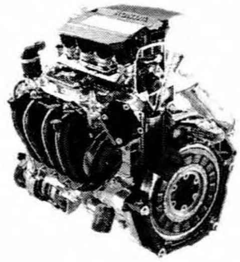
DO HYBRID ELECTRIC VEHICLES REALLY WORK?



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ABSTRACT

Most articles about hybrid vehicles concentrate on the benefits, this paper introduces the limitations of hybrid vehicles. These include effects on the vehicle electrical system, extra vehicle weight and the requirement for battery monitoring. To achieve this, the paper briefly describes how a hybrid vehicle functions and then examines the output of a hybrid vehicle software simulator (ADVISOR 2002). A comparison of hybrids against standard cars is also made. Suggestions for future research is also made.

Index Terms— Hybrid Vehicles, Batteries, SOC, SOH, Drive Cycle, ECE15, EUDC, Hybrids vs. Diesels.

1.INTRODUCTION

The reduction and cleaning up of vehicle emission has been ongoing for many years, partly driven by increasingly stringent environmental legislation. Engineers have been steadily improving vehicle emissions by introducing technologies such as fuel injection to improve engine efficiency and catalytic converters to remove unwanted gases. A new technology is currently being introduced to further reduce emissions. This new technology is called «Hybrid Electric» This paper examines how «Hybrid Electric» technology could be used to reduce emissions further. Potential problems with introducing hybrid technology are also discussed. The methods by which emissions can be reduced are first discussed. Then the performance of a hybrid electric vehicle is discussed via a software simulation and finally a comparison with other vehicles on the market is made to highlight the benefits for vehicle buyers and users.

2.METHODS TO REDUCE EMISSIONS

Vehicle manufacturers have been set ever more demanding vehicle emission legislation to help reduce global emissions of CO_2. Hybrid Electric is one of the new technologies that can help to lower emissions. Emissions are caused by the burning of fuels to release energy. Therefore energy usage must be reduced; this can be achieved in a vehicle by the following methods:

- Reduce weight
- Improve engine efficiency
- Reduce energy losses

Each of these methods will now be discussed further in the sections below.

3. WEIGHT REDUCTION

Basic physics shows that the kinetic energy of a body is related to it's mass (essentially it's weight). The following equations shows this relationship.

$$E = \tfrac{1}{2} \cdot m \cdot v^2$$

Where E = kinetic energy, m = mass, v = velocity

Therefore reducing the weight of the vehicle will reduce the energy required to move the vehicle and thus reduce emissions.

Hybrids have two propulsion systems the Internal Combustion Engine (ICE) and the electric motor. The extra propulsion system will add weight to the vehicle. The additional components that are required are an electric motor / generator, a battery or storage device, control electronics and thermal management systems for the battery, motor and power electronics.

Therefore some of the gains from the hybrid technology are lost through increased weight. However as hybrids have two methods of propulsion the ICE could be downsized (made smaller) to save weight and hence compensate for the weight of the additional components.

3.1. Electromechanical Systems

A trend in the automotive design is to replace mechanical systems with electric / electromechanical systems. Table I shows examples of these electromechanical systems. These systems can improve comfort, reliability and efficiency.

Ideally a hybrid vehicle could be able to move with the engine turned off, however some systems such as power steering, brakes and air conditioning are currently powered directly by the engine. The simplest method to solve this problem is to add an electric motor to drive these components, however this adds weight. The best solution is to continue the trend and replace the system with an electrically powered electromechanical version; this would allow the system to function when the engine is turned off.

Mechanical System	Equivalent Electromechanical System
Belt driven cooling fan	Electric Fan
Wind up Windows	Electric Windows
Manual Seat Adjust	Electric Seats
Carburettor	Fuel Injection
Hydraulic Power Steering	Electric Power Steering
Heating	Electric Heating
Hydraulic brakes	Electric brakes
Belt driven cam shaft valves	Electric value actuation

Table 1. Mechanichal & Electromechanical Systems

4. IMPROVE ENGINE EFFICIENCY

The ICE is used to convert chemical energy of fuel into kinetic energy to move the vehicle. Improving engine efficiency is improving the amount of energy that is usefully converted into motion.

In slow moving traffic an engine remains at idle for long periods thus producing unwanted emissions and wasting fuel. If the engine on a hybrid is idling, the engine could be doing useful work to recharge the battery. A hybrid also enables the engine to be switched off when the battery is fully charged.

If the vehicle is moving at low speed, there may be sufficient power from the battery to drive the electric motor and move the vehicle. Thus removing the need to start the ICE.

As mentioned before hybrids allows the ICE to be downsized, this not only saves weight - the efficiency of the engine is also improved (e.g. a smaller engine which is working harder is more efficient than a larger engine). The electric motor is used to 'top up' the power from the engine. This topping up of ICE power has a limitation, it will only work when there is sufficient electrical energy in the battery.

If the battery on a hybrid vehicle becomes discharged, this 'top up' feature is no longer available. The vehicle is only powered by the ICE (which has been downsized) which results in lower levels of performance. Manufacturers sometimes quote vehicle power as a sum of maximum ICE power and electric motor power give a total power output. This extra power is also used in acceleration. This should be taken on the condition that this power is not always available. Think about the effect on vehicle response. For example what would happen if the battery be discharged during an overtaking manoeuvre? A dangerous situation could occur as well as driver dissatisfaction. The driver will be less confident with the vehicle due to power uncertainty. A method to remove/ minimize this characteristic is required. One option is to not downsize the engine. The electric motor would replace a fraction of the engine power, not supplement it (So not increasing total output power). However, this limits the benefits possible.

Table 1. Mechanichal & Electromechanical Systems

The summing of ICE and electric motor power should only be used if it is possible to maintain the battery charge so that there is always sufficient energy for an overtaking manoeuvre. However guaranteeing the availability of power and energy form a battery is not an easy task.

5.REDUCE ENERGY LOSSES

As the vehicle moves it will lose energy is through factors such as aerodynamic drag, rolling resistance and braking friction. Minimising these losses will reduce fuel consumption.

The brakes on a vehicle are where a large amount of energy is lost, as kinetic energy is converted into heat energy and dissipated. This is where the hybrid vehicle can gain the most benefit. Hybrids use regenerative braking to convert the kinetic energy into electrical energy that can be stored in the battery. The electric traction motor on a hybrid has dual function as it can act as a generator to charge the battery or provide electrical power.

The weight of the vehicle becomes less important if regenerative braking is fitted. In an ideal world all the energy used to accelerate the vehicle could be recovered by the regenerative braking. Thus the weight of the vehicle would not be that important. Also the extra weight of the hybrid components is not too important.

However it is not an ideal world, regenerative braking is not 100% efficient because:

- It is not possible to capture all the energy
- It is not possible to store all the energy

5.1. Capture all the energy

Regenerative braking generates the most power when the motor/generator operates at fixed high speeds. However this is not characteristic of typical braking. Even at high speeds the energy conversion is not 100% efficient, so it is not possible to capture all the kinetic energy.

5.2. Store all the energy

The rate at which the battery can absorb energy is limited. The battery must convert electrical energy into chemical energy. It is also not 100% efficient, the faster the energy transfer the greater the losses. Charge acceptance of the battery is dependant on the physical construction. Generally the capability to accept charge is related to the capacity. With a larger battery having higher charge acceptance than a smaller one. However the larger the capacity, the greater the weight.

Also the battery has limited capacity, at some time the battery will become full and no longer be able to store recovered energy.

6.SIDE EFFECT OF REGENERATIVE BRAKING

As mentioned before, if the battery is fully discharged, no power boost is available from the electric motor. Regenerative braking is affected in the opposite battery state, as no regenerative braking is available when battery is fully charged. This could again have an effect on vehicle handling, but regenerative braking should not be used to improve braking performance. The regenerative braking should replace a percentage of the full braking force. e.g. the stopping power will be 40% from regenerative braking and 60% from friction brakes under normal conditions, but if the battery is full charged 100% of the braking force will be from the friction brakes. As the vehicle slows the speed of the generator will reduce thus reducing it's braking effect, therefore the retarding effect of the friction brake must be increased. The ratio of braking from regenerative braking and friction braking must be dynamically adjusted during deceleration to avoid peculiar braking characteristics. This adds another complexity to regenerative braking.

However it is possible to use regenerative braking to improve braking performance if extra components were added to the vehicle. In this case, the power from the motor/generator could be simply dissipated as heat when the battery is fully charged, this is known as dynamic braking and is used in many applications such as trains and conveyor belts. Once again this will increase complexity and weight.

7. IMPLICATIONS ON THE ELECTRICAL SYSTEM

Hybrid Electric technology totally changes the electrical system on a vehicle.

The traditional alternator (electrical generator on a standard vehicle) is no longer used and is replaced with an integrated motor / generator to power the electrical systems and as an alternative to the alternator. Electromechanical systems are required on hybrid vehicles, as the ICE is not run continually.

As discussed previously, electromechanical systems such as electric steering and brakes will need to be fitted to hybrid vehicles, and therefore the electrical supply becomes safety critical. If the electrical power fails, systems such as the brakes and steering also fail, so the integrity of the electrical system must be maintained.

When the motor/generator is acting as motor, no power is supplied to the vehicle electrical system.. The motor/generator becomes a consumer of electrical power, and the battery must supply power for all electrical systems.

This has implications on the battery, if the vehicle power supply voltage was to drop very low (brown-out), then vehicle systems could fail. Therefore the battery is also a safety critical component.

The electronics content of cars has been ever increasing due to electromechanical systems and more comfort features, thus increasing the total electrical load. This inevitably tends to make the problem worse, and the performance required from the battery will become more demanding.

8. IMPLICATIONS ON THE BATTERY

The previous section has explained that the battery must be capable of powering all the electrical system of the vehicle. In this case a fully charged battery would be ideal to ensure electrical integrity. However to maximize regenerative braking opportunities the battery should be as 'flat' (discharged) as possible. Regenerative braking helps to reduce emissions through energy recovery and this opportunity should not be lost, therefore a flat battery helps to improve emissions.

These two extreme states causes a contradiction, therefore to ensure the battery is equally capable of both power supply and power storage, it should be at half capacity, which is commonly expressed as 50% (or 0.5) State of Charge (SOC).

Maintaining the battery at 50% SOC is running the battery in Partial State of Charge (PSOC) operation. However running batteries in PSOC tends to shorten the life of the battery. For example, in a lead acid battery, sulphation occurs in PSOC operation resulting in degradation.

The battery is running in a highly compromised state, since a fully charged battery is good for power assist and long battery life but the opportunity to recover energy is lost, the vehicle manufacturer must choose the compromise lower emissions or more power assist and longer battery life. This concept will be ned as '*Energy Balance*' in this paper.

The algorithm that controls energy balance is one of the most important considerations in the hybrid vehicle. It must decide on the compromises between emissions, safety, reliability, and battery life.

In order to maintain this energy balance, the State of Charge (SOC) of the battery must be determined accurately. Also the capacity of a battery tends to decrease with age, this being expressed as State of Health (SOH). So the SOC and SOH are important parameters for operation of a hybrid vehicle. The SOC is also needed to avoid overcharging the battery.

However there is currently no proven and reliable method to accurately obtain SOC and SOH for Hybrid use [1]. Although many methods have been proposed. [2][3][4][5]

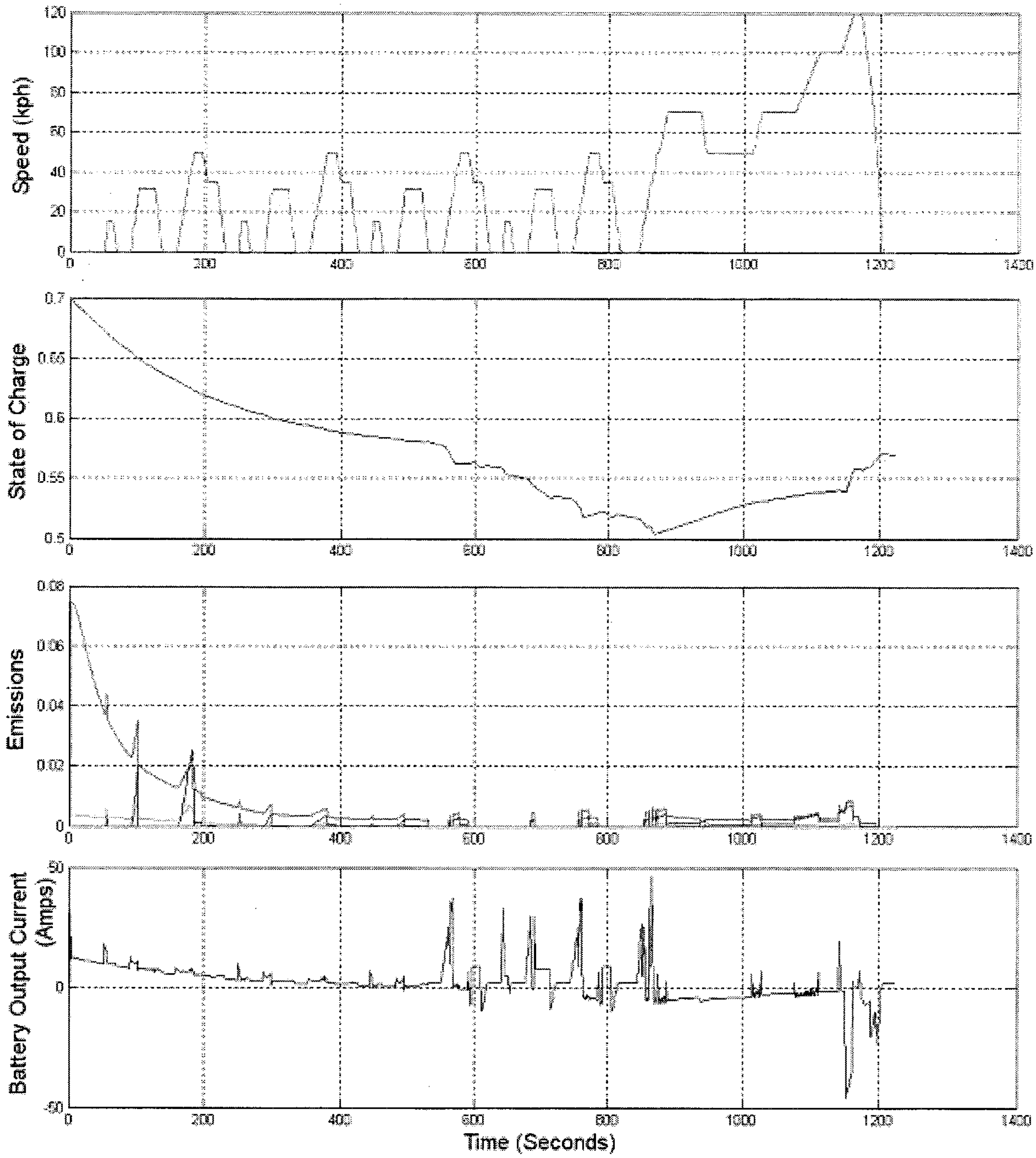

*Figure 1. **ADVISOR Simulation of a*** **Toyota Prius** ***in the ECE15 + EUDC drive cycle***

A partial solution to this problem is to use two batteries that are isolated but able to transfer energy between themselves. The second battery is maintained at full charge for emergency situations. However this leads to more weight and complexity and with the high electrical content on a modern vehicle this battery is unlikely to be small in size.

9. HYBRID DRIVE CYCLE PERFORMANCE

The last section has shown how the operation of a hybrid vehicle is a compromise. So how well do hybrids perform?

Official emission and fuel economy tests are performed using the standard driving cycles, such as the ECE15 + EUDC drive cycle. A drive cycle is a speed / time profile used for vehicle testing with the vehicle being driven on a rolling road (dynamometer) according to the drive cycle profile. The emissions and fuel economy are measured during the test and quoted against the drive cycle used. The ECE15 + EUDC test is conducted in two sections urban (city) for the first half and extra urban (highway) for the second half. The complete test gives the 'combined' result. Figure 1 shows the profile of the ECE15 + EUDC driving cycle and simulated responses of a vehicle to that cycle. The top graph with the y axis is labelled Speed shows the drive cycle. The first 800 seconds represents the city part of the drive cycle (ECE15). This consists of stops and starts with low speeds. The remaining part of the graph from 800 to 1400 seconds, shows the high speed highway part of the drive cycle (EUDC – Extra Urban Drive Cycle). The other three graphs show the simulation of the *Toyota Prius* (First Generation).

The simulation results were generated using the ADVISOR 2002 Advanced Vehicle Simulator which runs under *MATLAB / Simulink*. ADVISOR allows vehicle parameters and subsystems to be changed and the performance on various drive cycles to be simulated. The simulations shown are based on an unmodified *Toyota Prius*.

Returning to figure I, the second graph with the y axis labelled 'State of Charge' shows the simulated SOC of the battery over the duration of the drive cycle. The third graph with the y axis labelled 'Emissions' shows the simulated emissions for the vehicle over the drive cycle. This paper will not go into a detail detailed description of each type of emissions, but the assumption can be however made that lower emissions are better for this plot. The fourth graph with the y axis labelled «Battery Output Current» shows the simulated output current of the vehicle battery. A negative current shows current flowing into the battery (charging). The State of Charge graph shows the energy balance for this drive cycle runs the battery between 70% and 50% SOC. Notice how the battery energy is gradually depleted during the city part of the drive cycle. This is where a standard vehicle is least efficient and produces the most emissions. The emissions are highest just after start up in a hybrid (as the hybrid still uses a ICE). However using the battery will avoid loading the ICE when it is cold and least efficient, and hence helps reduce emissions. To demonstrate this, the ADVISOR simulator was modified so that no electric motor assist was used and the generator was used to recharge the battery unit it was fully charged after 200 seconds.

The result was a 30% increase in fuel consumption and 24% increase in CO_2 emissions over the drive cycle. Therefore if the battery is heavily discharged at start up, the hybrid vehicle will perform in a similar way to the simulation above. This situation could occur through self discharge of the battery. A NiMH battery as used by the *Prius*, can self discharge from 100% to 70% SOC in 30 days if the battery is at 20°C. But if the ambient temperature is 45°C (which can be easily achieved in warmer climates) the SOC can discharge to 20% SOC in 30 days [3]. This self discharge is fairly linear, so if the battery is at 50% SOC and parked for two weeks the battery will become fully discharged. If this battery is required to start the ICE, it will not be able to do so at this point.

Returning to Figure 1, examination of the drive cycle between 600 to 800 seconds shows the vehicle reaches near zero emissions. The Battery Output Current graph shows high activity at this time. Up to 40 amps of current is being used to move the vehicle. Also regenerative braking is in effect as the negative trace shows current flowing into the battery. This is an example of how energy balance is used to reduce emissions.

However this reduction in emissions is not 'free', since the State of Charge graph shows SOC is dropping rapidly, and cannot be sustained for long. However the drive cycle switches to highway driving, thus allowing the battery to be recharged. Using the flat battery simulation discussed earlier it could be assumed that if the city driving is extended, the emissions would also increase. This raises the question, has the hybrid vehicle been designed for this drive cycle or real world driving where the city driving could last for longer than 800 second (13 minutes)? Also if a journey started and ended in a city, when would the battery be recharged? The drive cycle finishes with the vehicle slowing down from 120 kph. Here the full effect of regenerative braking can be seen from the Battery Output Current Graph (just before 1200 seconds), Almost 50 amps of current is driven into the battery. This illustrates what a hybrid does, it recovers energy that would normally be lost in braking, and limits losses when the engine is idling. This stored energy is reused when most power is required such as in acceleration and moving from rest, or when the vehicle is least efficient such as just after engine start up and stop start driving.

10. HYBRID VS STANDARD VEHICLES

The previous chapters have shown the compromises necessary to implement a hybrid vehicle. So how does the performance of hybrids compare to standard cars?

Table II shows a selection of cars available in the United Kingdom. These cars were chosen because of their low emissions, with the first two cars in the table, the *Toyota Prius* and *Honda Civic 1.4 IMA* being petrol hybrids. Diesel engines are more efficient than petrol engines and hence produce less CO_2 and have better fuel economy for equivalent output. However, they do produce more particulate emissions (soot) than petrol vehicles. Most of the cars in the table are diesel for low CO_2 emissions; the exceptions are the hybrids and the *Diahatsu Charade* which is a petrol powered micro car.

Vehicle emissions are not a high priory to most vehicle buyers and users, the most desirable cars are mostly the more powerful ones. However cost is in an important issue, and one feature of hybrid vehicles is that they have good fuel economy.

So how much better does a hybrid vehicle perform against a non hybrid vehicle: From the Table II, the fuel economy of the hybrid is worse than the standard cars in the extra urban cycle (highway diving) and better in the urban cycle (city driving). This is averaged out in the combined cycle where the fuel performance is more or less the same.

To summarise:

- Hybrids outperform diesels in slow city driving.
- Diesels outperform hybrids in fast highway driving.
- Fuel economy is more or less the same for combined driving (66.6% City, 33.3% Highway by time)

If the fuel economy is more or less the same, how can the extra cost of a hybrid be justified? This extra cost could be about £3000 (4200•) for an equivalent sized car (*Prius* Vs *Focus Diesel in Table II*). The difference will be higher if the *Prius* is compared with a petrol car. The *Honda Civic*

Vehicle	CO_2 (g/100km)	Urban (mpg / l/100km)	Extra Urban (mpg / l/100km)	Combined (mpg / l/100km)	Maximum Weight (kg)	Engine Power (bhp)	Acceleration (0 to 62mph or 100 kph) seconds	Price (British Pounds / Euros)
Toyota Prius	104	56.5 / 5.0	67.3 / 4.2	65.7 / 4.3	1300	76	11.5	£ 17545 (24563€)
Honda Civic 1.4 IMA	116	47 / 6.0	65.7 / 4.3	57.7 / 4.9	1264	89	12.8	£ 15100 (21140€)
Honda Civic 1.7 CTDi	134	44.8/ 6.3	64.2 / 4.4	56.5 / 5.0	1264	99	11.5	£ 14100 (19740€)
Citroen C2 1.4 HDi	108	55.4 / 5.1	78.5 / 3.6	68.9 / 4.1	1083	69	13.5	£ 9095 (12733€)
Citroen C3 1.4 HDi 16V	112	53.3 / 5.3	76.3 / 3.7	65.7 / 4.3	1058	92	11.7	£ 12745 (17843€)
Citroen C4 1.6 HDi	125	47.1 / 6.0	70.6 / 4	60.1 / 4.7	1379	108	11.2	£ 14895 (20853€)
Ford Focus 1.6 TDCi	127	45.6 / 6.2	70.6 / 4	58.9 / 4.8	1426	108	10.8	£ 14620 (20468€)
Ford Fiesta 1.4 TDCi	114	53.3 / 5.3	76.3 / 3.7	65.7 / 4.3	1167	67	16.2	£ 10395 (14553€)
Diahatsu Charade 1.0	114	47.1 / 6	68.9 / 4.1	58.9 / 4.8	740	58	14.1	£ 5695 (7973€)
Honda Accord 2.2 i-CTDi	143	42.2 / 6.7	61.4/ 4.6	52.3 / 5.4	1523	138	9.4	£ 18900 (26460€)

Table 2. Vehicles and Performance. Source: What Car Magazine (United Kingdom) [6] Technical Data on all cars on sale in the UK

Hybrid is cheaper than the *Prius*, but the performance is lower.

Hybrids have lower CO_2 emission than diesels for an equivalent sized car. The car with the lowest CO_2 emission is a hybrid car the *Toyota Prius* (104 g/ 100km). Even though the fuel economy is approximate the same the hybrids have an advantage in CO_2 emissions.

However this advantage comes at a cost, the *Honda Accord* has the most similar to price to the *Prius* in table II, but the *Accord* is larger, more powerful (twice the power) and faster, but it is only 20% less fuel efficient, and produces 30% more emissions. The quoted fuel and emission figures are not likely to be based on a fully loaded vehicle, considering how the hybrid system is a compromise between many factors (Energy Balance).

What would happen if the *Accord* and *Prius* were fully loaded with four people including 80kg of luggage? Has the battery the ability to balance the extra energy of a full load? Will the fuel economy and emissions still be better in the *Prius*?

If a buyer was choosing a car based mainly on the CO_2 emission. Would they buy a *Prius*? A *Citreon C2 1.4 HDi* has only a slightly higher CO_2 emission than the *Prius* by 4g/100km. It is smaller but it is also half the price of the *Prius*. To archive this CO_2 rating the *Prius* is fitted with extra electronics, motors, batteries etc. If the CO_2 used during manufacture is considered, the *Prius* is likely to produce more CO_2 during manufacture. Therefore is the *Prius* more environmentally friendly than the *Citroen C2*?

The above factors have lead to vehicle manufactures quoting the following about hybrid vehicles:

«*I see it [hybrid technology] as a niche application. It has it's uses in congested areas, but elsewhere you can achieve results that are good or better with diesel engines. Why would a farmer in Scotland or Wyoming, ever want to buy a hybrid ?* « Helmut Panke, BMW's Chief Executive.[7]

«*Hybrids area a small way of participating in the environmental debate but, economically speaking, you can't justify the cost. The incremental cost to the consumer is $3,000 to $3,500 [£1,660 to £1,940]. Diesels are a much better proposition.*» Jim Padilla, President of the Ford Motor Company.[7]

However, in America exhaust emission regulation is tough on particulate (soot) and oxides of nitrogen produced by diesel engines. This makes it difficult and expensive for vehicle manufacturers to produce diesel cars for the US market, thus an ideal market for Hybrid vehicles. However in Europe where the regulations are not as strict, diesels now form almost 50% of new car sales.

«*A full hybrid system adds 150kg to the weight of the vehicle. We need to reduce the cost and weight. We are also working on increasing the efficiency of our diesel engines – even with all the devices needed to meet the new American regulations the cost of those does not reach that of the hybrid*» Burkhard Goeschel, Head of R&D at BMW.

Current hybrids are not good enough; a possible direction for future research for hybrid technology could be:

- Reduce the cost of hybrids.
- Better energy storage systems for improved energy balance.
- Advanced systems for maintaining energy balance to counter act the additional weight disadvantage and offer improved performance.

A diesel hybrid could be a solution, but the extra cost of diesel technology and hybrid technology will be combined producing an expensive solution.

11. CONCLUSIONS

Fuel consumption and emissions can be reduced by:

1. Reducing weight
2. Improving engine efficiency
3. Reducing energy losses

Do hybrids really work? Hybrids can improve engine efficiency by balancing energy and engine downsizing. Hybrids can reduce energy losses through regenerative braking. However part of the benefit possible is lost through increased weight due to extra components required.

The electrical system in a hybrid is based on a battery which needs to be partially charged most of the time. Therefore battery monitoring and electrical system management is essential. The battery SOC and SOH are important parameters to monitor and maintain. Failure to do so will result in failure of the hybrid system when high or low SOC are achieved.

Petrol hybrids are more fuel efficient in city driving, but diesel engines are more efficient in urban driving. The biggest advantage of hybrid technology is its ability to reduce the emissions of a compact car to a level lower than a small city car, but with a large cost.

Due to the extra cost of the hybrid technology, it is difficult for hybrids to demonstrate extra '*value*' for the vehicle buyer.

Hybrids will need to be cheaper to become mainstream or offer advantages over diesels, this could be achieved by improving the energy balance of the hybrid for improved performance and better fuel economy.

However, there is not a technology better than hybrid technology. Diesel engines come close but there are the particulate and nitrogen oxide emission problems associated with diesel.

ACKNOWLEDGEMENTS

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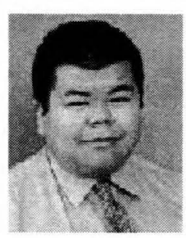

Stephen Wan was born in London in 1972. He obtained his Masters Degree by Research, from the University of Warwick. He has also attend Hatfield Polytechnic (University of Hertfordshire) reading Electrical, Electronic Engineering. He is a member of the Institution of Electrical Engineers. After leaving university he worked as a software developer in the HVAC (Heating, Ventilation, and Air Conditioning) industry. Developing bespoke CAD and quotation tools. He has been a Research Fellow in the Warwick Manufacturing Group at the University of Warwick since 1998. Whilst at Warwick he has been working with the automotive industry working in areas such as Telematics, Automotive Batteries, Hybrid Vehicles and Manufacturing He is also involved in supervising students on the Master of Science in Engineering Management at Warwick