

**THE CONVERSION OF A PERSONAL WATERCRAFT TO ELECTRIC/HYBRID
DRIVE THROUGH THE USE OF MATLABSIMULINK®**

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ABSTRACT

Over the past three years, McGill University has pushed to advance power-sports vehicle drivetrain technology towards cleaner, quieter and more efficient alternatives. Projects to date include a hybrid SAE race car, series hybrid snowmobile, electric snowmobile and an electric SAE Baja. McGill's most recent project looks at the possibility of integrating advanced vehicle technologies in a personal watercraft (PWC). More precisely, the project investigates the feasibility of developing an electric or hybrid personal watercraft.

This paper presents baseline PWC power requirements developed from on-water tests of a fully instrumented BRP Sea-Doo GTI SE. Using data from on-water tests, a model of the current gasoline drivetrain was developed using Matlab*Simulink*®. Performance targets were set for an electric/hybrid watercraft. These performance targets were then used to design and evaluate various electric and hybrid watercraft Matlab*Simulink*® models.

The electric and the gasoline watercraft models were compared on a performance basis. Two drive cycles, corresponding to different riding conditions, were developed at McGill University and used to compare the different models.

INTRODUCTION

Personal watercrafts (PWC) are propelled by gasoline powered jet drive systems. These systems are safe, powerful, and allow for great maneuverability. Unfortunately, these crafts are far from being considered 'green vehicles'. Many small lakes have banned PWC use because of their environmental impact. Lately, the industry has addressed these problems by using more efficient four-stroke engines. For example, BRP claims its three person GTI and GTI SE models 91% cleaner than its seven year predecessor by using ROTAX's 4tec engine (BRP, Bombardier Recreational Products, 2006). But, even with an industry-wide shift towards 4-stroke technology, fuel efficiency of PWC rivals that of much larger machines such as cruise ships and helicopters (Fuel Efficiency in Transportation, 2007).

GOAL

Since personal watercrafts rank close to the bottom of the list in terms of vehicle fuel efficiency, it is natural to look at possible ways of improving their fuel consumption. To look for possible ways of doing so, McGill University looked at what is being done in other vehicles to improve their fuel efficiency. In recent years, gas-electric hybrid technology has proven itself to be a viable way of improving fuel economy in cars. Furthermore, recent results on McGill designed an electric plug-in hybrid snowmobiles indicate that electric and plug-in hybrid technology can potentially be applied to small, powersports vehicles. The question under investigation in this

paper is therefore: Can electric or plug-in series hybrid technology be applied successfully to a PWC while still performing to a conventional PWC's minimum standards?

METHODOLOGY

The following steps were taken to address this question:

1. Investigate the propulsion system of conventional PWC.
2. Instrumentation of a PWC.
3. Validate the theoretical performance of the PWC propulsion system.
4. Determine the PWC's change in performance behavior for different loading conditions by varying both onboard load and towing load
5. Determine a “minimum standard” for PWC performance to serve as a target for the electric drive system
6. Develop MATLAB^{Simulink}® models of electric and plug-in series hybrid drivetrains for use in a PWC
7. Evaluate these drivetrains against the “minimum standard” for PWC performance

PWC PROPULSION SYSTEM

A PWC's jet drive takes in rotational energy directly from the engine's drive shaft to turn an impeller. The impeller aspirates water through the intake grate, accelerates it, and ejects it through the exit nozzle at the rear of the vehicle. By virtue of the principle of conservation of momentum, the watercraft is propelled forward.

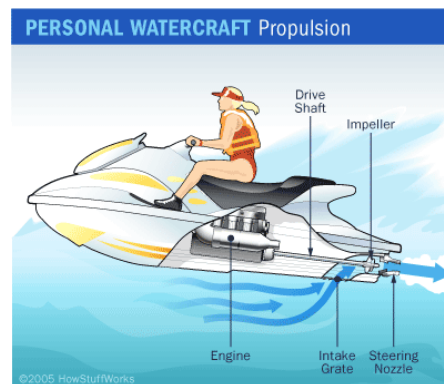


Figure 1- Jet Drive Schematic (Wilson)

Assuming no cavitation at the impeller, the theoretical power required to turn an impeller is solely proportional to the cube of its rotational speed $P \propto N^3$ (Henshall, 1972), and therefore the torque is proportional to the square of its rotational speed $T \propto N^2$. As seen by this relation, the torque absorbed by the impeller is solely dependent on its rotational speed. Altering riding or loading conditions should simply change the velocity of the vehicle. It is therefore theoretically possible to predict the torque demand by knowing the impeller RPM required to achieve a desired velocity.

INSTRUMENTATION OF THE PWC

Real – time data acquisition, from on-water tests, was used to fully characterize the PWC. An ISAAC V7 Professional data acquisition system (DAQ) was used to record data from five sensors in real time. The following sensors were fed into the DAQ: Binsfeld TorqueTrak9000 Torque Telemetry System, ISAAC DTCMAG magnetic tachometer, ISAAC DTCFFW-101 fuel flow sensor, Garmin 16A global positioning antennae to measure velocity, and the vehicle’s throttle position sensor. The data from these sensors allowed McGill University to characterize the vehicle.

THEORETICAL VALIDATION

As previously mentioned, it is expected, in theory, that the torque absorbed by the impeller is proportional to the square of its rotational speed: $T \propto N^2$. This torque relationship was confirmed by on water-test: $T_{N-m} = 1.806 \times 10^{-6} N^2 - .000386N, 1700 \leq N \leq 7400$ (Figure 2), and was shown to correlate well between different riding conditions and load cases. It is believed that the torque curve developed above is potentially a 15 – 20% underestimate of the actual torque curve. This doubt comes from the fact that the engine of the instrumented PWC is rated at 97kW while experimental results show a max power output of 74.5kW. Possible causes of this error include the highly variable temperature of the engine's drive shaft, the incredibly hot and humid environment in which the electronic system had to perform, and the fact that the exact shaft alloy composition was unknown. Even though this is a sizable error, the relationship of the trend is still apparent and confirmed by theoretical results. Keeping in mind the possible error, the relationship has been used to develop the models.

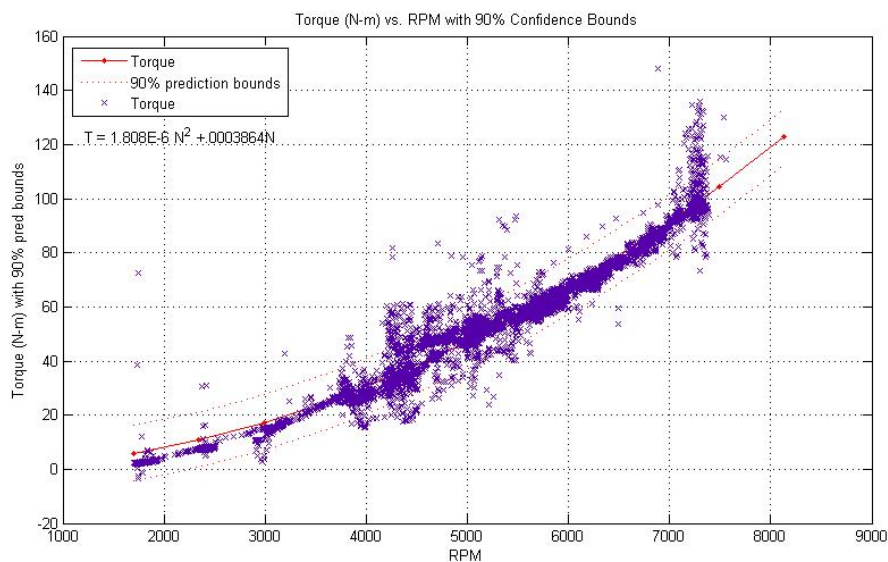


Figure 2 - Torque Required to Spin Impeller at Given RPM

EFFECT OF VARYING LOADING CONDITIONS

The PWC was tested with one (65 kg), two (153 kg) and three (218 kg) passengers to fully characterize the different load cases. In each test the throttle was used to increase the engine's speed in increments of 200-400 RPM. At each new engine speed plateau, 'steady state' conditions were reached, minimizing transient effects. By testing the entire RPM range of the engine the relationships governing the craft's performance for different load cases were developed.

Velocity

As is common with vehicles designed to plane on water, the velocity profile is divided into three regions: sub-planing, transition and planing. The transition region separates the planing and sub-planing regions and is characterized by a very abrupt change in velocity. Changing vehicular loads was found to affect the location and shape of the transition region. The slopes of the sub-planing and planing region proved to be independent of the load case. Adding more weight to the vehicle moves the transition region towards higher engine speeds and makes the transition region more pronounced and abrupt. This can be seen in Figure 3. Forty data points were chosen to define the velocity map. The resulting MatlabSimulink® map is shown in Figure 4.

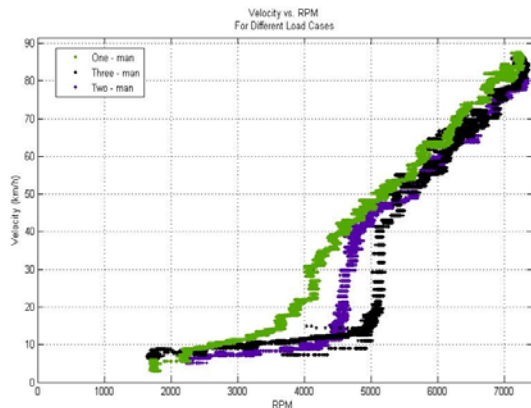


Figure 3 - Velocity Profile of Watercraft Developed From On Water Testing

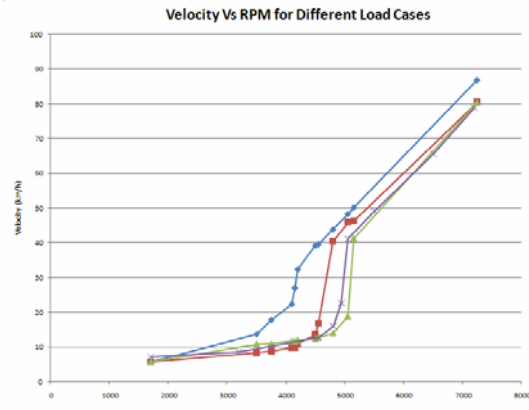


Figure 4 - Velocity Map Developed for MatlabSimulink®

Fuel Efficiency

The fuel efficiency, as a function of engine speed, was calculated using fuel flow and velocity data. As seen in Figure 5, there are two significant decreases in fuel consumption: the first around 3000 RPM and the second near 5000RPM (for the three-man load case). The first drop is associated with a quick decrease in fuel flow which is believed to be caused by the PWC's engine fuel map. The second drop in fuel consumption is caused by the rapid increase in velocity from the decreasing water resistance as it passes through the transition region. Prior to planing the vehicle is between 2.8 times to 3.5 times less efficient (140 L/100km) than while on plane (40 L/100km to 50 L/100km).

Fuel efficiency is also dependent on the loads imposed on the vehicle. By decreasing the weight on the Sea-Doo by 153 kg, it was found to reduce fuel consumption by 8.7% and 4.7% at transition and open throttle, respectively. Fuel efficiency results can be seen in Figures 5 and 6.

Given the size of its fuel tank, at full throttle the tested PWC can run for up to 80 minutes, consuming 60 L of fuel and traveling nearly 110 km. As a basis for comparison, even the least fuel efficient sports car, according to the US EPA's 2008 fuel efficiency rating, the Lamborghini Murcielago Roadster, can travel 330km on 60 L of fuel (United States Environmental Protection Agency, 2008). Furthermore, even at its optimal speed, the tested PWC consumes 41.25% more fuel per passenger-km than a helicopter and 27.1% more fuel than the RMS Queen Elizabeth cruise ship (Fuel Efficiency in Transportation, 2007).

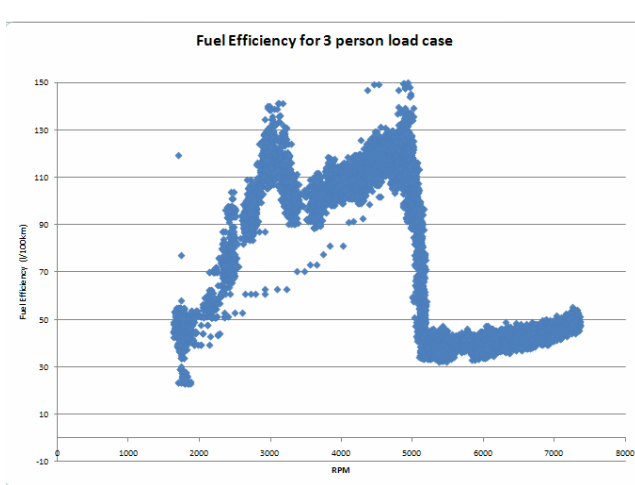


Figure 5 - Fuel Efficiency vs. RPM for Three Person Vehicular Loading (218kg)

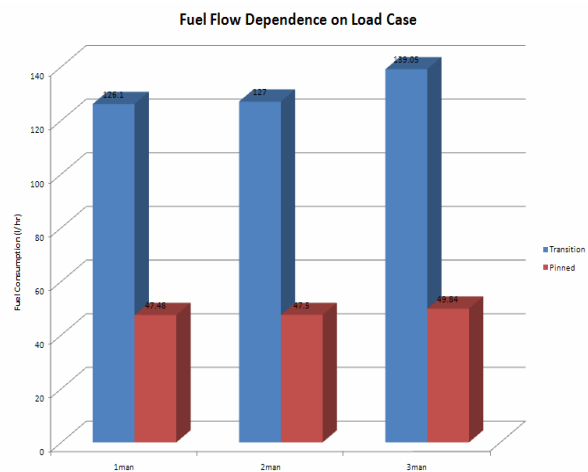


Figure 6 - Fuel Consumption Dependence on Vehicular Loading

Towing Power Requirements

Two real life towing scenarios were investigated. The first is wakeboarding, and the second is tubing.

After on-water testing, it was found that on average 50 kW was needed to pull an average 65kg wakeboarder out of the water, and then approximately 22.4 kW to tow the boarder once out of the water. Based on an actual wakeboarding run, the drive cycle, shown in Figure 7, was developed. It was used to compare the electric MatlabSimulink® models. For a wakeboarding drive cycle, the minimum standard for PWC performance was defined as having each of the three riders aboard completes about four of these 175 sec runs, for a total of 35 minutes of riding before recharge.

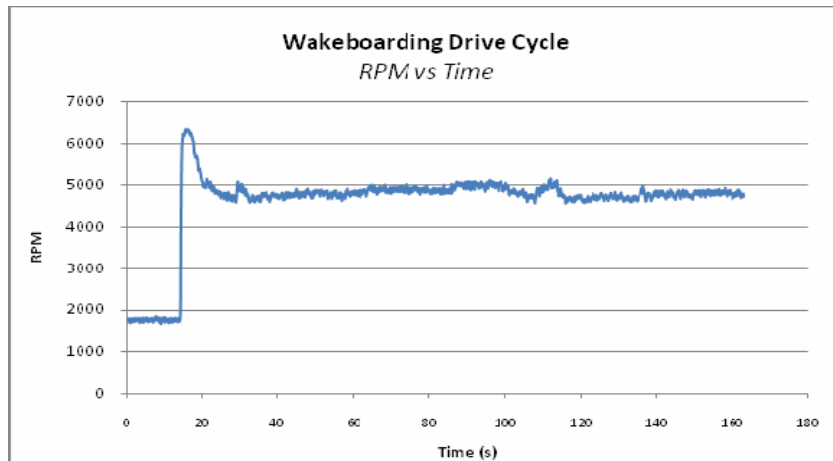


Figure 7 - Wakeboarding Drive Cycle, RPM vs. Time

Using on-water tests as a reference, the drive cycle in 8 was developed. Again, it was assumed that to meet the minimum standard of PWC performance for tubing, on average each rider should be able to take four of these 3.75 minute runs for a total riding time of 45 minutes before recharge.

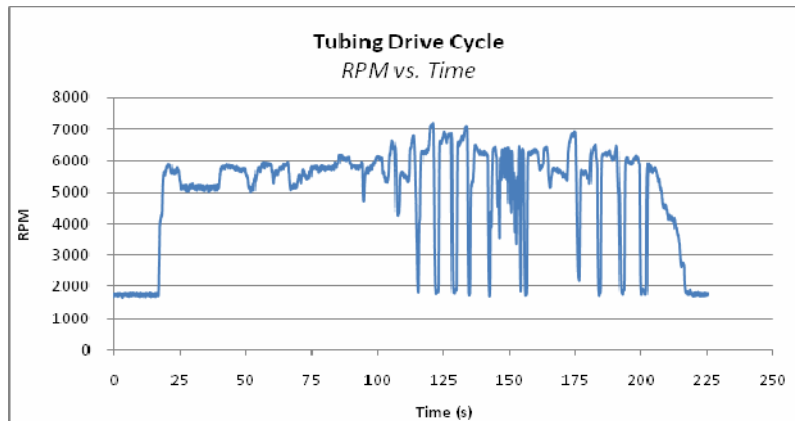


Figure 8 - Tubing Drive Cycle, RPM vs. Time

DRIVETRAIN MODELS

Twenty one electric PWC drivetrain models were developed in a MATLABSimulink® environment. Some used lower cost series wound motors and others used much more technologically advanced permanent magnet motors. The battery packs used in all drivetrains are assumed to have an energy density of 105Wh/kg and are capable of the required high discharge rates by the drive cycles. To be able to compare performance criteria the vehicle’s electrical components cannot weigh more than 125kg; the weight of the gas engine and fuel tank. The battery pack’s size is therefore limited by this weight restriction. Table 1 summarizes the specifications of the most viable MATLABSimulink® models developed.

The drivetrain constitutes of the name of the motor used and the number of motors used. The motors used are:

1. Briggs & Stratton ETEK (ETEK – X)
2. Perm PMG-132 (PMG –X)
3. Advanced DC 203-06-4001 (203 –X)
4. Advanced DC FB1-4001 (FB1 – X)

Table 1 – Summary of Selected MATLABSimulink® Models

Drivetrain Name	Motor Type	Power Density(kW/kg)	Drivetrain Weight (kg)	Power (kW)	Battery Weight (kg)	Battery energy (kWh)
ETEK – 2	PM	.63	19.02	11.98	105.98	11.13
ETEK – 4	PM	.63	38.12	24.02	86.88	9.12
ETEK – 6	PM	.63	57.81	36.42	67.19	7.05
ETEK – 7	PM	.63	66.71	42.03	58.29	6.12
ETEK – 8	PM	.63	76.28	48.06	48.72	5.12
PMG – 2	PM	.63	22.50	14.18	102.5	10.76
PMG – 3	PM	.63	33.75	21.26	91.25	9.58
PMG – 4	PM	.63	45.00	28.35	80.00	8.4
PMG – 5	PM	.63	56.20	35.41	68.80	7.22
PMG – 6	PM	.63	67.50	42.53	57.50	6.04
PMG – 7	PM	.63	78.75	49.61	46.25	4.86
203 – 1	Series	.33	48.55	16.02	76.45	8.03
203 – 2	Series	.33	97.10	32.04	27.90	2.93
203 – 3	Series	.33	145.65	48.06	OVERCAPACITY	
203 – 4	Series	.33	194.20	64.09		
FB1 – 1	Series	.35	64.90	22.72	60.10	6.31
FB1 – 2	Series	.35	129.80	45.43	OVERCAPACITY	
FB1 – 3	Series	.35	194.70	68.14		

Performance Targets

Using the previously defined drive cycles the MATLABSimulink® drivetrain models and the original PWC vehicle were compared to the minimum standard for PWC performance for both tubing and wakeboarding. Results evaluated by using two criteria:

1. The drivetrain's capability of achieving the performance of one tubing or wakeboarding cycle.
 - a. Pass = 100% of power requirements are achieved
 - b. Satisfactory = 90 - 100 % of power requirements achieved
 - c. Cond Pass = 50 – 90 % of power requirements achieved
 - d. Fail = Less than 50% of power requirements achieved
2. The PWC must be able to complete 35 minutes of wakeboarding or 45 minutes of tubing on one charge as prescribed by either drive cycles.

Thus, in order to have a valid drivetrain it must first pass step 1 and complete step 2 completely.

RESULTS

After evaluating all of the drivetrain models, according to the performance targets prescribed above, the results are tabulated in Table 2.

Table 2 – Configuration Results

	Tubing Run Time (min)	Drive Cycle Completion (%)	Tubing Power P/F	Wake Run Time (min)	Drive Cycle Completion (%)	Wake Power P/F
Gas	195.00	433.33	Pass	241	557.14	Pass
ETEK – 7	8.26	18.35	Cond-Pass	11.54	32.97	Pass
ETEK – 8	6.30	14.01	Satisfactory	8.83	25.22	Pass
PMG – 6	7.91	17.58	Satisfactory	11.46	32.75	Pass
PMG – 7	5.84	12.99	Pass	8.51	24.31	Pass
203 – 3	2.45	5.44	Cond-Pass	3.29	9.42	Satisfactory
203 – 4	OVERCAPACITY		Satisfactory	OVERCAPACITY		Pass
FBI – 2			Pass			Pass
FBI – 3			Satisfactory			Pass

DISCUSSION

Pure-Electric- Power

As seen in Table 2 there was only one motor configuration that completed both drive cycle power demands, all the while being light enough to incorporate the motors, motor drive, and batteries within a 125kg package. This configuration was the seven PMG-132 configuration. This configuration was viable because of the pancake style permanent magnet motor's have incredible power to weight densities of .63 kW/kg. Both series wound DC motors have power densities of .33 kW/kg and .35 kW/kg for the ADC203-06-4001 and ADCFBI-4001, respectively. Even though series wound motors pack more power in a single motor, their lower power density makes it impossible to develop a drive system with enough power while weighing less than 125kg.

Even using motors with some of the highest power densities available it would still be impossible to offset the low power density of batteries. Adding some of the most advanced battery cells currently available, the PWC could still only perform 34% of the 35 minute wakeboarding drive cycle and 13% of the 45 minute tubing drive cycle. The low energy density of batteries (105wh/kg) makes it impossible to develop a small electric watercraft with similar performance characteristics and range as the gasoline powered PWC. Until battery energy densities reach a minimum of 1kWh/kg it will be extremely difficult to implement electric vehicle technologies into personal watercrafts. Even at 1kWh/kg, it is expected that the vehicle will only have 25% of the gasoline range, but at least it will be able to complete both drive cycles.

Advances in both motor power and battery density are needed to use electric components to make electric personal watercrafts. Both power densities need to increase substantially to compete with the incredible power density of internal combustion engines (1.22kW/kg for a Rotax 4-tec 130hp) as well as the energy density of fuel (12.7kWh/kg).

Series Hybrid

McGill University has already implemented plug-in series hybrid technology in two vehicles; an SAE Formula car, and a snowmobile. A series hybrid has two main advantages. First, the vehicle is able to run in all-electric mode and therefore has no direct emissions. Second, the gas engine is usually optimized to run at its most efficient engine speed. In a series hybrid, this mechanical energy is converted to electrical energy and is later converted back to mechanical energy. The losses incurred by converting the engine's energy into these various forms can in some applications overshadow the increased efficiency of the gas engine. It is believed that in the case of the PWC a transmission, possibly a continuously varying one, would be a better way to narrow the gas engines RPM band, thereby increasing its efficiency. In this application, it is believed that in most cases it would be more beneficial to use the engine's mechanical power to drive the impeller directly or in parallel with electric motors, than in a series configuration.

Parallel Hybrid

Made very popular by vehicles like the Honda Insight, Civic and Accord hybrids, this system comprises of both an electric and internal combustion engine driving the driveshaft. The main drawback is that it is impossible to run in all-electric mode. In a parallel hybrid PWC, both the motor and the ICE would drive the impeller at the same time. This therefore reduces size of the required ICE. In a vehicle that has no weight restrictions this can be a very efficient way of reducing emissions and fuel consumption. Unfortunately in personal watercrafts by adding electric components, the weight of the vehicle will increase. As shown previously this would increase the required power to achieve a given velocity.

If it was possible to run on all electric at low speeds, this could be a potential solution. Because this system cannot do this, it would potentially be more advantageous if a parallel/series hybrid was used.

Parallel/Series

In a parallel/series PWC the main benefits would be the ability for the vehicle to run on all electric at low vehicular speeds. By doing so the electrical components would be very small and light. One or two PMG-132 could suffice. At higher velocities a regular gasoline engine would run the watercraft. To recharge the batteries, a small amount of energy from the gasoline engine, would be used to generate electricity. Out of all three hybrid solutions this seems like the most viable one. Unfortunately, no modeling has been completed and so it is impossible to further comment at this time.

CONCLUSION

1. The performance characteristics of a personal watercraft are easily found using on-water testing and easily modeled using Matlab Simulink ®.
2. Even a low power personal watercraft was found to consume more fuel than the average helicopter or the RMS Queen Elizabeth Cruise ship. It was also confirmed that a planing vehicle is nearly 3.5 times more efficient than a non-planing vehicle.
3. Personal watercrafts require a tremendous power to operate at required performance levels. Very few electric motor configurations were able to accomplish all of the performance targets. Many of the configurations that developed enough power were deemed too heavy. For those not deemed to be overcapacity, the range of the vehicle was minute in comparison to the gas-powered PWC.
4. Of the motors examined, the Perm PMG-132 had the largest power density in both mass and volumetric terms. Its power density allowed the development of a very powerful system in a very light package. Unfortunately, it still had a very limited range.
5. Even with some of the most advanced batteries available, with an energy density that is 120 times smaller than gasoline's energy density, it's nearly impossible to package an electric energy source small and light enough to power a PWC for any considerable range.
6. Advances in both battery and motor technologies are needed for this project to become viable.
7. A parallel/series hybrid PWC has some potential, but no explicit modeling has been carried out. Thus McGill University is unable to further comment on its viability at this time.

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