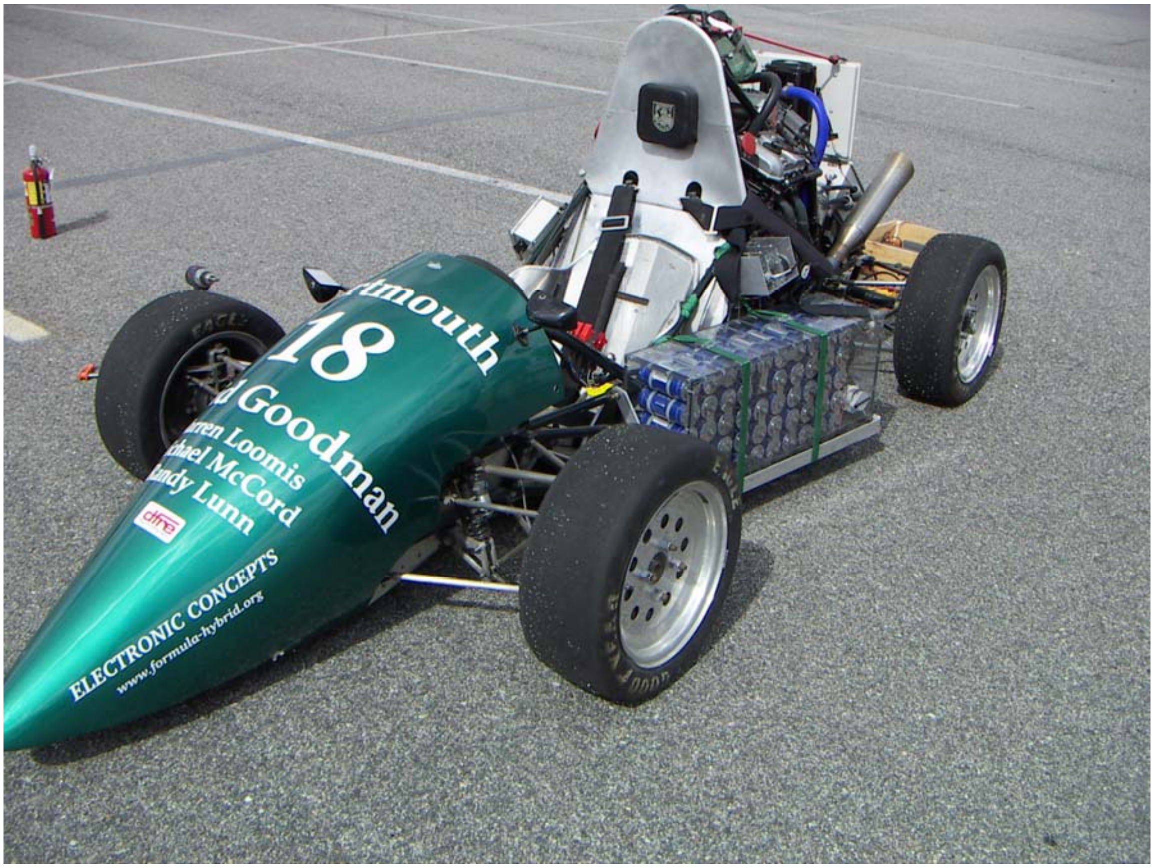
Thayer School of Engineering
at Dartmouth College

Dartmouth Formula Racing - Hybrid



Dana Haffner

ENGS 199 – Hybrid Vehicle Technology
Final Report
June 5, 2006

Acknowledgments:

Doug Fraser

Professor Charles Sullivan

Professor John Collier

Dartmouth Formula Racing – Team and Captains

Hybrid Electrical Team: Arne Kepp, Naota Nakayama, Jacob Goodman

Special Acknowledgment: Reed Sibley and Abby Davidson
-For letting me use parts of our Hybrid Mechanical Team Final Report.

Table of Contents

List of Figures and Tables

1.0 Introduction

In this paper I will document the internal combustion engine (heretofore only referred to as engine) and chassis challenges involved in converting a standard Formula SAE car to a hybrid drive system. Sections 2, 3, and 4 will go through the details of the 2005-2006 Dartmouth hybrid team's decisions and implementations, while Section 5 is intended for use on the Formula-Hybrid website as a guide and helpful start in these two areas for other schools who would like to enter in the Formula-Hybrid competition. Common pitfalls and overall challenges will be discussed in this section (5).

2.0 Specifications

Due to the subject of this paper being limited to the engine and chassis conversion, most of the discussion will revolve around the work of the 05-06 Hybrid Mechanical Team. For this I would like to acknowledge the help of Reed Sibley and Abby Davidson, my fellow teammates for this task. Our need was "to construct an optimized test bed for hybrid racecar technology." Our goals pertinent to the engine and chassis were to minimize weight, securely fit and mount all components, and to select and appropriately modify our engine. The corresponding specifications are shown in the chart below.

Specification	Quantification	Justification	Validation
Make it all fit	Everything can be securely mounted	Necessary to use our chosen components	ProEngineer. Observation post-mounting
Secure, strong mountings	Parts remain fixed under maximum applied load	Safety for driver and parts	ProMechanica ensures reasonable factor of safety.
Center of gravity	45/55 (front/back), Low to ground	Ideal racecar longitudinal CG. Same goals as DFR	Weight analysis in ProEngineer
Powerful Engine-Generator System	25-30 hp	Necessary to quickly recharge capacitors and complete endurance event	Test generator voltage output; stock engine specs

Figure 1: Mechanical Specification Chart

3.0 Engine: Selection

To fully understand the selection of our ICE amongst our overall series hybrid configuration it is first necessary to understand the differentiation between its role in the hybrid as compared to a FSAE car. Formula SAE rules require an engine inlet restrictor plate with a 20mm opening, which effectively serves to limit the peak power from the engine. A similar limitation to this in a series hybrid system such as ours would be to limit the power of our electric motor. So with regard to our ICE, a hybrid system could be configured such that the restrictor-limited power no longer serves as the peak power, but rather the average. This is because our ICE is intended to run at constant optimal rpm. An FSAE engine is only ever at optimal speed during acceleration, whereas our engine will always be running at optimal speed to charge our ultracapacitors. This is an advantage over a standard FSAE car because it is essentially increasing the power available for the electric motor to put to the wheels.

Once we had fully ascertained the engine's purpose in our hybrid drive system, we were able to choose the 250cc 4-stroke option based on its power output, size, general fuel efficiency, and peak rpm. The power delivered by the engine is important for meeting our endurance specification; for this reason we chose a high performance motorcycle engine. We later found that in a study of high-performance auxiliary power units prepared for the Office of University Research and Education for the U.S. Department of Education (whose objective was to investigate small, high-speed, gasoline engines for use in a series hybrid vehicle) the researchers' conclusion was that a Yamaha 250cc 4-stroke engine would be the best commercially available engine for this application,[1] further confirming our 250cc 4-stroke decision.

[1] http://www.webs1.uidaho.edu/niatt/publications/Reports/KLK331_files/KLK331.htm

The next step was then to obtain a specific 250cc 4-stroke engine. We explored a variety of options including sponsor solicitation, eBay, salvage yards, various online forums, and classified ads. After extensive research, we settled on a Kawasaki EX 250 Ninja engine, which we found on eBay for $124.35. Perusing various sales venues indicated that even with extensive repairs, this would be by far a more cost effective option than a motocross racing engine, and it puts out comparable power, approximately 28 peak horsepower (see Dyno Graph in Appendix A**).** In addition, the Ninja 250 engine is liquid cooled, which would allow us to reliably run it close to peak power output. Through discussion on several sport bike online forums, we learned that the bike is also quite common. The fact that the bike is largely unchanged since the late 1980s, coupled with its popularity, indicates that it should be a very reliable system and there should be an abundance of used parts and experience working with the engine.

3.1 Engine: Rebuild

Once the engine arrived we concluded that it would require an extensive cleaning and rebuilding. We first disassembled the engine to determine what needed to be replaced. We replaced the whole gasket set and thoroughly cleaned all parts. Disassembling the engine also revealed that the pistons in the engine had seized and that an oxidation or carbon layer had built up in the cylinders. Honing the cylinders could not adequately remove the build-up and smooth them out, so they had to be bored out. The pistons were then replaced with 0.5mm oversized pistons. The other major modification we made to the engine was removing the transmission and clutch. Since the engine will be used solely to drive the generator system, we may operate it with a fixed gear ratio. Thus, the clutch and transmission assembly was unnecessary weight and complexity. This, however, required the fabrication of a new output shaft, which is discussed in the following section.

3.2 Engine: New Output Shaft

The new output shaft was essentially a longer version of the original clutch shaft. It was constructed to fit the existing engine bearings and gears that mate with the crank shaft and water pump. Because one of the bearings does not have an inner raceway but rather rides directly on the shaft, we had to have the shaft specially treated. We used 4140 steel that was heat treated to have a hardness rating of about 55 on the Rockwell C scale. We deemed this sufficient hardening since the original shaft was measured and found to have a rating of 60. The hardening ensures reduced wear along the bearing-shaft interface and hence better longevity for the part. The shaft was also ground to create a smooth surface for the bearing to rotate upon, also reducing wear.

We went through several iterations of shaft design and ProMechanica analysis until we arrived at a satisfactory factor of safety of 3.3. The final ProMechanica analysis can be seen in Figure 2. Force calculations on the shaft can be found in Appendix B, and the shaft drawing in Appendix C.

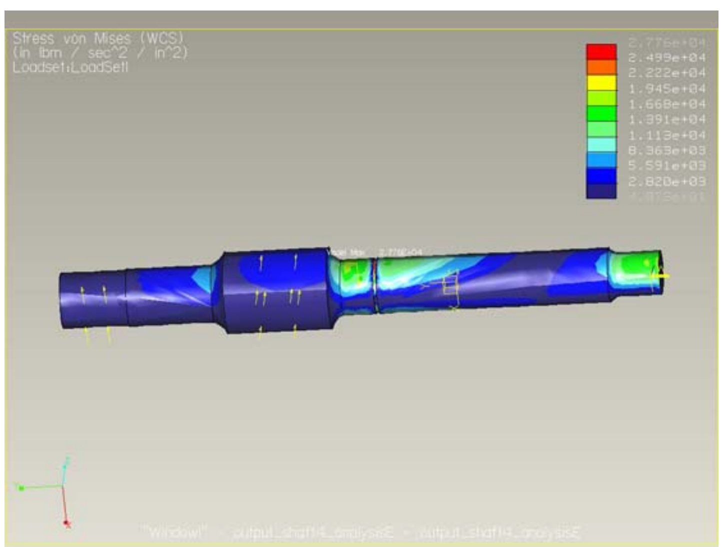


Figure 2: Shaft Analysis

To accommodate the revamped drive shaft, we created a new opening in the engine casing. The drive shaft is now sent directly out the clutch cover, which has been narrowed and includes a seal housing. The new drive shaft orientation and clutch cover opening can be seen in Figure 3.

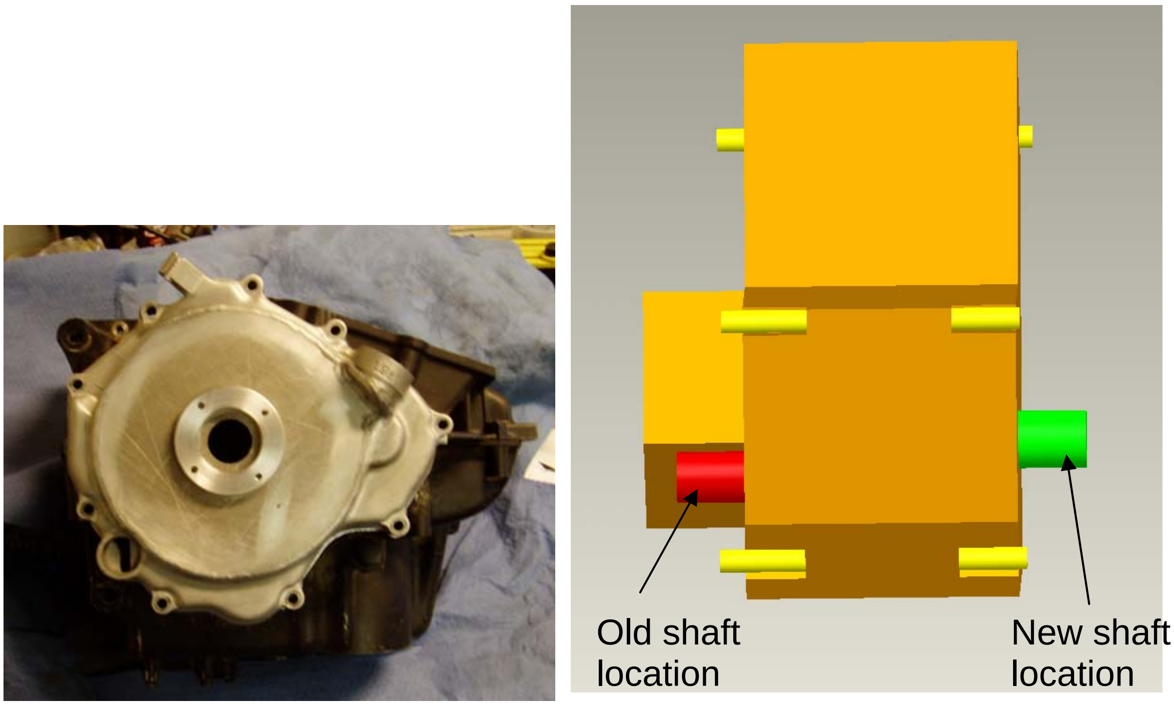


Figure 3: Shaft Relocation

3.3 Engine: Timing Pulley System

Once rebuilt, the engine needed to interface with the generators. We considered three options for connecting the two components: V-belt, timing belt, and roller chain. The three qualities with which we were most concerned were reliability, strength, and weight. Regarding reliability, we wanted a system that would transfer the power from the engine to the generators with minimal losses. This effectively ruled out the V-belt, which could possibly slip, thereby decreasing the power delivered to the generators. In terms of strength, both a timing belt and roller chain could handle our system's torque. Because of its considerable weight advantage, however, we chose the timing belt. The timing belt is also a more elegant solution, both due to its more streamlined looks and reduced noise.

After choosing our power transfer system, we calculated the size of our components. Consulting with the hybrid electrical team, we determined that an optimal speed for the generators would be ~3600 RPM. Though the engine dyno chart (Appendix A) indicates that the engine reaches maximum power at ~12,000 RPM, we assumed the engine would run at ~10,000 RPM for our calculations (to use a conservative model). The gear ratio between the crankshaft and output shaft is 3.087, so the output shaft is spinning at 3240 RPM when the engine revs to 10,000 RPM. Using the RPMs of the generators and engine output shaft, we determined that an appropriate pulley sprocket ratio between the engine and generators would be 1.11. We performed the required calculations for choosing suitable belts and sprockets based on our loadings, operating speeds, and center distances. The complete system weighs 10 lbs, uses a 20cm wide belt and has a design life of ~15,000 hours. In addition, a system design produced by the product engineer (Appendix D**)** provided us with the proper shaft loadings and geometry to use in our output shaft force calculations.

After testing, we are now able to look at these gear ratio numbers again. In actuality our engine was run around 8000 rpms, which puts our output shaft at 2592 rpms, and our generators at ~2877 rpms. This is only 80% of their optimal speed, which explains why they were only outputting around 82 V instead of their expected 96 V. Given more time to test and drive the car, the gear ratio is definitely something that we would change to gain more efficiency.

4.0 Chassis: Selection

One of the first steps to designing a racecar is to design its chassis. Given the nature of our cause, however, we were not afforded this luxury. We chose to recycle the 2003 DFR car, Myra, and convert her to a hybrid drive system, dubbing her "el-Myra." This offered us both benefits and disadvantages. While it is of course advantageous, given limited time, resources and manpower, to have an already-made car at our disposal, it is less than ideal in other respects. First, extensive frame modifications needed to be made to retrofit all of our components. Second and most importantly, the additional weight added by the hybrid system has very serious repercussions on the suspension and vehicle dynamics because the 2003 car was designed to be much lighter. Our final weigh in came to 1015 pounds, nearly twice as much as Myra's intended 575 pounds. The following sections will discussion these issues in greater depth.

4.1 Chassis: Frame Modifications

We spend a considerable amount of time designing our component placement in ProEngineer with the considerations of accessibility, and appropriate weight distribution in mind. In order to best accommodate the geometry and loads of our new components, extensive modifications of the chassis were necessary. We also made sure to design all of our mountings so that our components are not fixed and may be removed fairly easily for repair at any time.

Our final design for out component placement took all of these considerations into account. We placed our motor and generators very low, with our engine sitting just above the generators. It was necessary to have the engine and generators in a vertical configuration with the shafts in the same plane for the timing belt. In addition, having the engine above the generators is ideal as opposed to the generators above the engine because it provides easiest access to the engine, whereas no tuning really goes on with the generators. The ProEngineer design of the final design can be seen in Appendix E – note that the electric motor is shown in red, ICE in orange, and generators in blue. This set up resulted in a significant improvement in weight distribution and therefore handling performance of the car. We were also able to account for convenient mounting points for the motor, which is the component that will induce the highest load on the frame. Though this design required extensive rear chassis modifications, its advantages outweighed the extra work.

To implement the overall design, we removed a total of 72 inches of steel tubing. To restore the integrity of the frame and mount the engine, generators, and motor, we then added 194 inches of steel tubing. This exhaustive process of cutting and welding the tubing further demonstrated to us the disadvantages of having a frame that was not designed around the car's components.

4.2 Chassis: Center of Gravity

A center of gravity (CG) analysis was an important factor when considering component placement. It was an especially important factor in our decision to modify the frame and lower the motor in the chassis. Ideally a race car would be completely centered laterally, weighted 45/55 (front/back) longitudinally, and as low to the ground as possible. The front/back offset allows for more tractive forces in the rear in an effort to increase maximum tire thrust. Appendix F shows the exact breakdown of the calculations in finding our center of gravity in these three dimensions based on our most major components.

Our results show that we were able to maintain our left-right CG at just 0.44 inches to the right, essentially centered laterally. Our front/back ratio is 43/57, which is also close to ideal. Finally, our CG is only 8.5 inches above the ground.

4.3 Chassis: Weight Considerations

Weight minimization was a major consideration throughout our design process, and even so we still ended up with a half ton vehicle. After the engine removal, Myra weighed in at 445 lbs. Funding for new lighter capacitors offered us some weight savings, however there were many areas of unavoidable weight gain, such as our 150 pound electric motor. A breakdown of our weights can be found in Appendix G, with the total coming to 1015 pounds without the driver. The consequences that this weight gain has on the vehicle dynamics systems are unavoidable. Our shocks, springs, and antiroll bar set up were chosen for a 575 pound vehicle, and not nearly sufficient for el-Myra. Because these systems are not doing their job, the suspension geometry does not live up to its intended performance either. Vehicle dynamics and handling are greatly compromised and something that is important to be addressed by the 2006-2007 hybrid team. For our purposes, however, this year's goal was to have a successful working model of a hybrid drive system, so the first step of so-called “just getting it to work” has been accomplished. The opportunities for improvement from here are endless.

5.0 Recommendations for other teams: (SECTION FOR THE WEBSITE)

*Note: These are only the recommendations with regard to the chassis and engine. It does not represent the entirety of the guide to be posted on the website.

If you are reading this then you are probably interested in how one would convert an FSAE car into a car fit for the Formula-Hybrid competition. The following section will provide you with a few bits of advice and some overall suggestions based on our experience with this project.

The first step is to find an old FSAE car. If your school does not have any lying around, start asking other schools. There are over a hundred FSAE cars made every year and many schools just discard those that are over a year or two old.

Once you have obtained your old FSAE car, the next step is to decide on what type of hybrid drive train you plan on implementing. We would encourage other teams to examine a variety types of hybrid drive systems, however, because the series hybrid system is where our experience lies, our recommendations are all derived from our work with such.

Next you will need to evaluate the condition of your current chassis and decide on what major modifications will need to be made. Be wary that you will most likely be adding a significant amount of weight to what your frame and suspension were originally designed for. Also keep in mind that extensive frame modifications can change the way your frame was intended to distribute its load, so always perform analyses to avoid unfortunate failures.

With respect to the internal combustion engine, it was of great help to us to pick a common model. This provided us with an abundance of spare parts and people with experience working with the engine when we needed it.

6.0 Appendix A: Engine Dyno Graph

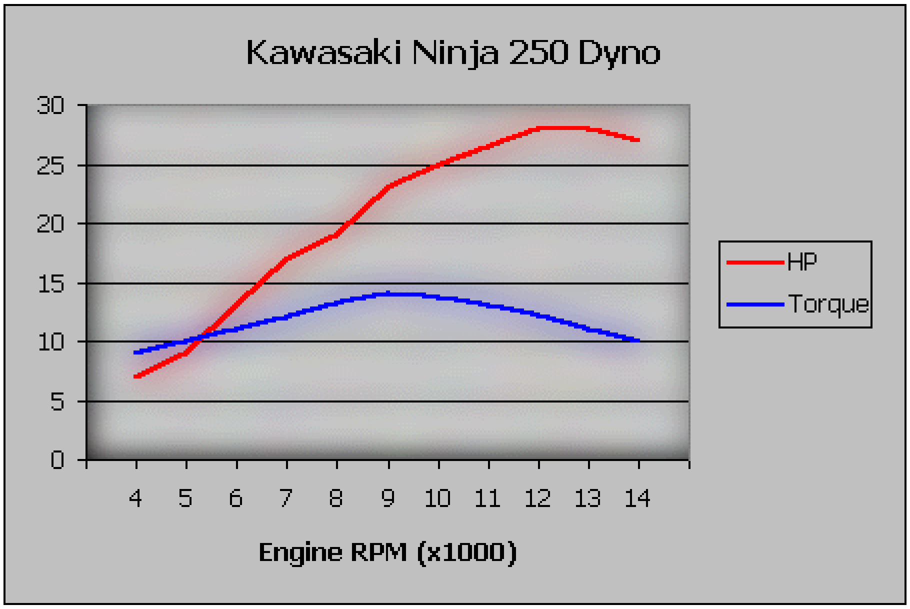
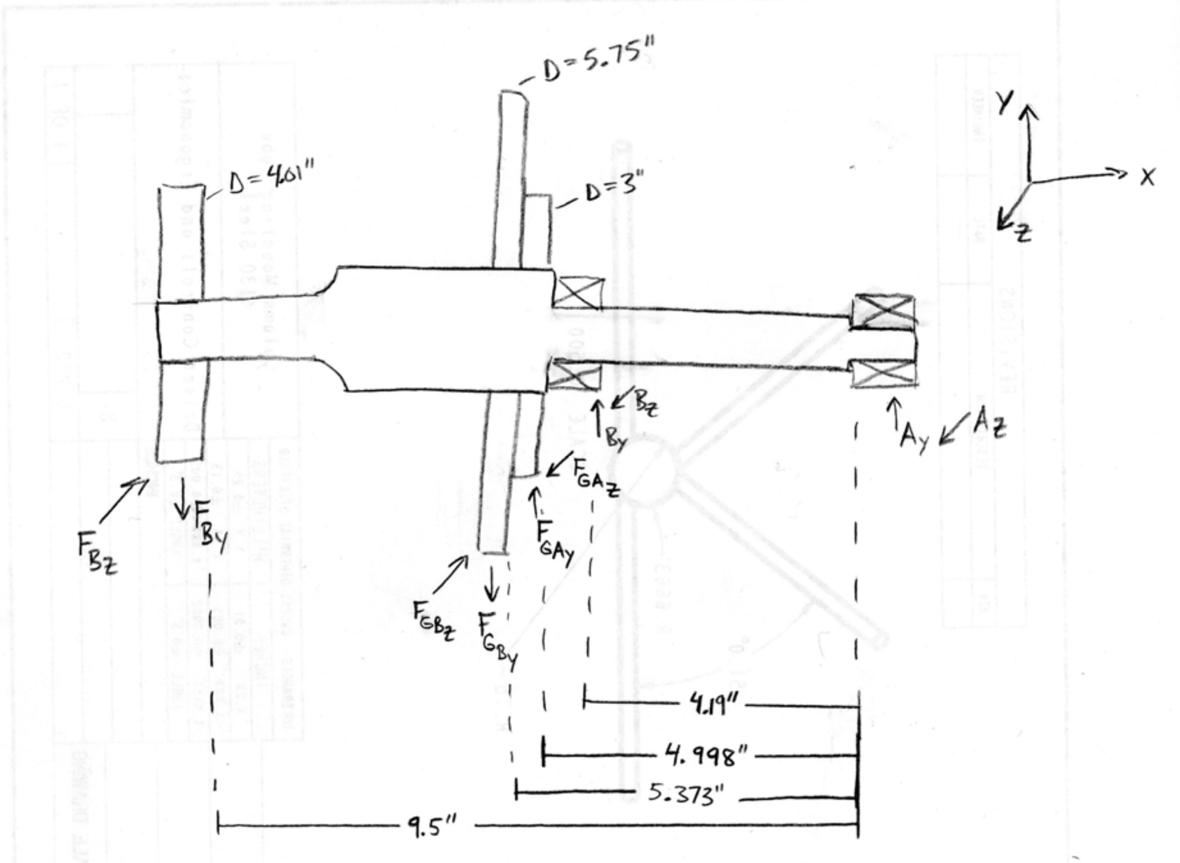
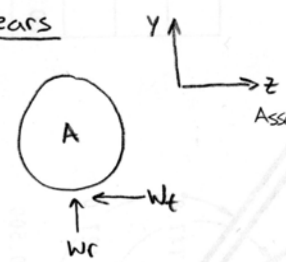


Figure 4: Engine Dyno Graph

7.0 Appendix B: Force Calculations



Gears



Assume $\phi = 25°$

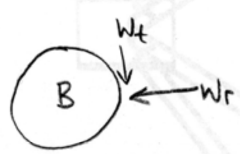
$$W_t = \frac{(126{,}050)\,h_p}{(d)(N_a)} = \frac{(126{,}050)\,30}{3''\,(3239.4\text{ rpm})}$$

$$W_t = \boxed{389.115 \text{ lbf} = F_{GA_z}}$$

$$W_r = W_T \tan\phi$$

$$= 389.115 \tan 25°$$

$$W_r = \boxed{181.45 \text{ lbf} = F_{GA_y}}$$



$$W_t = \frac{126{,}050\,(30)}{(5.75'')(3239.4)}$$

$$W_t = \boxed{203.02 = F_{GBy}}$$

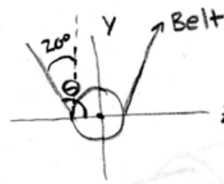
$$W_r = 203.02 \tan 25°$$

$$W_r = \boxed{94.67 \text{ lbf} = F_{GB_z}}$$

$P = 30\,hp$

$\omega = 10{,}000 \times \left(\dfrac{23\,T}{71\,T}\right) = 3239.4\ RPM$

Loading from Gates Corp:



$F_B = 359.54\ lbf$

$\theta = 110°$

$F_{B_z} = F_B \sin 20°$

$\boxed{F_{B_z} = 122.97\ lbf}$

$F_{B_y} = F_B \cos 20°$

$\boxed{F_{B_y} = 337.86\ lbf}$

$$\sum M_{A_z} = 0 = B_y(4.19'') + F_{GA_y}(4.998'') - F_{GB_y}(5.373'') - F_{B_y}(9.5'')$$

$\boxed{B_y = 809.93\ lbf}$

$$\sum F_y = 0 = A_y + B_y + F_{GA_y} - F_{GB_y} - F_{B_y}$$

$\boxed{A_y = -428.50\ lbf}$

$$\sum M_{A_x} = 0 = B_z(4.19'') + F_{GA_z}(4.998'') - F_{GB_z}(5.373'') - F_{B_z}(9.5'')$$

$\boxed{B_z = -63.94\ lbf}$

$$\sum F_z = 0 = A_z + B_z + F_{GA_z} - F_{GB_z} - F_{B_z}$$

$\boxed{A_z = 107.355\ lbf}$

8.0 Appendix C: Engine Output Shaft Drawing

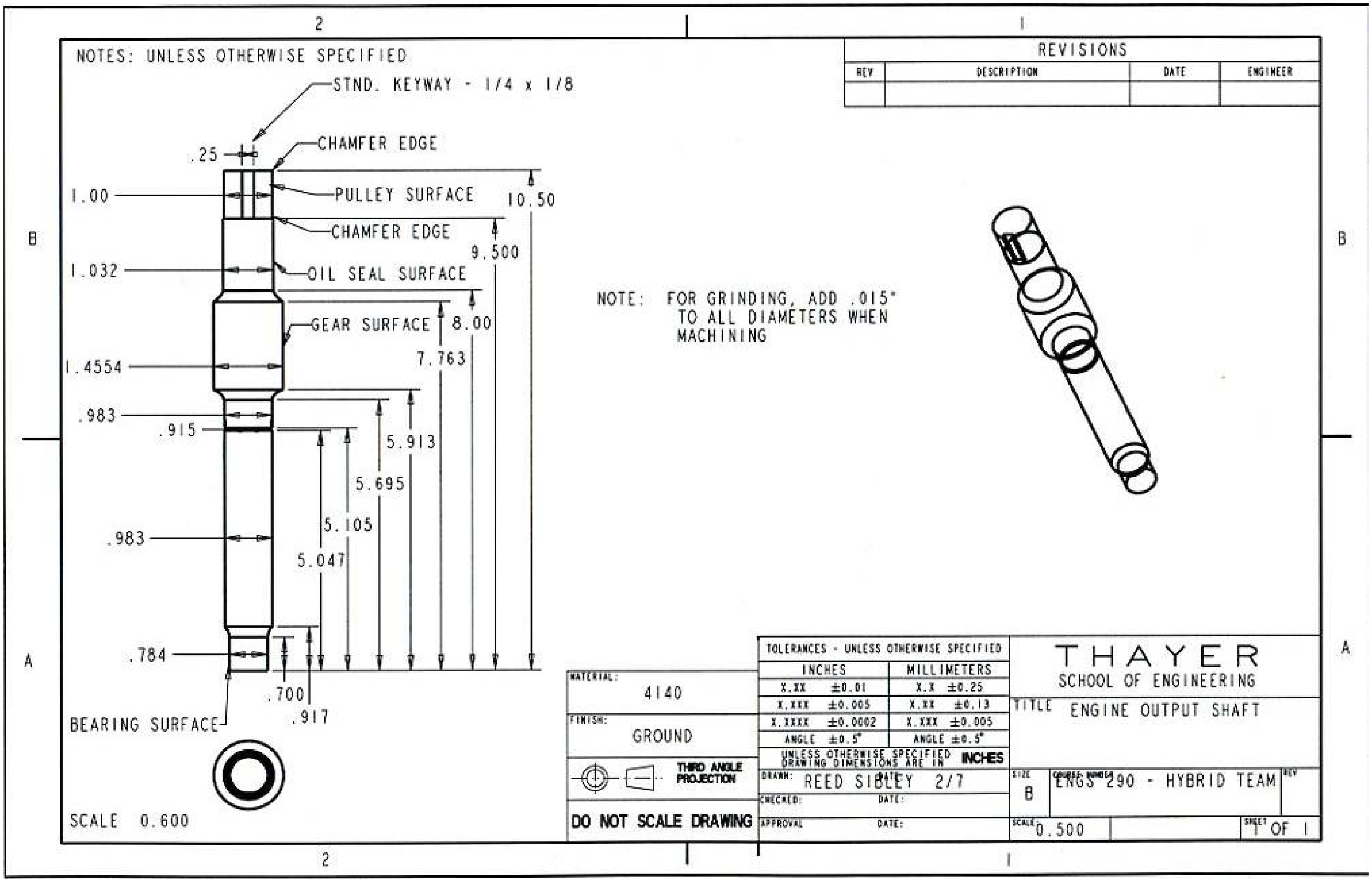


Figure 5: Engine Shaft Drawing

*Note: Oil seal part #: Napa 10584

9.0 Appendix D: Timing Pulley System

Design IQ™ — Belt drive design software by the Gates Corporation

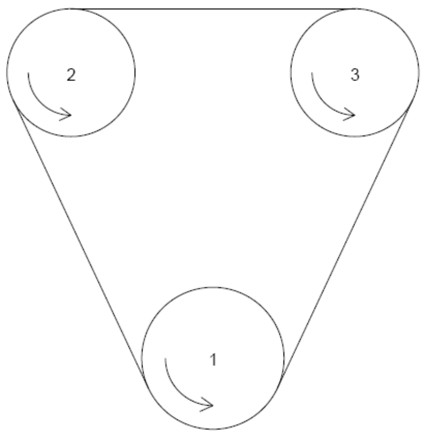
Ver. 1.20.010
DB Ver. 0.192

Page 1

A Tomkins Company

Company: Reed at Dartmouth Generator Drive 2-3-06

Reed at Dartmouth Generator Drive 2-3-06



Belt Data: (inch)

Selected Belt: PowerGrip GT2 960-8MGT-30
Pitch Length: 37.795 inches (120 Teeth)
Belt Width: 30

Layout Data: (inch)

	X	Y	Diameter	Ratio	Wrap Angle	Arc Length	Span Length	
1	0.000	0.000	40 Grooves (3.96 OD)	1.00	129.80° (14.4 T)	4.542 (14.4 T)	9.001 (28.6 T)	P40-8MGT-30
2	-4.000	8.066	36 Grooves (3.56 OD)	0.90	115.10° (11.5 T)	3.625 (11.5 T)	8.000 (25.4 T)	P36-8MGT-30
3	4.000	8.066	36 Grooves (3.56 OD)	0.90	115.10° (11.5 T)	3.625 (11.5 T)	9.001 (28.6 T)	P36-8MGT-30

Dynamic Data: (Hp)

Condition 1 / 1 **100% of time**
Belt Speed = 3412 ft/min

Pulley	RPM	Rot.	Load	SF	Span Tension	TR (180°)	Shaft load / Angle	FR	Weighted FR
1 (Dr)	3250	CCW	30 HP	1	331.5954 lbf	8:1	359.5400 lbf@110°	92.73%	92.73%
2	3611.1	CCW	15 HP	1	186.5224 lbf	1.78:1	444.0953 lbf@317°	3.64%	3.64%
3	3611.1	CCW	15 HP	1	41.4494 lbf	4.5:1	207.5283 lbf@190°	3.64%	3.64%

Tensioning Information: (Force/Deflection)

Span:1

	New Belt		Used Belt *		
	Minimum	Maximum	Minimum	Maximum	Deflection
Installation Tension per belt	187 lbf	205 lbf	131 lbf	149 lbf	
Deflection Force per belt	12.4 lbf	13.6 lbf	8.93 lbf	10.1 lbf	0.141 inches

* For used belts, the belt tension should be measured and recorded before removal so that the belt can be reinstalled at the same tension.

Levi R. Campbell (5)
Date: 03-Feb-06

File Name:

Design IQ™ — Belt drive design software by the Gates Corporation

Ver. 1.20.010
DB Ver. 0.192

Page 2

Company: Reed at Dartmouth Generator Drive 2-3-06

Reed at Dartmouth Generator Drive 2-3-06

Tensioning Information: (Force/Deflection)

Span:2

	New Belt		Used Belt *		
	Minimum	Maximum	Minimum	Maximum	Deflection
Installation Tension per belt	187 lbf	205 lbf	131 lbf	149 lbf	
Deflection Force per belt	12.3 lbf	13.5 lbf	8.84 lbf	10.0 lbf	0.125 inches

* For used belts, the belt tension should be measured and recorded before removal so that the belt can be reinstalled at the same tension.

Tensioning Information: (Force/Deflection)

Span:3

	New Belt		Used Belt *		
	Minimum	Maximum	Minimum	Maximum	Deflection
Installation Tension per belt	187 lbf	205 lbf	131 lbf	149 lbf	
Deflection Force per belt	12.4 lbf	13.6 lbf	8.93 lbf	10.1 lbf	0.141 inches

* For used belts, the belt tension should be measured and recorded before removal so that the belt can be reinstalled at the same tension.

Tensioning Information: (Sonic Tension Meter)

Sonic Input Data: Span 1
Unit Weight: STM 505C/507C (305): 5.5 (0.55)
Belt Width: 30 mm
Span Length:229 mm

	New Belt		Used Belt *	
	Minimum	Maximum	Minimum	Maximum
Installation Tension per belt	187 lbf	205 lbf	131 lbf	149 lbf
Span Frequency	155 Hz	163 Hz	130 Hz	139 Hz

* For used belts, the belt tension should be measured and recorded before removal so that the belt can be reinstalled at the same tension.

Tensioning Information: (Sonic Tension Meter)

Sonic Input Data: Span 2
Unit Weight: STM 505C/507C (305): 5.5 (0.55)
Belt Width: 30 mm
Span Length:203 mm

	New Belt		Used Belt *	
	Minimum	Maximum	Minimum	Maximum
Installation Tension per belt	187 lbf	205 lbf	131 lbf	149 lbf
Span Frequency	175 Hz	183 Hz	146 Hz	156 Hz

* For used belts, the belt tension should be measured and recorded before removal so that the belt can be reinstalled at the same tension.

Tensioning Information: (Sonic Tension Meter)

Sonic Input Data: Span 3
Unit Weight: STM 505C/507C (305): 5.5 (0.55)
Belt Width: 30 mm
Span Length:229 mm

	New Belt		Used Belt *	
	Minimum	Maximum	Minimum	Maximum
Installation Tension per belt	187 lbf	205 lbf	131 lbf	149 lbf
Span Frequency	155 Hz	163 Hz	130 Hz	139 Hz

* For used belts, the belt tension should be measured and recorded before removal so that the belt can be reinstalled at the same tension.

*NOTE: Part data above is for the 30mm sprocket system. The parts we actually used are for a 20mm system. They are the following:

Drive Sprocket: P40-8MGT-20
Driven Sprockets: P36-8MGT-20
Idler Pulley: 32S-8MGT-20-IDL-SPRK
Timing Belt: 1200-8MGT-20

10.0 Appendix E: ProEngineer Design Schematics

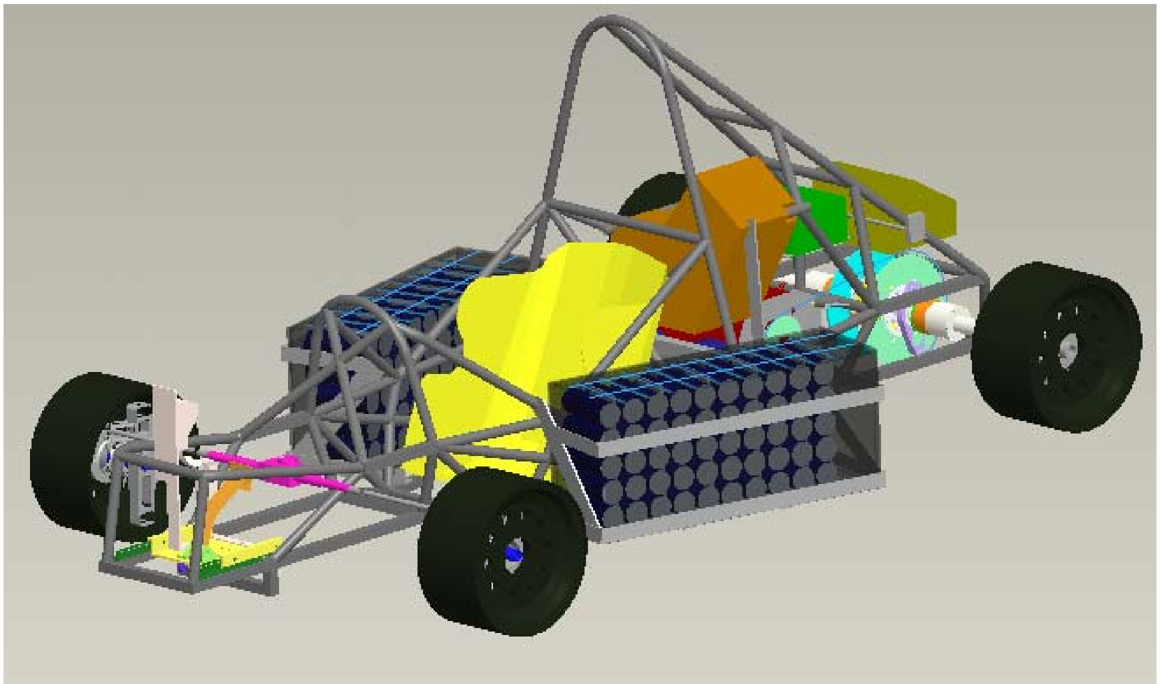


Figure 6: Isometric View

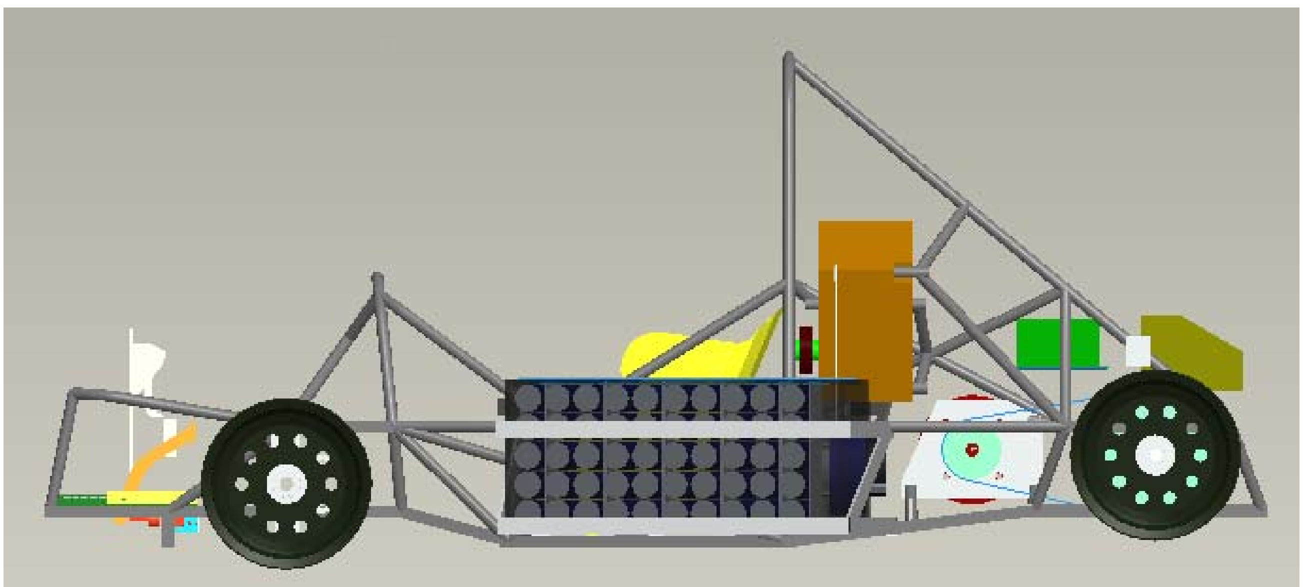


Figure 7: Side View

11.0 Appendix F: Center of Gravity Analysis

Length (front-back)

Component	Weight (lb)	Position (in) F=-1, B =1	Moment (in-lb)
Motor	150	21.25	3187.5
Controller	20	21.5	430
Engine	80	12.25	980
Generator (left)	21	16.85	143.85
Generator (right)	21	16.85	143.85
DC-DC Converter	20	45	900
Battery	10	3.5	35
Cap Bank (left)	55	-10.04	-552.2
Cap Bank (right)	55	-10.04	-552.2
Driver	170	-2.02	-343.4
Sums:	***602***		***4372.4***

Resultant position of CG (moment sum/weight sum) = 7.26 inches back from center

Width (left-right)

Component	Weight (lb)	Position (in) L= -1, R = 1	Moment (in-lb)
Motor	150	4	540
Controller	20	1.5	30
Engine	80	-5.2	-416
Generator (left)	21	-4.5	-94.5
Generator (right)	21	4.5	94.5
DC-DC Converter	20	1.1	22
Battery	10	8.75	87.50
Cap Bank (left)	55	-18.87	-1037.85
Cap Bank (right)	55	18.87	1037.85
Driver	170	0	0
Sums:	***602***		***263.5***

Resultant position of CG (moment sum/weight sum) = 0.44 inches right of center

Height

Component	Weight (lb)	Position (in) Ground = 0	Moment (in-lb)
Motor	150	8.22	1233
Controller	20	16.82	336.4
Engine	80	18.5	1480
Generator (left)	21	4.5	94.5
Generator (right)	21	4.5	94.5
DC-DC Converter	20	15	300
Battery	10	4.17	41.7
Cap Bank (left)	55	8.07	443.85
Cap Bank (right)	55	8.07	443.85
Driver	170	3.59	610.3
Sums:	***602***		***5078.1***

Resultant position of CG (moment sum/weight sum) = 8.44 inches off the ground

12.0 Appendix G: Weight Analysis

Weight Analysis

	(lbs)
Chassis	
Starting Vehicle Weight	575
Removed Engine/Trans.	-130
Energy Storage System	
Ultracapacitors and boxes	110
Generator	40
Engine	80
Engine systems (exhaust, fuel, cooling, carburetors)	40
Inductor	20
Converter	20
Mounting Hardware	35
Wiring & Safety System	
Relays & Fuses	5
Cables and Wiring	15
Battery	10
Drive System	
Motor	150
Controller	20
Mounting Hardware	20
Subtotal without Driver	**1013**
With Driver	
Driver	150
Total w/Driver	**1163**