# HYDROGEN FUEL CELL MOTORCYCLE WITH TRIPLE HYBRID DRIVE TRAIN

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# HYDROGEN FUEL CELL MOTORCYCLE
# WITH TRIPLE HYBRID DRIVE TRAIN

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requirements for the award of the degree of
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To my Father and Mother,
for their love and support during my long years overseas.

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## ABSTRACT

Motorcycles are major vehicles used for mobility especially in Southeast Asia, with their number doubling in the last decade. Motorcycles are also a major reason for air and noise pollution especially in the cities. In this study the hydrogen fuel cell powered motorcycle prototype was designed, fabricated and tested. The design criteria included futuristic style, ergonomic, low noise, zero exhaust emission and high tank-to-wheel fuel efficiency. Other criteria are handling flexibility, dynamic stability, good acceleration under any road and weather conditions. A triple hybrid power train was developed consisting of a 7 kW proton exchange membrane fuel cell, Lithium polymer batteries and super-capacitor connected to an electric drive with two permanent magnet motors. The fuel system consists of two light weight carbon fibre-aluminium cylinders with total capacity of 52 litres storing 1.25 kilogram hydrogen at 350 bar. To ensure its safety against hydrogen leakage, hydrogen leak detectors connected to an automatic hydrogen supply shut-off function was installed. A water cooling system was also designed, fabricated and tested and used to remove the heat produced by the fuel cell stack and power electronics. It keeps the fuel cell stack temperature below 75°C. Hollow stressed members of the fuel cell mounting and vehicle frame were used which allowed the flow of cooling water and process media to the fuel cell. An on board data acquisition system was developed to acquire real time data such as speed, distance travelled, hydrogen consumption, power produced and other information. Laboratory test on the analysis and performance of the triple hybrid drive train system used a water brake dynamometers which was customized to collect the required data especially the acceleration response and efficiency of the power train under Worldwide Harmonized Motorcycle Test Cycle 1 and 2 (WMTC). Different hybridization configurations were compared. The main road test was conducted during the successful participation in the technology class, of the 4,000 kilometre South African Solar Challenge 2008. During the real time test, the motorcycle was subjected to different road conditions including steep terrain, flat road, variable weather conditions and endurance. A mobile hydrogen refuelling system was designed to refuel the motorcycle safely and efficient. Results from the endurance test showed that the motorcycle performed according to the design criteria. The maximum speed achieved was 82 km/h slightly lower than the designed 100 km/h due to the road conditions, a trade off from hill climb capability with 30% slope, to maximum speed have been made. The maximum tank-to-wheel fuel efficiency achieved was 42.9% using WMTC2. The best fuel consumption measured was 68.9 km for one litre petrol equivalent. The hydrogen fuel cell motorcycle showed good driving behaviour without fatal breakdown under robust road and weather conditions. Also the triple hybrid drive train was found to increase the peak power by 57% compare to a non-hybrid drive train thereby reducing the fuel cell load cycles by 35%. Finally, the result of the study can be used to predict the range, traveling time and efficiency of the motorcycle or any vehicle using triple hybrid drive train.

# ABSTRAK

Motosikal adalah kenderaan yang paling banyak digunakan untuk tujuan bergerak terutamanya di Asia tenggara dengan jumlahnya yang telah meningkat sebanyak dua kali ganda dalam dekad sebelum ini. Motosikal merupakan diantara punca utama menyebabkan pencemaran bunyi dan pencemaran alam sekitar terutama di bandar-bandar besar. Dalam kajian ini prototaip motosikal Hidrogen berkuasa sel fuel telah direkabentuk, difabrikasi dan diuji. Kriteria rekabentuk termasuk rekabentuk futuristik, ergonomi, rendah bunyi, pencemaran sifar dan kecekapan tenaga tangki-ke-roda yang tinggi. Kriteria rekabentuk diatas jalan adalah kawalan fleksibiliti, kestabilan dinamik, dan pecutan yang baik dalam sebarang keadaan jalan raya dan keadaan cuaca. Enjin pacuan tiga-hybrid berkuasa 7 kW telah dibangunkan komponennya terdiri daripada sel fuel *proton exchange membrane*, bateri Lithium polimer dan super-kapasitor yang disambungkan ke motor elektrik dengan dua magnet jenis tetap tanpa berus. Sistem bekalan bahanapi pula terdiri daripada dua tangki hidrogen ringan dibina dari dua lapisan aluminium-gentian karbon yang mempunyai kapasiti 52 liter menyimpan 1.25 kilogram gas hidrogen pada tekanan 350 bar. Alat pengesan kebocoran hidrogen telah dipasang dan disambung kapada injap-penutup. Sistem penyejukan menggunakan air telah di rekabentuk, difabrikasi dan diuji untuk mengawal suhu operasi dibawah paras 75°C. Sistem perolehan data diatas kenderaan dibangunkan untuk mendapatkan data seperti kelajuan, jarak, penggunaan hidrogen, kuasa yang dihasilkan, dan data yang lain. Ujikaji engin pancuan tiga-hybrid telah menggunakan brek air dinanometer yang diubahsuai khusus untuk mengumpul data terutama dalam tindakbalas pecutan dan kecekapan tenaga menggunakan piawaian *World Harmonized Motorcycle Test Cycle 1 and 2* (WMTC). Perbandingan prestasi telah dibuat menggunakan konfigurasi enjin tiga-hybrid yang berbeza. Ujian diatas jalan raya berjaya dilakukan di *South African Solar Challenge* pada tahun 2008 sejauh 4,000 km. Semasa ujian masa sebenar, motosikal telah tertakluk kepada pelbagai keadaan jalan termasuk kecerunan yang curam, jalan rata, keadaan cuaca berubah-ubah dan ketahanan. Keputusan ujian ketahanan menunjukkan prestasi motosikal adalah mengikut kriteria rekabentuk yang telah ditetapkan. Kelajuan maksimum yang dapat dicapai adalah 82 km/j, rendah sedikit dari kelajuan yang direka 100 km/j disebabkan oleh keadaan jalan, akan tetapi kebolehan mendaki bukit cerun sebanyak 30%, kelajuan maksimum telah dapat dicapai. Kecekapan maksimum tangki-ke-roda adalah 42.9% mengikut piawai WMTC2. Penggunaan bahanapi terbaik adalah 68.9 km untuk satu liter petrol setara. Motosikal hidrogen berkuasa sel fuel dengan enjin pacuan tiga-hybrid telah menunjukkan prestasi yang baik dari segi pemanduan dan ketahanan enjin dalam semua keadaan jalan dan cuaca. Dan kuasa Enjin pacuan tiga-hybrid boleh menjana sebanyak 57% kuasa puncak yang lebih tinggi dibandingkan enjin tanpa hybrid, dan mengurangkan beban kuasa pusingan sel fuel sebanyak 35%. Keputusan dalam kajian ini boleh digunakan untuk meramalkan jarak, masa perjalanan dan kecekapan motosikal ataupun kenderaan yang menggunakan sistem engine pacuan tiga-hybrid.

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| | | |
|---|---|---|
| 350/750 bar | - | Pressure levels for hydrogen storage tanks |
| 3G network | - | 3rd Generation Mobile Phone Network |
| AC | - | Alternating Current |
| AFC | - | Alkaline Fuel Cell |
| BATC | - | Business & Advanced Technology Centre |
| cap | - | capacitor |
| cc | - | cubic centimetre |
| CNG | - | Compressed Natural Gas |
| CNC | - | Computer Numeric Control |
| CO | - | Carbon Monoxide |
| $CO_2$ | - | Carbon Dioxide |
| conc | - | concentration |
| const | - | constant |
| cRIO | - | compact Real-time Input Output module |
| DC | - | Direct Current |
| DC/DC | - | DC/DC converter / Power conditioner |
| dis | - | discharge |
| DMFC | - | Direct Methanol Fuel Cell |
| DOD | - | Degree of Discharge |
| ECE-15 | - | The United Nations Economic Commission for Europe specification for urban driving cycle simulation |
| ECU | - | Electronic Control Unit |
| emf | - | electro motive force |
| EU | - | European Union |
| EUDC | - | Extra Urban Driving Cycle – specification for European urban driving cycle simulation |
| EV | - | Electric Vehicle |

| | | |
|---|---|---|
| FC | - | Fuel Cell |
| FCEV | - | Fuel Cell Electric Vehicle |
| FPGA | - | Field Programmable Gate Arrey |
| GDL | - | Gas Diffusion Layer |
| GHG | - | Greenhouse Gas |
| GPS | - | Global Position System |
| $H^+$ | - | Hydrogen ion |
| $H_2$ | - | Hydrogen |
| $H_2O$ | - | Water |
| HEV | - | Hybrid Electric Vehicle |
| HHV | - | Higher Heating Value |
| ICE | - | Internal Combustion Engine |
| IMMA | - | International Motorcycle Manufacturers Association |
| init | - | initial |
| ISO | - | International Organization for Standardization |
| KL | - | Kuala Lumpur |
| KLMTC | - | Kuala Lumpur Motorcycle Test Cycle |
| LED | - | Light Emission Diode |
| LHV | - | Lower Heating Value |
| makan | - | Eating (Malay) |
| MCFC | - | Molten Carbonate Fuel Cell |
| MEA | - | Membrane Electrode Assembly |
| minum | - | Drinking (Malay) |
| NEDC | - | New European Driving Cycle |
| NGM | - | New Generation Motors |
| NI | - | National Instruments |
| $O_2$ | - | Oxygen |
| OCV | - | open circuit voltage |
| OEM | - | Original equipment manufacturer |
| PAFC | - | Phosphoric Acid Fuel Cell |
| PEM | - | Proton Exchange Membrane |
| ppm | - | Parts per million |
| PTFE | - | Poly Tetra Fur Ethan / brand name: Teflon |
| pwr | - | Power train |

| | | |
|---|---|---|
| PWT | - | Powered Two Wheelers |
| R&D | - | Research and Development |
| rosak | - | Broken, Spoiled (Malay) |
| SAE | - | Society of Automotive Engineers (SAE International) |
| slpm | - | standard litter per minute |
| SOC | - | State of Charge |
| SOD | - | State of Discharge |
| SOFC | - | Solid Oxide Fuel Cell |
| TTW | - | Tank to Wheel Efficiency |
| UC | - | Ultra-capacitor |
| UN | - | United Nations |
| US / USA | - | United States (of America) |
| UTM | - | Universiti Teknologi Malaysia (University of Technology Malaysia) |
| WBZU | - | Weiter-Bildungs-Zentrum ( Education Center) |
| WMTC | - | Worldwide harmonized Motorcycle Test Cycle |
| WOT | - | Wide open throttle |
| WTW | - | Well-to-wheel |
| ZSW | - | Centre for Solar and Hydrogen Research |

# LIST OF SYMBOLS

## ROMAN LETTERS

| | | |
|---|---|---|
| A | - | Ampere (unit) |
| C | - | Colum (unit) |
| ℃ | - | Celsius (unit) |
| d | - | Day (unit) |
| F | - | Farad (unit) |
| h | - | Hour (unit) |
| J | - | Joule (unit) |
| K | - | Kelvin (unit) |
| km | - | Kilometre (unit) |
| kg | - | Kilogram (unit) |
| l | - | Litre (unit) |
| m | - | Meter (unit) |
| N | - | Newton (unit) |
| sec | - | Second (unit) |
| V | - | Voltage (unit) |
| W | - | Watt (unit) |

## ITALIC ROMAN LETTERS

| | | |
|---|---|---|
| $A$ | - | Area (Frontal Area of Vehicle) |
| $a$ | - | Acceleration |
| $C$ | - | Capacity (Battery) |
| $Cd$ | - | Aerodynamic resistant |

| | | |
|---|---|---|
| $CG$ | - | Centre of Gravity |
| $D$ | - | Diameter |
| $E$ | - | Energy |
| $e$ | - | Electron |
| $F$ | - | Force |
| $h$ | - | Height |
| $I$ | - | Current |
| $i$ | - | Gear ratio |
| $\underline{i}$ | - | Current in integral |
| $K$ | - | Motor constant |
| $L$ | - | Inductant |
| $M$ | - | Motor |
| $m$ | - | Mass |
| $n$ | - | number of cells (fuel cell / battery) |
| $o$ | - | open |
| $P$ | - | Power |
| $p$ | - | Pressure |
| $Q$ | - | Thermal energy |
| $R$ | - | Resistant |
| $r$ | - | radius |
| $s$ | - | Series (battery series connection) |
| $T$ | - | Temperature |
| $t$ | - | time |
| $V$ | - | Voltage |
| $\bar{V}$ | - | Volume |
| $\dot{V}$ | - | Volumetric flow rate |
| $v$ | - | Speed |
| $\underline{v}$ | - | Voltage at integral |
| $W$ | - | Watt (unit) |
| $X$ | - | Number not defined |
| $x$ | - | x-Diagram axis |
| $y$ | - | y- Diagram axis |

## GREEK LETTERS

| | | |
|---|---|---|
| α | - | Hill slope angle |
| β | - | Angle (general use) |
| δ | - | Air density |
| η | - | Efficiency |
| μ | - | Rolling resistant |
| λ | - | Stoichiometric ratio of hydrogen / oxygen in fuel cell |
| ρ | - | Partial pressure |
| σ | - | Tilting angel of motorbike |
| τ | - | Torque |
| ω | - | Angular Speed |
| Δ | - | Delta, difference |
| Ω | - | Ohm (unit) |

## SPECIAL CONSTANTS

| | | |
|---|---|---|
| g | - | Gravitational constant (9.8 $m/s^2$) |
| F | - | Faraday constant (96485 mol e/mol) |
| $R_{H_2}$ | - | Gas constant for hydrogen (8.31398 J/mol.K) |
| π | - | Pi circular constant (3.14) |
| a | - | Empirical constant at gas equation ($a = 0.42748 \cdot R_{H_2} \cdot 2T_c^{2.5}/p_c$ ) |
| b | - | Empirical constant at gas equation ($b = 0.8664 \cdot R_{H_2} \cdot T_c/p_c$; $R_{H_2}$) |

## SUBSCRIPTS

| | | |
|---|---|---|
| acc | - | acceleration |
| accel | - | acceleration |
| acceleration | - | acceleration |
| aux | - | auxiliaries |

| | | |
|---|---|---|
| average | - | average |
| back | - | preposition back |
| bat | - | battery |
| booster | - | booster motor |
| cursing | - | cursing |
| DC bus | - | DC bus (power train voltage) |
| dcdc | - | DC/DC converter |
| eff | - | efficiency |
| fc | - | fuel cell |
| front | - | preposition front |
| HHV | - | higher heating value |
| $H_2$ | - | hydrogen |
| in | - | input |
| instant | - | instantaneous |
| LHV | - | lower heating value |
| loss | - | losses |
| out | - | output |
| NGM | - | new generation motor / main motor |
| max | - | maximum |
| OCV | - | open circuit voltage |
| roller | - | dynamometer roller |
| system | - | system |
| wheel | - | wheel |

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# CHAPTER 1

# INTRODUCTION

Motorcycle usage is growing rapidly, especially in the emerging markets. Greenhouse gasses (GHGs) and noise pollutions are emitted. These are sought to be the main cause of global warming. A hydrogen fuel cell motorcycle operates without local emissions and low noise. Hydrogen as an energy carrier can be provided through environmentally friendly ways. The fuel cell drivetrain efficiency and performance can be improved with hybridization. This thesis investigates the design of the Pios fuel cell motorcycle with a triple hybrid drivetrain.

## 1.1 Background

Pollution from millions of motorcycles in Asian cities contributes to a significant part of air pollution. 77% of all motorcycles worldwide are in Asia, according to figures presented by Rodger (2008). Distribution of motorcycles by region was presented by the International Motorcycle Manufacturers Association (IMMA) 2010 report, (IMMA, 2010). The growth pattern of motorcycle population in the period of 2000-2008 can be observed in Figure 1.1 and Table 1.1. The increase in motorcycle population among emerging markets is the main driving force of growth in the worldwide motorcycle market. In the South American market, Brazil had shown a strong growth of motorcycle population from 2.2 million in 2000 to 9.1 million in 2008. In Asia, China led the growth in the motorcycle market. The number of motorcycles increased from 37.72 million in 2000 to 89.537 million in 2008. The number of motorcycles remained stagnant in most of the developed economies over the same period. Especially in countries like Japan, motorcycle population shrank from 13.974 million in 2000 to 12.787 million in 2008. In Europe, there was a trend of larger size motorcycle replacing smaller size mopeds. The number of motorcycles increased from 15.17 million to 21.7 million while mopeds decreased from 15.04 million to 12.3 million from 2000 to 2008. The author feels this shift from mopeds to larger motorcycles represents the paradigm shift in consumers' behaviour from only satisfying transport needs to the desire of more comfort and leisure.

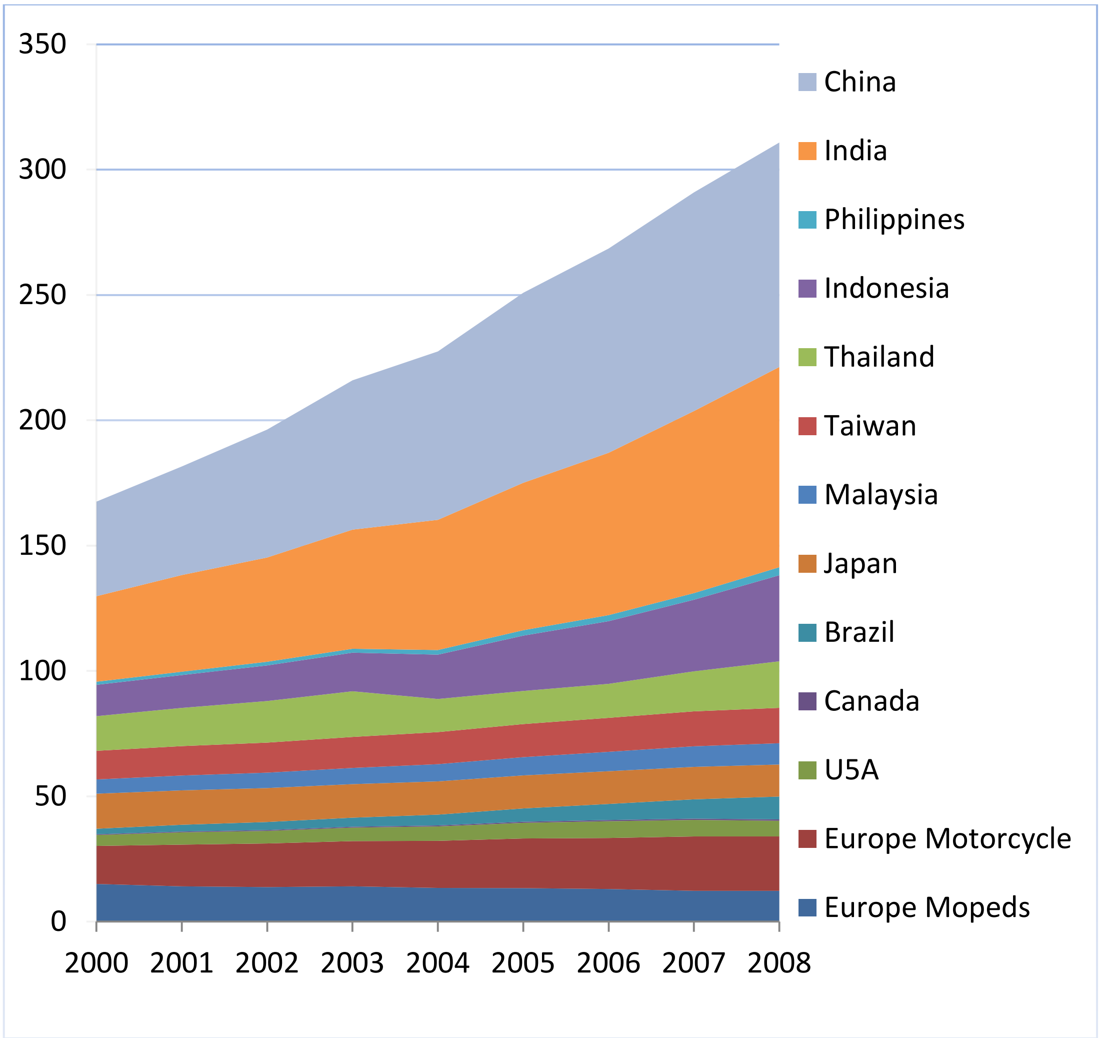


Figure 1.1 Development of the number of powered two wheelers (PTW) from the year 2000 to 2008 by region figures in millions. The number increased by 85% while the main increase was in the Asia with 100%. Now Asia has 83% of all PTWs.

Table 1.1 Number of powered two wheelers (PTW) in millions by region and year (International Motorcycle Manufacturers Association, 2010).

| Region / Year | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|
| Europe Mopeds | 15.04 | 14.09 | 13.788 | 14.099 | 13.456 | 13.378 | 13.028 | 12.3 | 12.3 |
| Europe Motorcycles | 15.17 | 16.64 | 17.412 | 18.041 | 18.788 | 19.812 | 20.348 | 21.7 | 21.7 |
| USA | 4.3461 | 4.903 | 5.004 | 5.37 | 5.74 | 6.23 | 6.69 | 6.588 | 6.233 |
| Canada | 0.311 | 0.318 | 0.35 | 0.373 | 0.409 | 0.443 | 0.485 | 0.512 | 0.562 |
| Brazil* | 2.2 | 2.7 | 3.2 | 3.6 | 4.3 | 5.3 | 6.4 | 7.7 | 9.1 |
| Japan | 13.974 | 13.72 | 13.54 | 13.369 | 13.261 | 13.175 | 13.06 | 12.935 | 12.787 |
| Malaysia | 5.686 | 5.921 | 6.143 | 6.464 | 6.862 | 7.284 | 7.733 | 8.217 | 8.487 |
| Taiwan | 11.423 | 11.733 | 11.984 | 12.367 | 12.794 | 13.195 | 13.557 | 13.943 | 14.117 |
| Thailand | 13.816 | 15.236 | 16.581 | 18.21 | 13.207 | 13.195 | 13.557 | 15.962 | 18.56 |
| Indonesia* | 12.5 | 13.1 | 14.2 | 15.4 | 17.688 | 22.078 | 25 | 28.555 | 34.337 |
| Philippines | 1.2361 | 1.338 | 1.47 | 1.552 | 1.846 | 2.157 | 2.409 | 2.639 | 3.192 |
| India | 34.118 | 38.556 | 41.581 | 47.519 | 51.922 | 58.799 | 64.743 | 72.615 | 79.864 |
| China | 37.72 | 43.308 | 51.028 | 59.558 | 67.17 | 75.786 | 81.473 | 87.217 | 89.537 |
| TOTAL | 167.54 | 181.56 | 196.28 | 215.92 | 227.44 | 250.83 | 268.48 | 290.88 | 310.78 |

* Data for Brazil and Indonesia 2000 to 2003 retrieved from Rogers (2008).

Malaysia is one of the most motorised countries in the world, by number of motorised vehicles per person. Among all the vehicles, more than half of them on Malaysian roads are motorcycles. As of 2009 7,458,128 motorcycles were registered in Malaysia (Nabhan 2010) as shown in Figure 1.2. It was the most amongst all the vehicles registration. Motorcycle became the most popular mode of transport in Malaysia. In addition, Malaysia has the world's second highest motorcycle density of 0.314 motorcycles per person after Taiwan where there are 0.614 motorcycles per person. It is also noted that in 2009, local sales of motorcycle in Taiwan dropped by 42.8% year on year from 2008 mainly influenced by the major upgrade of public transport systems in metropolitan areas.

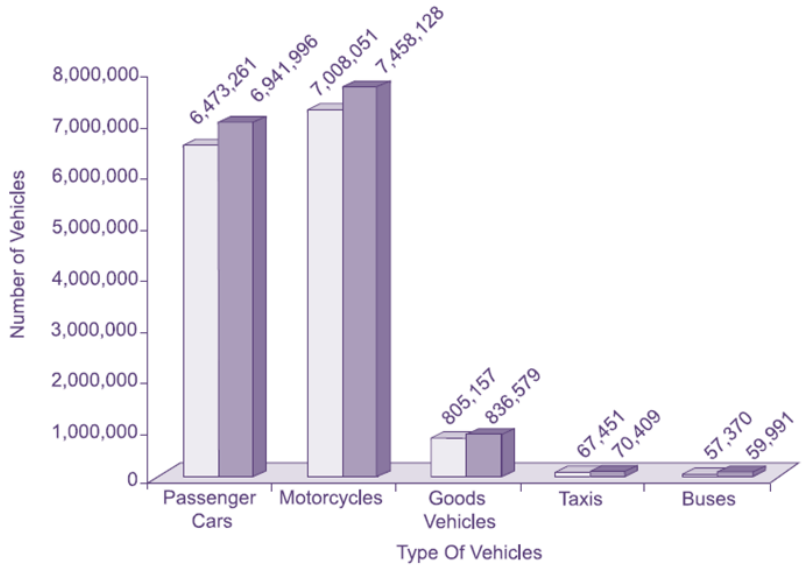


Figure 1.2 Number of vehicles registered in Malaysia in 2008 and 2009 (Nabhan, 2010).

Global warming is a well discussed issue in many publications. Scientists, political leaders, environmentalist and even sceptics discussed this issue from various perspectives, but they all accept global warming as a fact (Okamura, 2009; Gore, 2006; Riis *et al.*, 2006; Lomborg, 2001). Air pollution is a major factor for global warming (Philipon, 2010). Personal transport contributes significantly to the total greenhouse gas emission (Quaschning, 2010).

As an alternative to combustion engine powered motorcycles, hydrogen fuel cell powered motorcycles have their advantages in many aspects. Firstly, while internal combustion engines emit $CO_2$, $NO_x$ and other gashouse gases during their operation, hydrogen fuel cells produces only pure water ($H_2O$). Secondly, due to the limitation of the Carnot cycle, internal combustion engine powered motorcycles usually operate with 25% tank to wheel efficiency. However, hydrogen fuel cell system operates based on electrochemical reactions with up to 50% tank to wheel efficiency. Thirdly, the noise produced in electrochemical systems is lower than noise from thermo-mechanical systems.

Using chemical batteries to electrify motorcycles is another popular way to reduce operation emission and improve drivetrain efficiency. However, this technology faces some critical challenges. Due to the low energy density of batteries, the range of the motorcycle is limited. In addition, the long charging time of battery becomes another hurdle as users are used to refuel petrol motorcycles within couple of minutes. Compared with battery electric motorcycle, fuel cell electric motorcycles have the advantage of significant higher range and faster refuelling. The range and refuelling time of fuel cell motorcycles is comparable with petrol powered motorcycles.

### 1.1.1 The Source of Hydrogen

Hydrogen as a fuel, offers the highest energy efficiency for fuel cell motorcycles. Hydrogen is an energy carrier and it needs to be produced. Conventionally, hydrogen is produced from fossil fuel, for example, steam reforming of natural gas. But there are also many sustainable ways of hydrogen production, such as thermal cracking of biomass, direct photo electrochemical water splitting (Minggu *et al.*, 2010) and solar thermal cracking of water, referred as the “golden hydrogen” by Arno A. Evers (Evers, 2010). The most common is the electrolysis of water. The hydrogen produced is as clean as the source of electricity. It is possible to achieve 100% renewable electricity by 2050 according to studies of Klaus et al. (2010). Even the petrol company Shell foresees a significant energy change towards renewable energy until 2050 (Shell, 2011). In addition, the cost of renewable energy is cheaper than nuclear energy if social cost is taken into consideration (Scheer, 2007). As a signal of change, the German government decided to close down all nuclear power plants by 2020 and encouraged the use of renewable electric power generation (Dolak *et al.*, 2011). To boost renewable energy generation, feed-in-tariff was firstly introduced in Germany (Scheer, 2007) and then adopted by many countries including Malaysia in 2011. However, most of the renewable energy sources are intermittent. There is a need for electricity energy storage. Some methods to temporary store electricity include hydro pump storage (Janardhan and Fesmire, 2011a), large batteries (Hammerschlag and C.P.Schaber, 2008) and intelligent load balancing (William *et al.*, 2010; Sweet, 2009). It is also possible to integrate electrolysers with the intelligent grid to store extra electricity during off peak hours in the form of hydrogen gas. Subsequently, the hydrogen gas can be used as vehicle fuel.

Genske et al. (2009 ) shows in his study that in 2008, 28% of the primary energy in Germany was used for mobility. That means an efficiency improvement in the mobility sector has a huge influent on the prime energy consumption.

### 1.1.2 The Energy Consumption and Greenhouse Gas Emissions of Vehicle Drive Trains

In 2010, there were two bored based studies published, on the Well to Wheel (WTW) energy efficiency and WTW greenhouse gas emission, about the comparison of different vehicle drive trains. The first one from the European Union was about energy efficiency of different drive trains; the second one from the US department of Energy (DOE) was a financed study by the Argonne National Laboratory on greenhouse gas emissions of street vehicles (Wang, 2010; Thomas, 2011; Winter, 2011).

The European Study is based on wide data collected from car manufacturers, oil and gas companies, utilities, industrial gas companies, equipment manufacturers, wind energy companies, electrolyser companies, non-governmental organisations and governmental organisations (Zeroemissionvehicles and European_Union, 2010).

The European study looks among others at the usability of passenger cars in terms of range and compare their Well to Wheel efficiency based on different feedstock for the primary energy. The results show that in most cases the battery electric vehicles have the highest Well to Wheel efficiency but cannot provide enough range to replace all categories of the European vehicle fleets. The second best in the most fuel feedstock scenarios are hydrogen fuel cell vehicles which have the range performance to fully replace petroleum based drive trains in all passenger care segments; further details are given in Appendix B1.3 “Energy efficiency analysis of different drive trains”. From an energy point of view a mixed approach of pure electric vehicles for city driving and plug in electric vehicle with fuel cell range extender for intercity (and city) driving would be preferred.

An interesting further result of the study is that the infrastructural cost for electric charging stations and for hydrogen refilling stations is actually the same. As the hydrogen refilling station is about 30 times more expensive than an electric car quick charging station. However, it can serve 30 times more cars as the recharge time is much faster and the achieved range per refilling is much longer so the frequency of return to the refilling station is less than the charging station. For a massive implementation of electric vehicles additional infrastructure costs for the reinforcement of the electricity grid need to be considered as well.

The US Study takes a more conservative approach based on the current electricity mix (49% coal according to Janardhan and Fesmire (2011b)) and vehicle fleet consumption the $CO_2$ emission per mile travel is calculated; the hydrogen greenhouse gas emissions are based on reforming of natural gas to hydrogen. The $CO_2$ emission per mile for an average gasoline US internal combustion engine (ICE) car is: 473 grams/mile, for a battery electric vehicle (BEV) are 337 grams/mile of $CO_2$-equivalent and for a hydrogen fuel cell electric vehicle are 260 grams/mile. The statistics in Figure 1.3 is taking this conservative approach into account and only minor changes in the feedstock of the electricity production, towards less $CO_2$ and general Green House Gas (GHG) emissions from now to the year 2035. The figures of the BEV represents the replacement of small and midsize car by BEV because of range and power consumption limitations for big cars. The Plug-in Hybrid Electric Vehicle (PHEV) scenario takes in plug-in electric vehicles like the Chevy Volt. The mixed scenario takes in BEV and PHEV depending on the best suitability. The study shows a clear advantage for hydrogen fuel cell vehicles to reduce the greenhouse gas emissions by more than 50% if all vehicles are replaced.

The truth will be somewhere in between. First the change of vehicle drive trains take time, and I truly hope that the electricity production mix will reduce the $CO_2$ emission by implementing more renewable energy (not nuclear energy) and by this the greenhouse gas emission WTW will also be better for electric cars (Riis *et al.*, 2006).

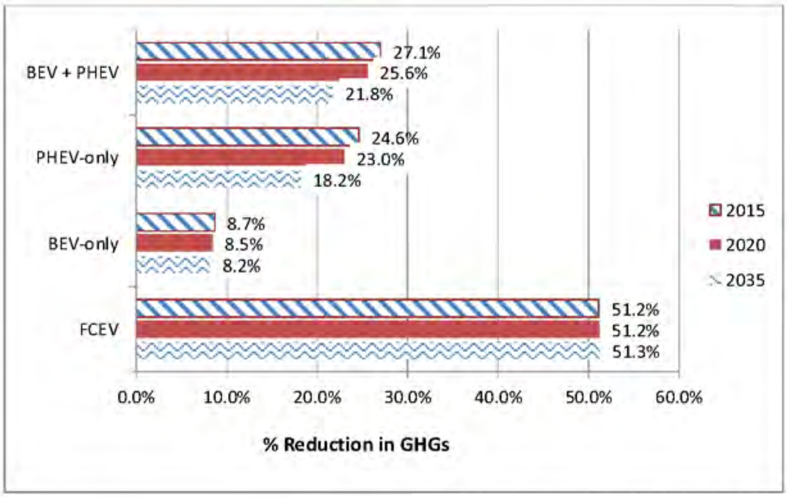


Figure 1.3 US Study on reduction of traffic based greenhouse gas emission (GHG) for replacing the existing vehicle fleet with a new vehicle fleet based on different drive trains (Thomas, 2011).

## 1.2 Problem Statement

Personal mobility plays a vital role in the modern society. Motorcycles are major vehicles used for mobility especially in Southeast Asia, with their number doubling in the last decade. However, most of the motorcycles on the road presently are powered by internal combustion engine using fossil fuel, which poses several threats to the society and environment. The ICE engine has a low tank to wheel efficiency due to its engine characteristic. It also creates noise pollution when millions of ICE vehicles operate on the road daily. The use of petrol and diesel creates significant $CO_2$ emissions. Many oil dependent countries face national energy security threats as fossil fuel reserves can only be found in limited regions. Hence, it is critical to investigate alternative energy sources and motorcycle power train solutions to help countries moving away from oil dependency, increase efficient use of energy and cut down pollutions created by both greenhouse gases and noise.

Only very limited studies on triple hybrid drive trains with fuel cells, batteries and ultra-capacitor were done. These studies never get applied to a fuel cell powered two wheeler yet. That led to one of the research gaps for the study.

## 1.3 Research Objective

(i) To design, fabricate and test a hydrogen fuel cell powered motorcycle prototype and study the effect of different design parameters including ergonomics, weight distribution, vehicle mass, aerodynamic drag, rolling resistance on its fuel economy.

(ii) To design, demonstrate and simulate a portable hydrogen-refilling system based on multi stage pressure equalisation.

(iii) To determine and test all fuel cell motorcycle drives train components and derive different promising (meaningful/ practical) hybridisation configurations

(iv) To test and compare different drive train hybridisation configurations in terms of acceleration performance, drive train component efficiency and tank to wheel efficiency.

## 1.4 Research Scope

The research scope covers the following elements:

- The design parameters for a fuel cell motorcycle.
- Considerations of industrial design, weight analysis and distribution, basic ergonomics, process media flow, hydrogen storage and mobile hydrogen refilling.
- Data acquisition system to measure the major individual drive train components separate and extended data acquisition system to measure the input and output parameters of whole fuel cell drive train in a dynamometer set up.
- Comparison between drive train architectures in terms of performance by acceleration tests and efficiency by drive cycle test; leading to recommendations of drive train architectures.

## 1.5 Theses Outline

The introduction looks at worldwide increasing individual road transport with powered two wheelers and its consequences for air- and noise pollution. It is also broad in the content of the global warming discussion. As possible solution pathway the bigger picture of a hydrogen society with hydrogen production is described. Together they build the background framework for this study of the hydrogen fuel cell motorcycle. The objectives can be summarized in: - design, analyse and fabricate of fuel cell motorcycle, - develop, test and simulate of portable hydrogen refuelling system,- determine and test drivetrain components and hybrid drive train configurations, develop data acquisition system and analyse drive cycle tests.

The second chapter is the literature and technology review, it starts with the basic historic background and looks on the current state of technology and research. It looks on other fuel cell two wheeler projects. It looks on fuel cell drive train hybridisation, - different possibilities of drive train components, - the selection of hybrid configurations and drive cycles.

The third chapter is giving an overview of the research approach and contains the equations used for the research.

The forth chapter looks on the fuel cell motorcycle from the industrial and mechanical point of view. It starts with the target design parameters and ends with the achieved parameters. Furthermore, it shows the practical picture of hydrogen mobility with the fuel cell motorcycle road test and a study on hydrogen consumption; - it explains and simulates the portable hydrogen refuelling.

The chapter five is about the fuel cell drive train and fuel cell drive train variations. It explains and measures all drive train components individually, - explain the measurement system, - gives an overview of the motorcycle schematics. It explains the selected hybrid drive train configurations and gives the results for acceleration and drive cycle tests.

Chapter 6 presents conclusions and recommendations.

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