlash effect occurs. The backlash effect can be unfavorable if the gear material is brittle as it will eventually fracture due to the repeated impact. This problem can be solved by designing the gears with relatively lesser clearance or

backlash and enhance the performance. Another thing which occurs while regenerative braking is that the differentials with the negative torque tend to rotate the wheel backwards but the wheels are braked and don't move. This is not a very big issue and the effects are minimal and can be neglected.
Another condition worth considering is when the regenerative brakes are applied instantly and the magnitude of change of the torque is much larger than when a car is gradually decelerated. In such case the shearing of the gear tooth can occur because of the sudden torque change. This situation again can be resolved by making considerations while designing the torques generated by braking and setting them to be lesser (including safety factor)than the torque that can be handled by the gears in the differential.

Section 4.4.8 - Differential Potential Solutions

The requirement for the test bed is very simple in terms of the type of the differential. Since there will not be any differences in the traction of the two wheels because all the tests will be carried out on the same surface, the need for traction adding devices will be eliminated. Further assessment and analysis by the team also cleared the use of a single differential as opposed to two of them (rear and front). The planetary gear will be used at the rear end as it takes into account the principle of the regenerative braking. Therefore an open differential will be used and it will be mounted at the front end of the test bed.

Section 4.4.9 - Differential Price Information

For the time being the differentials price information is as below:

Model	Rating	price	Source
TBD	TBD	TBD	TBD

Table 6 – Prices for differential gears

Section 4.4.10 - Differential Conclusions

After having discussed various situations with respect to the entire setup, the mechanical team concluded the use of the simple differential for the test bed. The choice of the differentials subsequently led to the task of coming up with a way to get the required product. One option was to build the differential from scratch. This however was not carried forward because was a cumbersome project in itself. The ultimate decision on the differential was to purchase it form the market according to the specifications of the entire test bed.

Driveshaft Report
Preeti S. Abraham

Section 4.5.1 - Driveshaft Problem

IPRO 342's objective is to build a hybrid vehicle test bed to test a scaled down hybridized model of the Bluebird Vision school bus. In order to accomplish this objective, suitable driveshafts that transfer power from the internal combustion engine simulator and the electric motor to the loads at the wheels need to be selected.

Section 4.5.2 - Driveshaft Background Information

A driveshaft transfers power from the transmission to the driving axles in order to turn the wheels of an automobile. Figure 1 shows an example of a driveshaft.

Figure 8 - A Driveshaft with two Universal Joints

Over the years, several driveshaft designs have been used to effectively transfer torque from an engine or motor to the wheels of a vehicle. A torque tube system is one that is occasionally used in automobiles with a front engine and rear drive. Figure 2 shows a torque tube.

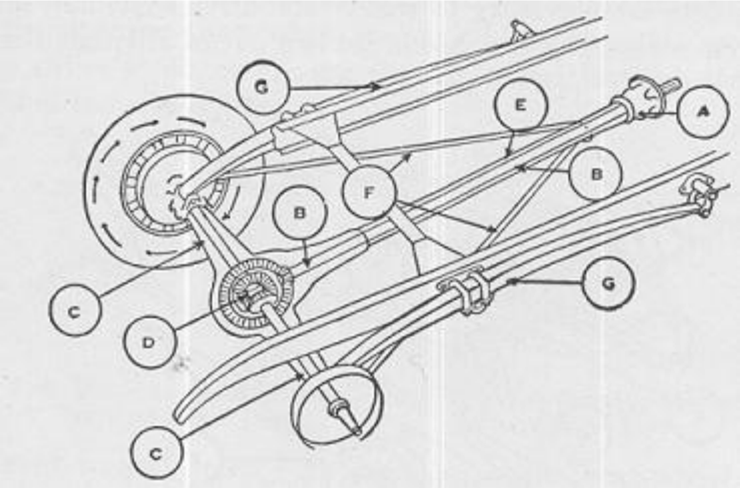


Figure 9 - Torque Tube

In Figure 2, ‘A’ indicates a universal joint, ‘B’ indicates the driveshaft which is enclosed by the torque tube ‘E’, ‘C’ indicates the axle shafts, ‘D’ indicates the differential, ‘F’ indicates the struts or radius rods that keep the rear axle aligned, and ‘G’ indicates the springs that absorb road shocks. A torque tube system consists of a hollow steel tube that extends from the transmission to the rear differential and axle. It is connected to the transmission using a ‘torque ball’. This contains a constant velocity joint or universal joint that allows for some flexure. The torque tube is simply bolted to the differential. The driveshaft itself is placed inside the torque tube.

Unlike a torque tube, a Hotchkiss driveshaft is not enclosed and it utilizes universal joints at both ends of the driveshaft. Simple cross-type universal joints may be used instead of constant velocity joints if they are correctly phased, and if the driving and the driven shaft are aligned parallel to each other. Figure 3 shows a Hotchkiss driveshaft.

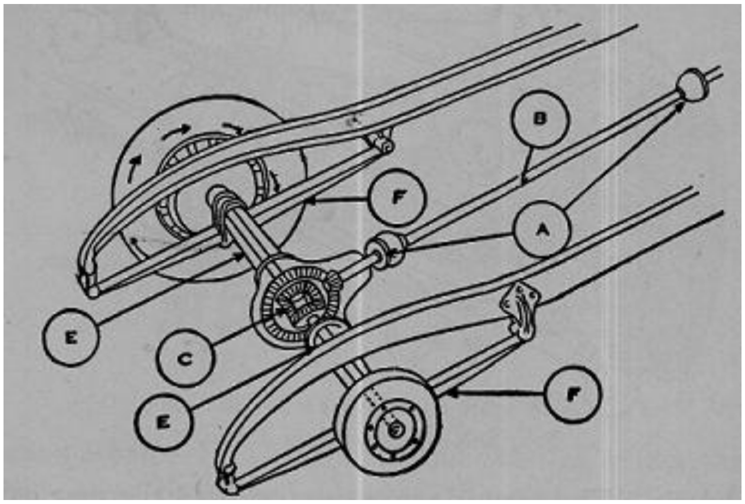


Figure 10 - A Hotchkiss Driveshaft

In Figure 3, 'A' indicates two universal joints in the driveshaft, 'B' indicates a Hotchkiss driveshaft, 'C' indicates the differential, 'E' indicates the axle shafts, and 'F' indicates the springs. Hotchkiss driveshafts used in trucks and other vehicles built on a truck frame utilize a third universal joint in the middle of the driveshaft, dividing it into two pieces.

A universal or Cardan joint allows a rigid rod to flex in any direction. It consists of two hinges located close to each other and with an angle of 90° between each other. Figure 4 demonstrates how universal joints work.

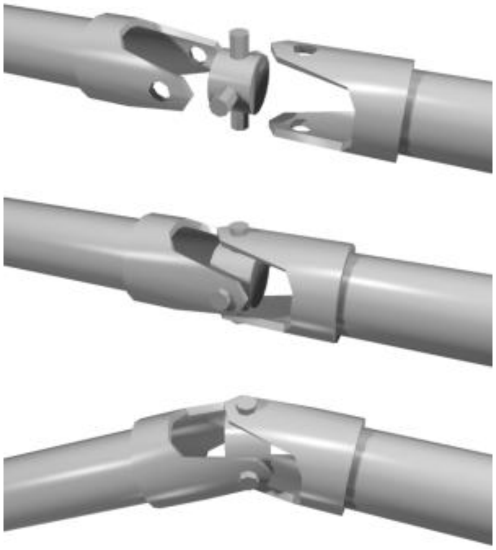


Figure 10 - Universal Joints

Although a universal joint allows for freedom of movement in a driveshaft, if the driving shaft and the driven shaft do not lie on the same straight line (i.e., if there is a bend in the driveshaft) the driven shaft rotates with an angular velocity of ω_2 that is different from the angular velocity ω_1 of the driving shaft. As the angle between the shafts moves towards 90°, the rotation becomes jerkier. At a relative angle of 90° the two shafts would lock.

In order to prevent jerky rotation, driveshafts are often constructed using three shafts with two universal joints between them. If both the driving and the driven shafts are parallel to each other and if the two universal joints are properly aligned with each other, the action of the second universal joint eliminates jerky rotation to ensure a uniform angular velocity in the driveshaft. However, this arrangement works best if the angle through which the shafts are bent away from a straight line is less than or equal to 45°.

The homokinetic or constant velocity joint is another solution that eliminates jerky rotation. A constant velocity joint works just like a universal joint, except that there is no difference between the angular velocities of the driving and driven shaft, regardless of the angle between them. Figure 5 shows a schematic of a constant velocity joint.

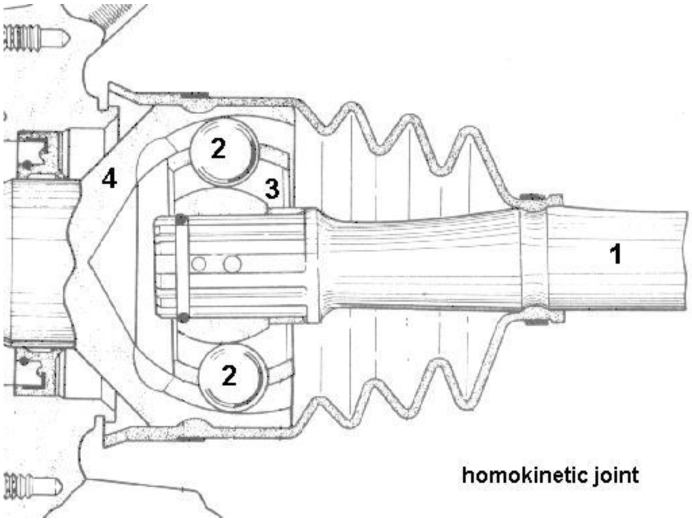


Figure 11 - A Constant Velocity Joint

In Figure 5, '1' indicates the driveshaft from the transmission and '2' indicates steel balls. These steel balls are contained within a cage, indicated by '3', and run in grooves in the spherical dome, indicated by '4'.

Section 4.5.3 - Driveshaft Potential Solutions

For IPRO 342's application, Hotchkiss driveshafts with single universal joints in the middle would be appropriate for connecting the differential and the ICE simulator to the planetary gear system. As the electric machine would be placed very close to the planetary gear system, a plain shaft without a universal joint would be sufficient for it. Torque tube systems would not be the best choice as it is a technology that has become rather outdated. Constant velocity joints are more expensive than universal joints and their use is warranted only when a large degree of flexure is expected in the driveshafts. As this will not be the case with the hybrid vehicle test bed, constant velocity joints will not be used.

It is expected that the driveshafts in the hybridized school bus model will experience torques up to 3 Nm. The applied torque on a solid shaft, T, is related to the maximum shear stress, τ_{max}, experienced by the shaft by the following equation:

$$\tau_{max} = (2T)/(\pi c^3) \quad (1)$$

where,

c = Radius of shaft

Using a safety factor of 2, τ_{max} would be equal to half the yield stress, σ_y, of the material used in the shaft. Thus, solving Equation (1) for the minimum safe radius of the solid shaft yields:

$$c = [(4T)/(\pi\sigma_y)]^{1/3} \quad (2)$$

Table 1 was created using a list of steels used in the steel solid shafts found on www.mcmaster.com.

Material	σ_y (Mpa)	Minimum c (m)	Minimum c (in)
AISI 1045 Steel	515	0.00195	0.0768
AISI 1566 Steel	1724	0.00130	0.0513
Type 316 Stainless Steel	240	0.00252	0.0990
Type 303 Stainless Steel	240	0.00252	0.0990
AISI 1070 Steel	385	0.00215	0.0846
12L14 Steel	235	0.00253	0.0997

Table 7 - Minimum Safe Radii of Various Available Shaft Materials

Using Table 1, suitable shaft radii were chosen from www.mcmaster.com. The suitable radii and the price range of the materials under discussion are given in Table 2.

Material	Suitable Radii (in)	Suitable Radii (m)	Price(USD)
AISI 1045 Steel	0.125 - 1.0		6.03 - 200.73
AISI 1566 Steel	0.125 - 1.0		4.22 - 332.36
Type 316 Stainless Steel	0.09375 - 0.625		5.04 - 187.63
Type 303 Stainless Steel	0.09375 - 0.25, 0.375		3.41 - 172.00
AISI 1070 Steel		0.005 - 0.015	5.52 - 82.14
12L14 Steel	0.125 - 0.15625		3.19 - 22.06

Table 8 - Suitable Radii and Prices of Various Available Shaft Materials

According to Table 2, the best option for IPRO 342's requirements would be solid shafts of radius 0.15625" (5/32") made out of type 303 stainless steel. The price would be between $6.12 and $27.57 per piece for shaft lengths between 6" and 48". These shafts would fit into the motors selected for the test bed without any adaptors. Furthermore, type 303 stainless steel has good corrosion resistance.

Aluminum shafts are not being considered for this application as they would reduce the overall weight and inertia of the hybrid vehicle test bed. As it is expected that vibrations will be a major issue with the test bed, this would not be desirable.

The universal joints most suitable for use with the type 303 stainless steel driveshafts selected are single universal joints with bored ends, made out of steel with a black-oxide finish for mild corrosion resistance. The bore diameter will be 5/16" to accommodate the driveshafts. The diameter of the universal joints themselves will be 5/8", and their length will be 2.25". Each of these joints will cost $25.95.

Once the driveshafts are inserted into the universal joints, holes will be drilled through both the universal joints and the driveshafts within them, and spring pins will be used to secure the driveshafts to the universal joints. The spring pins selected for this application will have a diameter of 1/16" and a length of 5/8" so that their ends will be flush with the outer edges of the universal joints once they have been put in place. These pins will be made of type 420 stainless steel, and will have double shear strength of 430 lb. A package of 100 spring pins will cost $3.43.

It was found that commercially available mounted ball bearings were not available for shafts of diameter less than 1/2". Thus, the decision was made to purchase 1/2" thick sheets of cast iron, and then machine the sheets into pillow blocks that would house ball bearings. Cast iron would add weight and inertia to the test bed, and would also effectively damp vibrations. The recommended cast iron sheet for three pillow blocks for the driveshafts is 12" by 3" and costs $58.82.

The appropriate ball bearings for the driveshaft pillow blocks are double shielded to keep dirt out. They have an inner diameter of 5/16" to match the driveshafts, an outer diameter of 7/8", and a thickness of 9/32". They cost $5.33 each, and have a dynamic load capacity of 325 lb and can work at a maximum speed of 2500 rpm.

A pillow block for the planetary gear arrangement is also required. The outer diameter of the planetary gear system is 75 mm, and commercially available mounted ball bearings were not available for shafts of diameter greater than 2.4375". Thus, a cast iron sheet that is 12" by 5" by 1/2" is selected to make the required pillow block. It costs $56.68.

The appropriate ball bearing for the planetary gear pillow block has an inner diameter of 3", an outer diameter of 3.5", and a thickness of 1/4". It costs $182.89, and can work at a maximum speed of 833 rpm.

Section 4.5.4 - Driveshaft Price Information

Table 9 contains the list of parts to be purchased, their part numbers, and their cost. All parts listed are from McMaster-Carr.

Part Name	Part Number	Number of Parts/Unit	Price/ Unit (USD)	Number of Units	Total Cost (USD)
Solid Shaft - Type 303 Stainless Steel - 5/16" Diameter - 36" Length	1257K77	1	27.57	2	55.14
Single Universal Joint with Bored Ends - Type 303 Stainless Steel - 5/16" Inner Diameter	6443K46	1	25.95	2	51.90
Spring Pin - 1/16" Diameter - 5/8" Length	92383A108	100	3.43	1	3.43
Gray Cast Iron Sheet - 12" by 3" by 1/2"	8928K481	1	58.82	1	58.82
Steel Ball Bearings - for 5/16" Shaft Diameter	6384K53	1	5.33	3	15.99
Gray Cast Iron Sheet - 12" by 5" by 1/2"	8928K791	1	56.68	1	56.68
Steel Ball Bearings - for 3" Shaft Diameter	6656K13	1	182.89	1	182.89
				Total Cost:	424.85

Table 9 - Parts List

Section 4.5.5 - Driveshaft Conclusions

This report has discussed the workings of various driveshaft designs, universal joints, and constant velocity joints. Further, a specific commercially available driveshaft and universal joints, and a pillow block design that will be suitable for IPRO 342's hybrid vehicle test bed have been recommended. The bases for these recommendations have also been discussed.

Power Split/Coupling Research
Mohammed Khader
Jatan Shah

Section 4.6.1 - Power Split/Coupling Problem

To select a power split/drive coupler for the hybrid test bed that is able to efficiently combine power ratings for an Electric Machine (EM) and an Internal Combustion Engine (ICE) and to send the combined power to the drive shaft. In addition to sending the power to the drive shaft, regenerative braking must be present to allow the ICE to generate energy in order to recharge the battery packs when braking occurs. The optional use of a small generator may help facilitate charging of the battery when braking, as a well as when idle (in addition to relieving stress from the traction motor), but this project will focus on using the EM as both the electric machine and also as a generator.

Section 4.6.2 - Power Split/Coupling Background Information

The heart of a hybrid electric vehicle (HEV) is no doubt the power split device. Without this piece of important hardware it would not be easy to create a parallel HEV. The main function of power split gear box is to take multiple traction inputs (i.e. internal combustion engine and electric machine) and combine or couple them to a single drive axle. However, it is also possible to create a parallel all wheel drive HEV by not connecting the electric system and combustion system at all. This type of configuration uses the road to effectively "split" the power distribution and it is outside the scope of this research. The key ingredients in a HEV are the obvious internal combustion engine (ICE), a transmission or continuously variable transmission (CVT), an electric machine, and a high voltage battery. Various configurations of a mechanically connected power splitting devices will be explored, and the best option will be presented.

There are already some hybrid vehicles on the market with more on the way. The Toyota Prius and the Ford Escape are two examples of current HEVs. The Toyota Prius uses a combination of series and parallel HEV designs with a 1.5 liter ICE, 33kW EM, and a 274V battery. The Ford Escape also has a similar setup as the Prius, but it uses a larger 2.3L ICE, 70kW EM, and 330V battery. They both make use of the planetary gear box (CVT) and a separate generator which is used for starting the ICE, charging the battery, or supplying power from the battery to the EM.

Section 4.6.3 - Power Split/Coupling Potential Solutions

For the purpose of this report there are three possible solutions for power splitting. The first approach is to use a combination of gears and chains to combine the ICE and electric machine power sources together. The second is to use a differential gear in reverse, i.e. connect the ICE and electric machines where the drive axles are normally connected and connect the main outer gear to the drive shaft (then connect to the differential). The third is to use a planetary gear box.

Section 4.6.4 - Power Split/Coupling Chain drive

The chain drive approach is mainly found in hybrid human-powered/electric bicycles, it is not common in the automotive industry. If chain gears were used to split power between the ICE and electric motor, it would make mounting very easy as chain links can be added or removed as needed. They are also lightweight compared to heavier gearing approaches. However the chain would become the "weakest link" of the HEV. Since it is not a solid piece of hardware there is a high possibly of it breaking. In a hybrid bicycle it is not a problem because the frame it self is a skeleton, therefore making replacements relatively easy. The power output of a hybrid bicycle is no where near that compared to a hybrid bus, and additional gearing is required because the chain and gear are at fixed ratio.

Section 4.6.5 - Power Split/Coupling Differential drive

Using a differential gear as a power splitting device is another solution not commonly found among hybrids. However, it is an interesting approach to distributing ICE and electric machine power. The original function of a differential gear is to evenly distribute power to opposing wheels. In the event that slipping occurs, more power is sent to that wheel to help stabilize the power distribution. For a HEV power split device the opposite is needed. In the HEV case the outputs are now the inputs, i.e. the ICE and electric machine, and the differential input now becomes the power split output. By using a differential as a power split device the requirement of combining the two power source is automatically done. In addition to power coupling we are presented a solution that does not need a transmission. Excess power from the ICE can be redirected to the batteries, or if too little power is available from the engine extra power can be gained back from the batteries. The biggest limitation in using a differential for power splitting is the fact it has not been done before. There is little to no research on how to correctly mount the gear or if any other accessories (for instance an electric clutch/brake) are needed. The differential gear may also cause a loss of efficiency if the HEV wants to run in electric vehicle (EV) mode only. In this case the ICE shaft must be clamped and a may cause power loss.

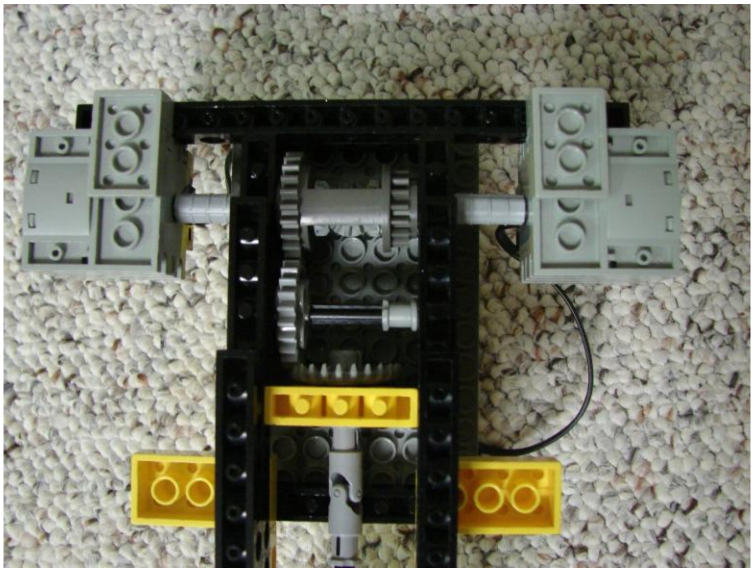


Figure 21 - A power split example of a differential gear

Section 4.6.6 - Power Split/Coupling Planetary Gear

The most widely used approach in HEVs today for power splitting makes use of a planetary gear box. The planetary gear functions as a CVT between the carrier gear connected to the ICE and the ring gear connected to the electric machine. The setup becomes a CVT when a generator is connected to the sun gear. By controlling the speed and direction of the sun gear the torque relationship between the ICE and electric machine are fixed. The planetary gear is also the power split device between the ICE and electric machine. If the main traction motor were to recharge the batteries during idle the HEV would have to wait for the electric machine to stop then spin the other direction to assist the ICE. However, by having the generator it is possible to relieve stress from the main traction motor, it also regenerates braking energy when the ICE is off and it recharges the battery when the ICE is idling as well. The generator also functions as an ICE starter, but the addition of a generating motor makes the power train setup a little more complicated and expensive to configure. Another option for this setup is to have the electric motor act as both the electric machine and the generator to avoid having two separate devices.

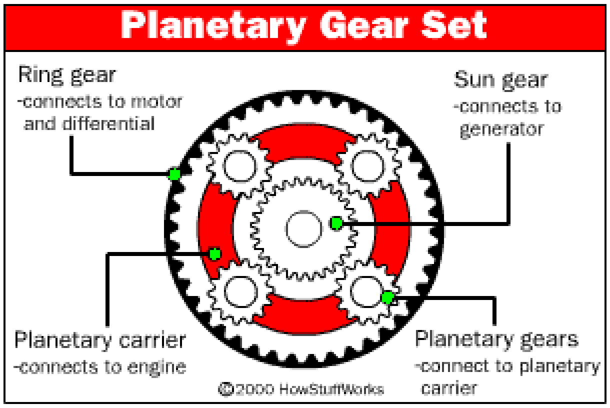


Figure 22 – Planetary gear used for power splitting

Section 4.6.7 - Power Split/Coupling Pros and Cons

Chain Drive Pros	**Chain Drive Cons**
• Cheaper • Space Saving • Simple Components • Easy to mount	• Chance of breaking • Not intended for automobiles/buses • Requires a transmission for the ICE • Requires clutch/brake for regen

Table 14 – Chain Drive pros and cons

Differential Drive Pros	**Differential Drive Cons**
• Innovative • No need for a transmission • Space saving • Durable	• Maybe difficult to get parts to scale • Not intended use • Requires electric clutch/brake • Complicated design

Table 15 – Differential Drive pros and cons

Planetary Drive Pros	**Planetary Drive Cons**
• Proven track record • No transmission required • Regen from idle or braking • Durable	• Gears must be aligned perfectly • Expensive • Large footprint

Table 16 – Planetary Drive pros and cons

Section 4.6.8 - Power Split/Coupling Conclusions

This section of the report concludes with the suggestion of using a planetary gear box as a power split/coupling device and instead of having both the electric machine and a generator, like the Toyota Prius and the Ford Escape, we suggest using the electric motor as an electric motor and also as a generator. The reason for this decision is mainly in its track record and due to the fact that large manufacturers such as Ford and Toyota make use of this gear box for their hybrid drive trains. In addition, this configuration makes regeneration and torque control simplified by having the electric motor act as both the electric motor and the generator. However, the cost for this setup is more than any of the other solutions and it also requires more space, but in comparison the benefits of a planetary gear box outweighs the drawbacks.

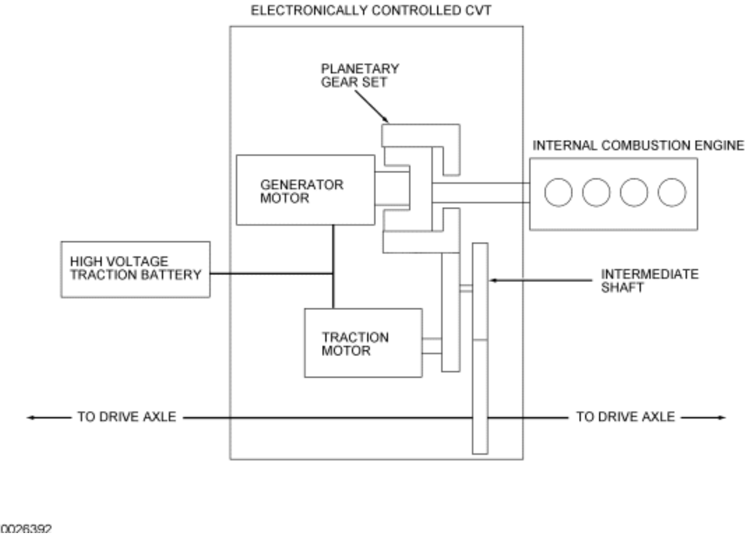


Figure 22 – Electronically Control CVT Drive Transaxle

Supporting Structure Research
Joel Fenner

Section 4.7.1 - Supporting Structure Problem

Determine a practical and effective design for the mechanical supporting structure to be employed in the hybrid test bed. The structure must support all of the components of the model hybrid system under all modes of operation while preserving acceptable component alignment and minimizing system vibration.

Section 4.7.2 - Supporting Structure Background Information

Hybrid electric vehicles, like conventional motor vehicles, rely upon mechanical structures to support the various components they employ. These structures must support the weight of the vehicle payload (passengers and cargo) and must be sufficiently robust as to tolerate the dynamic loading encountered in actual driving conditions. They must also support the components of the drive train and maintain the geometry of the system under a wide variety of loading geometries.

In the majority of cases where hybridization is performed to improve the efficiency of a vehicle, the structures are often optimized to achieve the necessary strength and rigidity at a minimum of weight in order to improve the overall efficiency of the vehicle. This is typically achieved through the use of specialized materials (Aluminum, Titanium, composites, etc.) and through innovative structure geometry. Hybrid vehicle supporting structures are therefore often somewhat unconventional when compared to standard motor vehicle counterparts.

Section 4.7.3 - Supporting Structure Potential Solutions

The “test bed” is intended to serve as a model of the drive train of an HEV primarily in terms of its power handling components. Through these may be modeled the equations applicable to a real HEV system, and thereby the corollary is drawn between the model and the actual machine. The static structure upon which the model is built, however, need not be so strictly linked to that of an actual HEV since it serves merely as a platform to support the working parts of the model. Therefore, it may be designed and constructed almost purely on the basis of its performance with a lesser interest in having it parallel the construction of supporting frames in real vehicles.

The supporting structure of the model is faced with three principal obligations. These are:

- To support and contain all mechanical components of the model under operating loads
- To maintain proper alignment of all mechanical components during operation
- To minimize undesirable mechanical vibration

To a certain extent, these criteria are linked to one another. The ability to tolerate normal running loads dictates the minimum size of components for a given geometry. The maintenance of mechanical alignment demands that components be of appropriate size and geometry to minimize deflection under load, often larger than those required to simply prevent failure. The minimization of vibration is also achieved through minimizing deflection under load, combined with the use of damping techniques.

Section 4.7.4 - Supporting Structure Basis for Design

The construction of an actual vehicle structure may be employed as a starting point. In the case of a truck or bus (see Fig. 1), the structure supporting the engine and drive train is primarily a sort of rectangular frame built up from standard metal forms (i.e. beams of "C" and "I" sections). These are then connected to one another, primarily by welding, to form a structure capable of supporting all the major components (i.e. engine, transmission, drive shaft & bearings, differential, axle). Since this structure is in common use without complaint, its general design has thereby proven itself to be an effective means of achieving the three essential goals.

Figure 23 – Example of a typical bus chassis showing frame construction

Since the power scale encountered in the model (on the order of 1hp) is decidedly smaller than that encountered in an actual vehicle, so may be scaled down the elements of the supporting frame. At such a small scale, welding may be replaced as a joinery method in favor of mechanical fasteners to make construction simpler.

Following this technique, a proposed form of bed construction is shown in figure 2. The frame consists of square bars (either solid or hollow) connected in a rectangular fashion by means of "angle iron" braces and flat plates. The components are fitted together by means of machine screws, with the bars being tapped to accommodate the screws. This construction has the advantage of being easy to fabricate with a minimum of available tools.

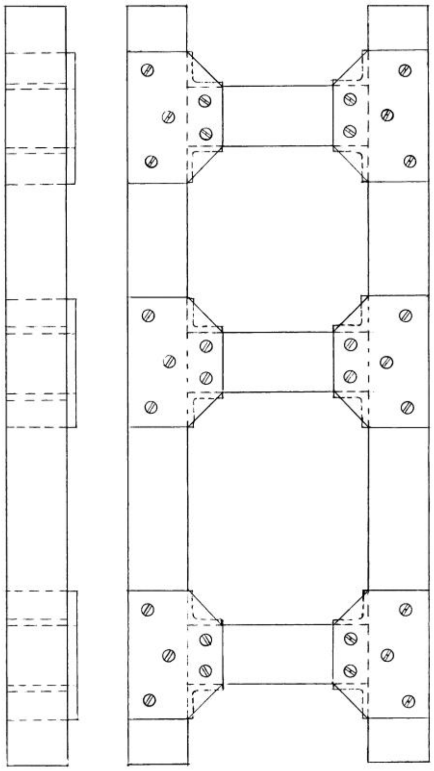


Figure 24 – Proposed form of test bed frame

Section 4.7.5 - Supporting Structure Material & Component Selection

Drawing upon machine tool design, cast iron can be employed effectively to achieve high precision in operation. Machine tools often employ large, thick sections of gray cast iron to provide appropriate structural rigidity and also a measure of vibration control through high mass. Furthermore, gray cast iron, by virtue of its high graphite content, naturally acts to dissipate mechanical vibration, further recommending its use. It is, however, more brittle than wrought steel alloys, and may be more difficult to fabricate into the needed components for the frame. It also is generally not available in a wide variety of prefabricated forms since it is produced only by casting.

Stainless and alloy steels possess higher rigidity than cast iron, along with the added benefits of greater ductility and a wider selection of prefabricated forms. Stainless steels in particular possess high corrosion resistance, which may be helpful in extending the working life of the supporting frame. Unfortunately, the microstructure of these steels does not contain the graphite structures found in cast iron, and therefore they do not possess integral vibration damping qualities.

Section 4.7.6 - Supporting Structure Price Information

Cast Iron

Description	**Price**	**Supplier**
Flat Stock 1/2" Thick, 3" Width, 1' Length	$58.82	Mc-Master Carr

Table 17 – Prices for Cast Iron

Stainless Steel (AISI 304)

Description	**Price**	Supplier
Square Tube, 3/4" X 3/4", .065" Wall, 3' Length	$14.35	Mc-Master Carr
Angle Brace 1/8" Thick, 1" X 1" Leg, 3' Length	$17.68	Mc-Master Carr
Sheet with 2B Finish .090" Thick, 12" X 12"	$26.64	Mc-Master Carr

Table 18 – Prices for Stainless Steel

Alloy Steel

Description	**Price**	**Supplier**
AISI 4130 Square Tube 3/4" X 3/4", .049" Wall, 3' Length	$22.03	Mc-Master Carr
AISI 1018 Angle Brace 1/8" Thick, 1" Leg Length, 6' Length	$10.40	Mc-Master Carr
AISI 4130 Sheet .080" Thick, 12" X 12"	$23.77	Mc-Master Carr

Table 19 – Prices for Alloy Steel

Section 4.7.7 - Supporting Structure Conclusions

Since existing designs for vehicle beds have proven themselves, it is recommended that the design for the supporting frame parallel such designs. This also fulfils the desire to produce a model of an HEV drive train that is as analogous to its real-world counterpart as possible. Furthermore, for the sake of preserving the integrity of the frame, stainless steel ought to be used extensively in the construction of the frame, especially since the incremental cost is small over non-corrosion resistant alternatives.

Section 5 - Recommendations

As stated earlier, IPRO 342's primary goal was to design a test bed for a HEV School Bus. It can clearly be seen from the results presented in the previous section of this report that the team has fulfilled its goal by thoroughly researching all the major components of a HEV. This has helped the team make recommendations on the selection of the best possible electrical and mechanical components for the test bed. Of course, the research and the recommendations that came out of this research are now well-documented in this report.

The next step is the actual implementation of the test bed, which should be carried out by future IPRO teams. The IPRO 342 team estimates that, together, implementing and testing the test bed could take at least a couple more semesters. Still, the team believes that future IPRO teams have plenty of documentation now to refer to, which should greatly simplify their tasks.

The next IPRO team must start by first reviewing all of the research, results, and conclusions documented by IPRO 342. This will not only help the new team understand the goals of this multi-semester IPRO better, but it will also allow the new team members to quickly familiarize themselves with the major hybrid electric vehicle components. Once the new teams have carefully read and understood all of the information presented in this report (in particular, the Results section), they will be more than ready to quickly adopt the recommendations made by the IPRO 342 team and buy the recommended components to build the test bed.

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