Designing a Hybrid Electric Scooter

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ABSTRACT

The development of a hybrid vehicle, especially a hybrid electric scooter consisting of an internal combustion (IC) engine, electric motor and batteries, is dependant upon a fine balance between developed power, power ratios of the IC engine and electric drive and the weight of those units and the batteries within the scooter. This paper describes the development of an equivalent 250cc performance scooter using a 50cc IC engine, 7.5kW max. brushless DC motor and drive and a minimum number of sealed lead-acid batteries.

1. INTRODUCTION

A number of manufacturers are at present, or have in recent times, developed hybrid electric scooters. Honda has worked on a hybrid scooter prototype which utilises a 50cc IC engine and is about 10kg heavier than a standard 50cc scooter[1]. It operates in series and parallel mode and stores energy in lightweight nickel hydrogen batteries. It produces a 1.6 times fuel economy[1] and 37% less carbon dioxide emission compared to a conventional 50cc scooter. Also the scooter stops engine operation in idle mode. Vetrix Corp.[2] have developed a hybrid methanol fuel cell-electric scooter with a performance similar to a 250cc motorcycle. It has 100km range and 100kph maximum speed. Honda also has been researching fuel cell scooters and unveiled a further three "green concept scooters" – fuel cell, gas-electric hybrid and all electric[3,4].

The development of a hybrid electric scooter at QUT has been pursued over a number of years with the aid of final year project students. The objective was to test the premise that a hybrid scooter with a 50cc internal combustion (IC) engine can, with the aid of a brushless DC motor and drive system of the correct size, perform like a 250cc motorcycle.

An Aprilia SR50 scooter[5] with Ditech two-stroke fuel injected engine was chosen as the base for the experimentation. This 50cc scooter with engine management system maximises engine efficiency and minimise exhaust gasses.

A Zytec[6] electric brushless DC motor drive system (E-Kart Drivechain) is used to develop additional torque at the rear wheel during acceleration and hill climbing. Because this power is only used for short periods the full peak power of the drive can be utilised. Whereas the peak power developed by the IC engine is in the range 3.7kW, the power needed from the electric drive system for short periods is 7.5kW to obtain near to 250cc motorcycle performance.

A Honda CD250 motorcycle was purchased to test the torque and power developed by a conventional 250cc motorcycle. Tests have also been conducted to determine fuel usage in city traffic. The peak power developed by this 250cc motorcycle was 12kW.

Modifications have also been carried out to the rear swing arm of the test scooter to accommodate a larger 650mm diameter BMW motorcycle rear wheel. This was implemented to achieve a higher top road speed without changing the operation of the CVT nor engine management system and to also give the scooter a different appearance.

2. APRILIA SR50 SCOOTER

The Aprilia SR50 scooter (figure 1) specifications are shown in table 1. The 2-stroke fuel injection engine operates, with the aid of an "automatic continuous variator" ("constant velocity transmission" CVT), under an engine management system (ECU[2]) to optimise the performance of the scooter. The CVT is housed in the enclosed rear wheel swing arm. The engine rpm, as a result of this control, remain within a narrow band of approximately 5000rpm to 8000rpm to maintain high efficiency and minimise exhaust gas emissions.

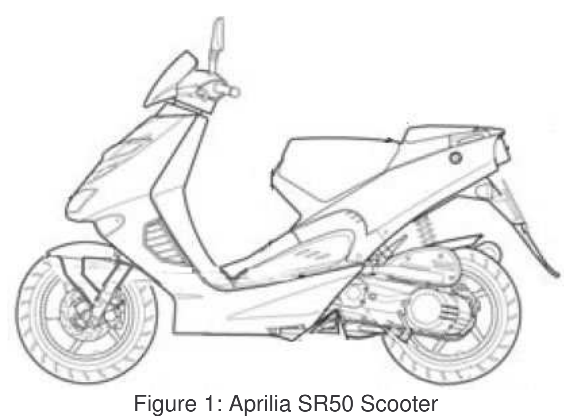


Figure 1: Aprilia SR50 Scooter

The Aprilia was tested on a dynamometer and test results are shown in figures 2, 3 and 4. Figure 2 and 3 show that the scooter accelerated up to 80kph and maintained an approximately constant power of 3.7kW output up to 70kph or an engine speed of 8000rpm. In reality, due to

[1] Riding on flat ground at 30kph

[2] Electronic Control Unit

windage and friction losses the scooter could not reach 80kph on the open road. Constant power curves are illustrated by dotted lines in figures 2 and 3. It can be seen in figure 3 that the rear wheel torque starts decaying around 70kph at the point that the engine management control is unable to maintain the constant engine power output.

Max. length	1775 mm
Max. width	720 mm
Wheelbase	1265 mm
Weight	106 kg
Engine Type	Two-stroke
Number of cylinders	Horizontal single cylinder
Total capacity	49.38 cm^3
Engine idle rpm	2000 ± 50 rpm
Clutch	Dry automatic centrifugal
Gear	Automatic continuous variator[3]
Cooling	Liquid
Control - Type	Electronic Injection via ECU
City petrol usage	50 km/litre[4]

Table 1: Aprilia SR50 Scooter Specifications

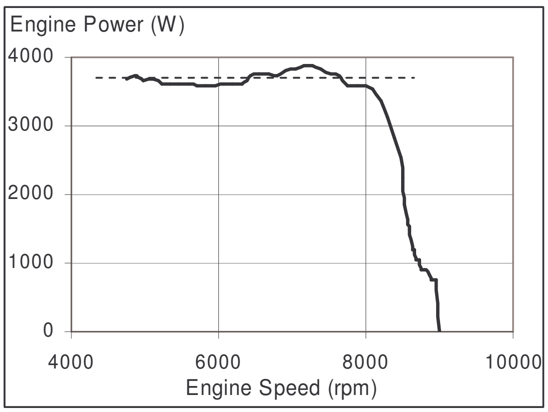


Figure 2: Aprilia power versus engine speed

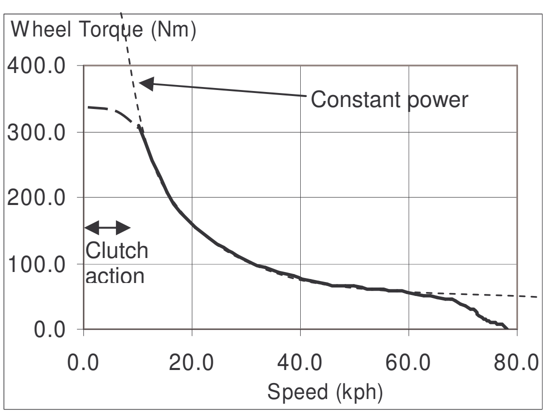


Figure 3: Aprilia Road Torque-Speed Curve

As indicated in figure 3, due to the centrifugal clutch action the torque developed at the rear wheel does not exceed 350Nm when accelerating from standstill to about 10kph.

[3] Constant Velocity Transmission (CVT)

[4] A Motor Week road test gave 40km/litre

Another important fact to note is that while driving in city traffic the petrol consumption allows 50km to be travelled on each litre of petrol.

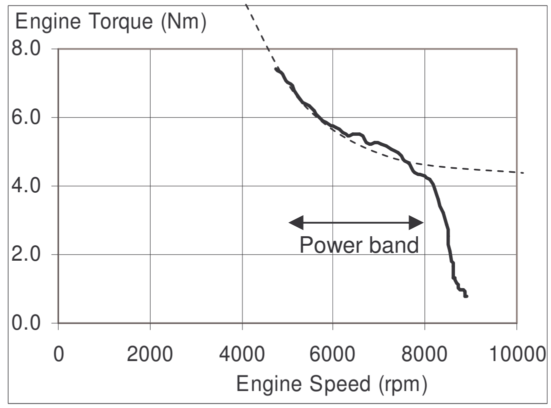


Figure 4: Aprilia Engine Torque-Speed Curve

3. Honda CD250 Motorcycle

Table 2 lists the technical characteristics of the Honda CD250 motorcycle (figure 5) which was used as the comparison vehicle.

Max. length	1950 mm
Wheelbase	1350 mm
Weight	159 kg
Engine Type	Four-stroke OHC
Number of cylinders	Vertical Twin
Total capacity	249 cm^3
Output Power	12 kW
City petrol usage	29 km/litre

Table 2: Honda CD250 Motorcycle Specifications

Figure 5: Honda CD250 Motorcycle

The dynamometer tests carried out on this vehicle are shown in figures 6 and 7 and illustrate that the maximum power developed was 12kW between 7000rpm and nearly 9000rpm. Figure 7 shows the torque developed at the rear wheel in each of the 5 gears and although theoretically the motorcycle can reach about 130kph this author has found that 100kph is a more realistic value when windage and friction of road travel is taken into account. At these speeds engine vibration is very apparent.

In road tests it has also been found that the average petrol usage is 29 kilometres per litre of petrol for city driving – 58% of the unmodified Aprilia scooter.

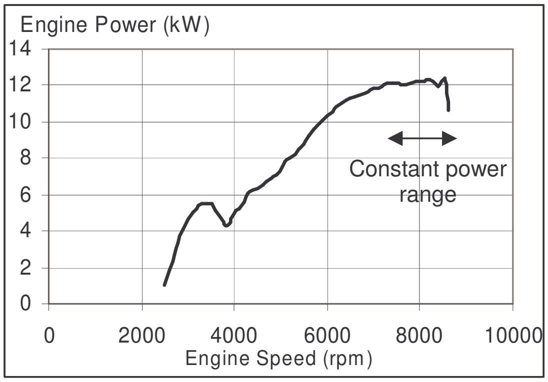


Figure 6: Honda CD250 power versus speed

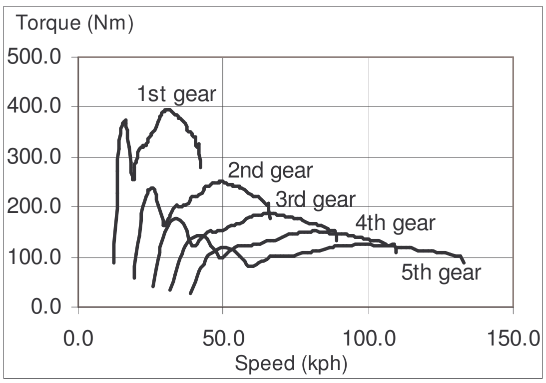


Figure 7: Honda Road Torque-Speed Curves

4. Brushless DC Motor Drive

The specifications for the Zytek brushless DC motor and drive system are shown in table 3.

Type	E-Kart Drivetrain
Rated DC link voltage	60 V
Max. DC link voltage	80 V
Cont. output power	6 kW
Peak output power	7.5 kW for short periods
Mass	7 kg Controller 11kg Motor
Max. speed	15 000 rpm
Max. torque cont.	8 Nm (~10 Nm peak)

Table 3: Zytek BDC Drive Specifications

Figure 8 shows the position of the electric motor with reference to the new large 650mm diameter rear wheel. Although not present on the existing scooter, an electric clutch will be mounted on the brushless DC motor shaft.

5. Hybrid Electric Scooter

Figure 8 illustrates the new rear wheel arrangement which incorporates a parallel connected hybrid electric system. This drivetrain, except for the centrifugal clutch, essentially mirrors that of the Toyota ES^3 concept vehicle[7]. Three clutches are used to accommodate the different power flow regimes for various operating conditions. Due to mechanical considerations – mainly the retention of the CVT - the original step down gear box mounted behind the centrifugal clutch has been removed and replaced by a chain gear system. The three clutches are (a) the centrifugal clutch C1 at the rear of the CVT, the electric clutch C2 on the brushless DC motor shaft and the electric clutch C3 on the shaft of the rear wheel.

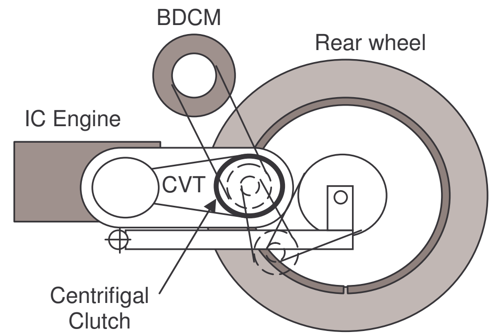


Figure 8: New sprocket and chain gearing arrangement

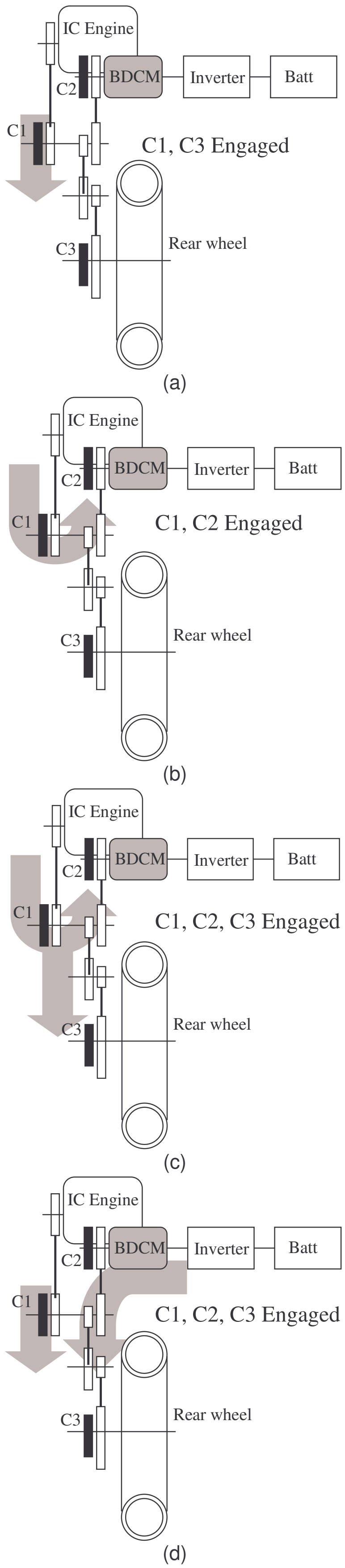
Figure 9 demonstrates how power flow varies for different operating modes. Switching the IC engine off during standstill however, may be difficult under this scheme due to restarting issues. A takeoff from the throttle position control of the IC engine management system is used to control the operation of the electric drive. Completion of the full management system is outstanding and at present and BDCM and rear wheel clutches are not installed so a very simple control strategy is implemented.

At present rear wheel torque-speed road tests on the Honda CD250 have not been completed and typical acceleration and braking profiles for city travel are unknown. However, Miller[7] reports of a five passenger car tested over 23 minutes of city driving. The hybrid car reached a peak acceleration power of 35kW and peak kinetic regeneration power of -20kW (regen. braking). The average driving power from the inverter was 11kW and average regenerated kinetic power over the 23 minute period was -1kW. The distribution of power spikes for traction generally fall in the 5kW to 15kW band while the peak power regeneration spikes fall in the -5kW to -10kW range. Determining these latter ratios while considering the power and torque characteristics of the Honda CD250 motorcycle, it is possible to determine probable driving characteristics for the hybrid scooter.

	Passenger Car	Percent	Hybrid Scooter
Peak +P	35kW	100%	12kW
Mean +P	11kW	31.4%	3.8kW
Peak –P	-20kW	57.1%	6.9kW
Mean –P	-1kW	2.9%	0.3kW

Table 4: Expected hybrid scooter traction and regenerative powers

It should be remembered though that additional power will be available to charge the batteries of the hybrid electric scooter whenever the IC engine is unloaded (scooter stationary) or underloaded (scooter driving along level road at low to medium speed).



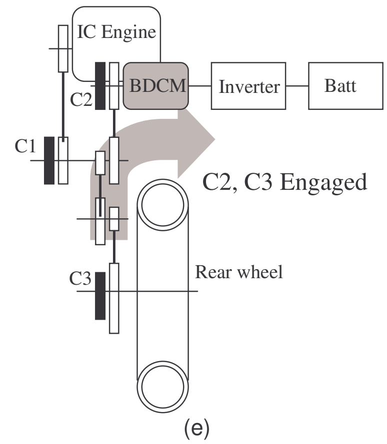


Figure 9: Hybrid scooter operating modes.
(a) Battery fully charged – constant speed on level
(b) Stationary – battery charging
(c) Battery charging – constant speed on level
(d) Acceleration or hill climbing
(e) Regenerative braking

The electric fraction EF for the hybrid scooter is given by:

$$EF = \frac{P_E}{P_E + P_{IC}} = \frac{7500}{7500 + 3700} \equiv 67\% \qquad (1)$$

This compares to 39% for the Toyota Prius[7] and 18% for the Honda Insight[8] hybrid cars showing that the scooter will rely much more heavily on the electric system and batteries for peak power support. Because of the small EF the Toyota Prius and Honda Insight they are referred to as "medium hybrid" vehicles.

5.1 Batteries

Hodkinson and Fenton[9] suggest that improved lead acid batteries will be used for short to medium term applications while Nickel-Metal Hydride and Lithium-Ion will be used in the medium term. Long term solutions are Lithium-Ion (polymeric electrolyte) and fuel cells.

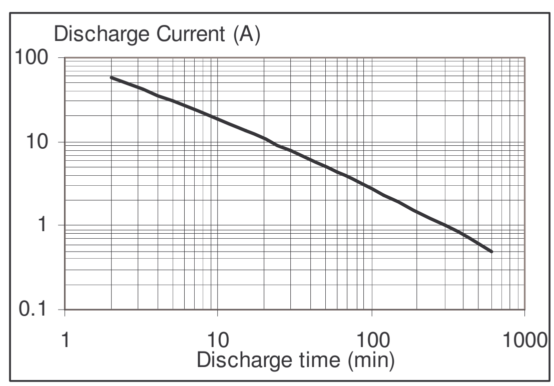


Figure 10: 6V Cyclon monobloc battery discharge current versus discharge time

With cost being a major factor in this work it was decided to use Cyclon sealed lead acid batteries from Hawker which utilise lead-tin electrodes and an absorbed glass mat electrolyte. The thin plate technology used means a high utilisation factor of the active plate material and low internal impedance. The batteries can thus discharge at very high currents and also be recharged very fast. Figure 10 shows the specified discharge rates for a 6V, 5Ahr

Cyclon monobloc battery[10,11]. As can be seen currents of up to 58A can be drawn from this battery for up to 2 minutes without damage. By extrapolation around 100A can be drawn for 1 minute[5]. This compares well with the peak current of the brushless DC drive system which can support up to 7.5kW. At this power and with a 60V link voltage the DC battery current required by the electric drive is:

$$I_{drive} = \frac{P_{peak}}{V_{link}} = \frac{7500}{60} = 125A \qquad (2)$$

It is required that ten 6V-5Ahr batteries are connected in series to achieve the required 60V nominal link voltage. The batteries are mounted in an open case under the foot panels of the scooter and connections sealed against the ingress of moisture.

5.2 HYBRID DEVELOPMENT VEHICLE

Using the performance characteristics of the Aprilia scooter modified to suit the new wheel diameter and adding the torque capability of the brushless DC drive system to it, the overall performance expected from the hybrid electric scooter can be determined. Table 5 lists the hybrid basic specifications and figure 11 compares the prospective hybrid scooter characteristics with those obtained from the Honda CD250 motorcycle.

Max. length	1930 mm
Max. width	800 mm
Wheelbase	1400 mm
Weight	145 kg
IC Engine Type	Two-stroke Dytech
Total capacity	49.38 cm^3
Engine idle rpm	2000 ± 50 rpm
Maximum power	
Electric Drive	Zytek E-Kart Drivetrain
Peak power	7.5 kW
Peak Torque	10 Nm
Batteries	Cyclon from Hawker
Technology	Sealed Lead-Tin
Type	6V-X Monobloc 5Ahr
Nominal link voltage	60V
Total weight	10 x 0.98 kg = 9.8 kg

Table 5: Hybrid Scooter Specifications

As can be seen by the results of figure 11, the "short period" prospective torque speed curve of the hybrid-electric scooter closely matches the characteristics of a 250cc motorcycle in its higher speed region. However, the hybrid scooter torque (line C) is about 100Nm lower that the 250cc test motorcycle at low speeds. If the hybrid power curve of figure 12 is considered it can be seen that at low speeds the power output from the 250cc test motorcycle is up to twice as much as that developed by the hybrid scooter. This is due to the characteristics of the electric drive as shown in figure 6 and the drivetrain configuration which has the electric motor connected to the load side of the CVT (as per the Toyota ES^3 concept vehicle).

[5] It is presently unknown whether the battery can support this current for long periods of time.

At present clutches C2 and C3 have not been installed and both the electric drive and the rear wheel are directly coupled, via sprockets and chains, to the centrifugal clutch. This does mean that at this stage of the development only very simple control features are possible and the electric drive reference is taken directly from the IC engine carburettor throttle position feedback. Road tests have not been carried out and the power flow predictions (drive and regen) of Table 4 can not be verified.

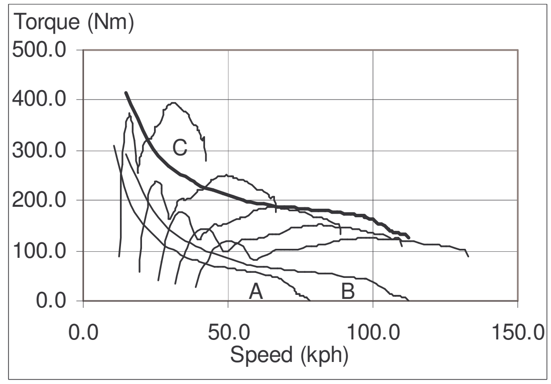


Figure 11: Prospective torque-speed characteristics at rear wheel of hybrid scooter.
A = original Aprilia scooter,
B = Aprilia scooter IC engine only with 650mm diameter rear wheel,
C = complete hybrid-electric scooter,
All other curves are for the Honda CD250.

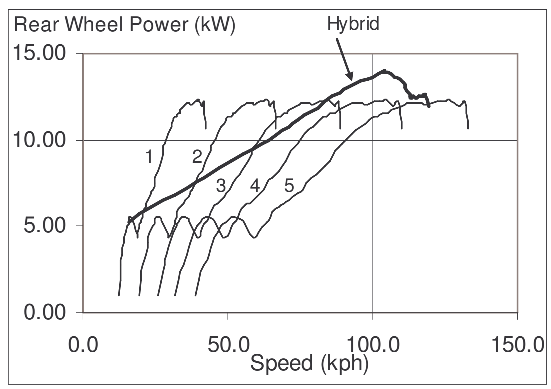


Figure 12: Total output power at rear wheel

The hybrid electric scooter has been ridden for short distances but problems were encountered with the set up of the Zytek E-Kart drive unit which is no longer supported by the company. Further work is needed in this area.

Figure 13 shows the hybrid scooter in its final form. A larger rear wheel can be seen mounted to the new swing arm which has been attached to the original CVT swing arm. The new swing arm supports the rear wheel on both sides of the scooter but the single rear suspension unit is retained. The electric motor can be seen to be mounted above and forward of the rear wheel and the battery case under the driver foot platform. A larger rear brake disk has also been installed on the 650mm diameter wheel.

(a)

(b)

Figure 13: Hybrid-electric scooter

6 CONCLUSION

Although the hybrid scooter is not finalised a number of design features and tests have been completed. Dynamometer tests were performed on the unmodified Aprilia SR50 scooter and its driving characteristics compared with the dynamometer test results from a 250cc motorcycle (Honda CD250). The original Aprilia scooter weighed 106kg while the Honda 250cc test vehicle weighed 159kg. The hybrid electric scooter weighs 145kg – 9% less than the 250cc motorcycle.

As a result of the CVT on the Aprilia scooter a constant power of 3.7kW could be achieved over a wide road speed range. However, the torque capability of the original scooter is limited especially at higher speeds (50Nm @ 70kph). The 250cc test motorcycle, although not able to maintain a constant high power output over a wide speed range, can via gear changing achieve very high starting torques (400Nm @ 35kph).

The rear wheel diameter of the Aprilia scooter was increased (650mm) to give a higher speed range (110kph compared to 80kph) without having to adjust the IC engine management system or the CVT. A 7.5kW peak brushless DC motor and drive has been added to the drivetrain and will act as both a drive and battery charger. The calculated hybrid scooter characteristics indicate that the scooter is not able to reach the same low speed torque capability (250Nm compared to 400Nm @ 35kph) as the 250cc test motor but can produce higher torque in the upper speed range (160Nm compared to 130Nm @ 100kph). Line C is dependant on the sprocket ratio between the BDCM and the centrifugal clutch and can be changed. This means that acceleration from standstill may be compromised but higher speeds can be maintained against strong winds or uphill travel.

The rear wheel and BDCM clutches are not installed and thus only very simple control of the hybrid scooter can be achieved. The scooter has been ridden but difficulties in setting up the electric drive system have limited the success of these tests.

From results obtained so far it can be seen that serious consideration must be given to interconnecting the electric drive directly to the crankshaft of the IC engine. This would mean that both the IC engine and electric drive would together provide torque to the rear wheel via the constant velocity transmission (CVT) and thus both the IC engine and electric drive could be operated in their maximum power region over a large speed range.

7 ACKNOWLEDGEMENTS

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