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Comprehensive Gaseous Hydrogen Storage Reservoir Design Study

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Abstract— The main purpose of this paper is to design the Hydrogen tank which fits in Toyota Prius. The stress analysis and material selection is also reported in this project. The various technical characteristics of Hydrogen fuel cell vehicle is also considered in terms of their design, power source configurations, and cost benefits in order to see their socio-economic and environmental impacts. Effects on energy consumption as well as global warming are also discussed in this paper in addition to providing recommendations on how to increase the efficiency of these vehicles which would help to reduce the cost. The scope of this paper is mainly limited to design and characteristic of Toyota Prius Fuel cell tank design. The recommendations provided are fairly general while the analysis and study done can be applied to other vehicles in automobile manufacturing industries.

Index Terms— Fuel Cell, Gaseous Hydrogen, Hydrogen Storage, Increase Efficiency, Reservoir, Stress Analysis, Tank Design.

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1 INTRODUCTION

In a world where environment protection and energy conversion are growing concerns, the development of Hydrogen fuel cell vehicles (FCV), electric vehicles (EV) and hybrid electric vehicles (HEV) has taken on an accelerated pace. The dream of having commercially viable EVs and HEVs is becoming a reality. FCVs, EVs and HEVs are gradually available in the market. Results of the analysis of the December 2011 Dashboard [1] confirm that Hybrid sales for the last quarter of 2011 exceeded the comparable level in 2010 by almost 5 percent.

A hybrid vehicle is a vehicle that uses two or more distinct power sources to move the vehicle while an electric vehicle is one which uses one or more electric motors for propulsion [1, 2]. There exist many power sources in the world for hybrid vehicles, the most common of which include hydrogen, compressed air, solar power, compressed/liquefied natural gas and liquid nitrogen. Electric vehicles on the other hand run on various electricity sources including batteries, electric double-layer capacitors, and fuel cells [3]. Fuel cell, Hybrid and electric vehicles are present in all sizes ranging from mopeds, bicycles and cars to trains, ships, aircraft and even nuclear submarines.

The design and development of Fuel cell, hybrid and electric vehicles goes back to the mid-19th century. Hybrid vehicles started with the development of first steam powered motor car and carriages in the early 1800’s while electric vehicles started when a small train was run on an electric motor back in 1835 in England. Hybrid cars started off by being steam and gasoline powered but over last few century, their power sources have gone on to be a combination of gas and electric, gas and hydrogen and some even solar powered [4]. Electric vehicles have also moved from being run by simple motors to having fuel cells and rechargeable electricity storage system (RESS) which consist of batteries and capacitors.

Over years demand for hybrid and electric vehicles has increased significantly due to rising costs and environmental concerns [2]. The burning of fossil fuels for gasoline has decreased the number of trees in the world and has also affected the overall air quality for all living and non-living creatures on this planet. In addition, price and oil and gasoline has been steadily rising over the decades, making hybrid and electric vehicles a cheaper and more efficient option [2]. Due to environmental benefits and rising oil prices, major automobile manufacturers spend millions of dollars on the research and development of hybrid and electric vehicles which are becoming more and more environmentally friendly and help to protect the eco-system.

Currently, hybrid and electric cars are more common than hybrid and electric ships, aircraft or trains. Presently, hybrid cars make up about 2%-4% of the overall automobile production in North America while the number of electric cars currently stands at about 40,000 in the United States[5]. In general, hybrid and electric vehicles seem to have similar market share with hybrid being ahead by a small amount while electric have the faster growth in the market share due to sky-rocketing oil prices and the general consensus to reduce the amount of gasoline used [5].

1.1 Hybrid Vehicles

As mentioned before a hybrid vehicle is one which has more than one power source such as internal combustion engine and an electric motor [2].This type of configuration is shown in Figure 1-1, Hybrid Electric Vehicle (HEVs) which is most common type of Hybrid Vehicles.

There are three main types of Hybrid configurations available in market. Series hybrid vehicle configuration

- Parallel hybrid vehicle configuration
- Series-parallel vehicle configuration

All three types of configurations are shown below.

Series Hybrid Vehicle Configuration: Series hybrid vehicle configuration is shown in Figure 1-2. In this, the petrol engine turns the generator. Electric power thus produced is fed to the electric motor that drives the wheels. The power flows

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to the wheels in series. In other words, power from the petrol engine to the electric motor is connected in series, hence the name Series Hybrid System. Example of this type of vehicle is the Chevrolet Volt developed by General Motor.

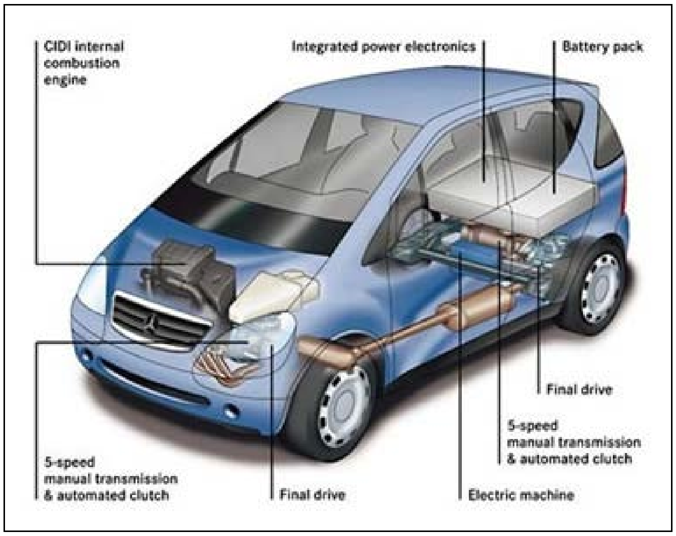

Fig. 1-1: Concept of Hybrid Vehicle [6].

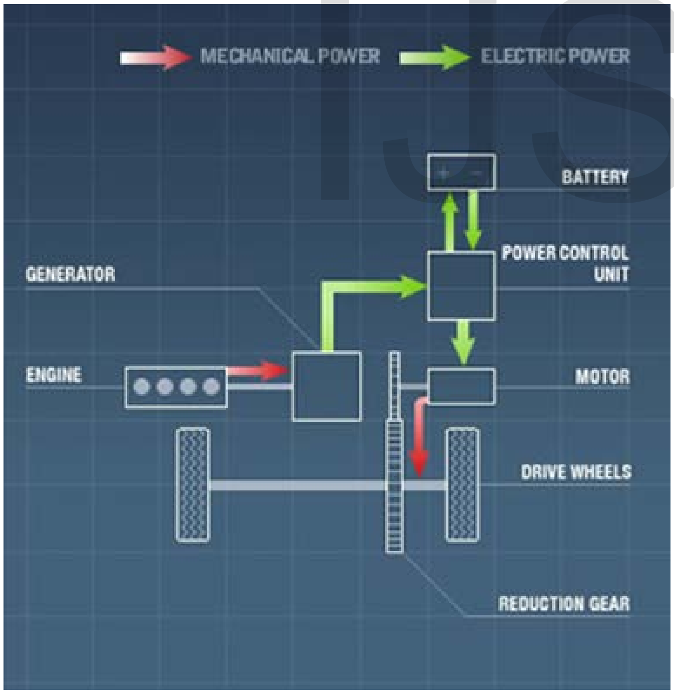

Figure 1-1: Schematic of series Hybrid Vehicle Configuration [7].

Parallel Hybrid Vehicle Configuration: The parallel hybrid vehicle configuration is shown in Figure 1-3. In this type of configuration, the wheels are driven by the petrol engine and the electric motor. The power source is selected according to the driving conditions. The name of the system comes from the fact that the power sources run in parallel. The petrol engine is the primary power source. The electric motor is used to supplement power during acceleration. However, the electric motor cannot be used to power the car while it is generating electricity. Examples of this type of system can be found in Honda's Integrated Motor Assist (IMA) system used in Civic, Accord, Insight and Belt-Alternator-Starter (BAS) system used in Chevrolet Malibu.

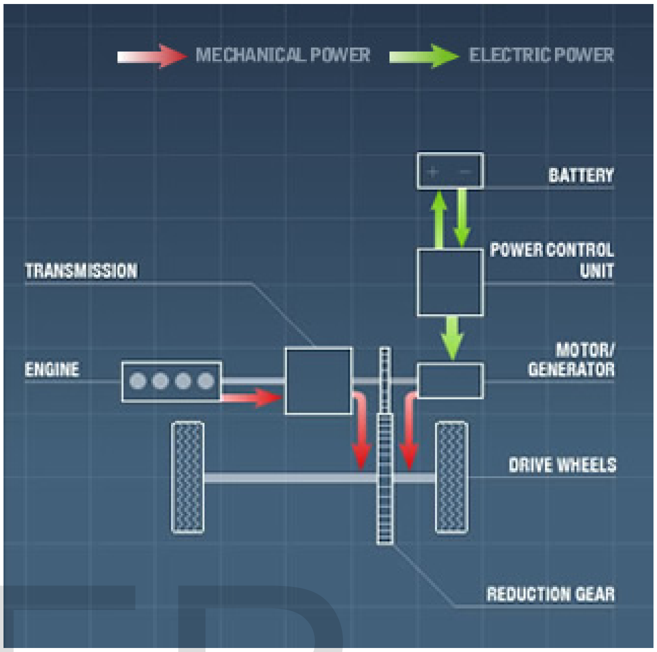

Figure 1-2: Schematic of parallel Hybrid Vehicle Configuration [7].

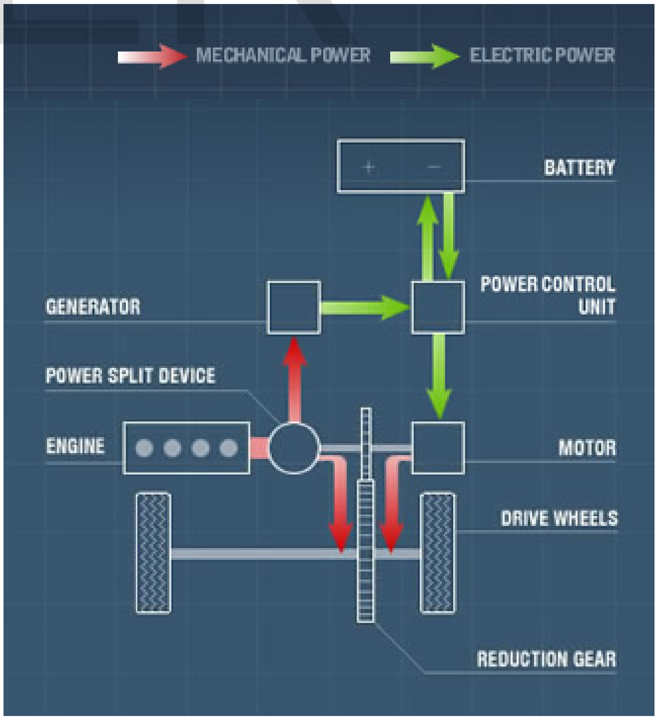

Figure 1-3: Schematic of Series-parallel (Power split) Hybrid Configuration [7].

Series/Parallel Hybrid Vehicle Configuration: With the Series Parallel Hybrid System, it is possible to drive the wheels using the dual sources of power (electric motors and/or gas/petrol engine), as well as to generate electricity while running on the electric motors. The system runs the car on power from the electric motors only, or by using both the gas/petrol engine and the electric motors together, depending on the driving conditions. Since the generator is integrated into the system, the battery can be charged while the car is running. Examples of this type of system are Toyota's Hybrid Synergy Drive (used in the Prius, Camry hybrid and others), Ford's Escape / Mariner Hybrid system, and the GM two mode hybrid system (used in the Chevrolet Tahoe and GM sierra). Series-parallel hybrid vehicle configuration is shown in Figure 1-4.

1.2 Electric Vehicles (EVs)

Electric Vehicles (EVs) do not use an Internal Combustion Engine to supply power to the wheels and drivetrain but they rely on electric motor to supply the power to the wheels. Most Electric vehicles (EVs) have more elaborate method to control the amount of electricity going to the motor and a system of gears to drive the wheels in a most efficient manner [5]. Due to high price of oil and increased concern over environmental impact of the petroleum-based transportation, has led to renewed interest in an electric transportation [3]. Electric vehicles today are electric cars, motorbikes, trains, airplanes and boats.

1.3 Fuel Cell Vehicles (FCVs)

A Fuel cell vehicle is a type of hydrogen vehicle which uses a fuel cell to produce electricity, powering its on-board electric motor. Fuel cells in vehicles create electricity to power an electric motor using hydrogen and oxygen from the air. Fuel cell vehicles have the potential to significantly reduce our dependence on foreign oil and lower harmful emissions that cause climate change. FCVs run on hydrogen gas rather than gasoline and emit no harmful tailpipe emissions. Several challenges must be overcome before these vehicles will be competitive with conventional vehicles, but the potential benefits of this technology are substantial.

FCVs look like conventional vehicles from the outside, but inside they contain technologically advanced components not found on today's vehicles. The most obvious difference is the fuel cell stack that converts hydrogen gas stored onboard with oxygen from the air into electricity to drive the electric motor that propels the vehicle. The major components of a typical FCV are illustrated in Figure 1-5.

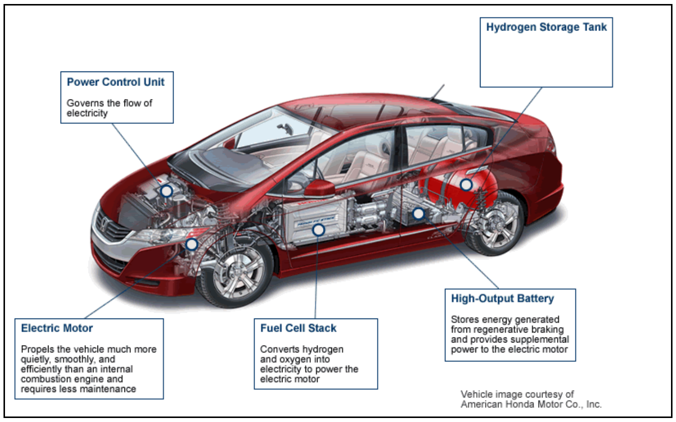

Figure 1-4: Concept of Fuel cell vehicle [8].

1.4 Fuel Cell Operation and Components

Fuel cell is an electrochemical device that uses hydrogen (fuel) and oxygen (oxidant) to generate electrical energy by means of an electrochemical reaction, with water and heat as its by-product. Main components of fuel cells are: 1. an electrolyte, 2. an anode and 3. a cathode. The fuel cell technology is important because it is clean, quiet and highly efficient process-two to three times more efficient than fuel burning. Fuel cell components are shown in Figure 1-6.

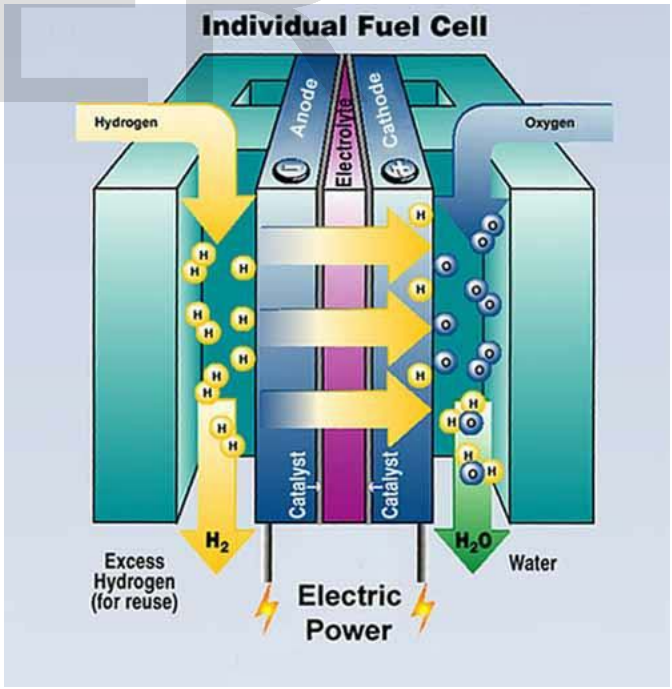

Figure 1-6: Fuel Cell Components [8].

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Types of Fuel Cells

- AFC : Alkaline Fuel Cells
- PAFC : Phosphoric Acid Fuel Cells
- PEMFC : Proton Exchange Membrane Fuel Cells
- DMFC : Direct Methanol Fuel Cell
- MCFC : Molten Carbonate Fuel Cells
- SOFC : Solid Oxide Fuel Cells

1.5 Hydrogen as a Fuel

There are many reasons behind the tendency of using hydrogen as a fuel instead of a lot of available alternatives. As we all know, the fossil fuels are the first choice for us due to factors like cheap, availability, accessibility, and abundance, but there are few serious drawbacks for them too such as emitting the pollutants and the greenhouse gases (CO, CO_2) leading to global warming and ozone layer depletion, ice melting, and climate change. The other negative points for fossil fuels are; highly increasing demands for them, increasing price of them, decreasing their reserves, reaching their production to the peak point, and being not secure. All of these factors push us to substitute them with clean energy sources which hydrogen will be one of them.

Hydrogen as a fuel has a lot of advantages which some of them are listed in the following:

- It is the simplest and most abundant element in the world
- It is sustainable and has no pollution
- It has very high gravimetric capacity and very low volumetric capacity compared to gasoline
- It can be produced by variety of methods

2 POWER SYSTEM OF PRIUS V

Take Toyota Pius v as the model to calculate and design the hydrogen storage tank. Its specifications are sown in Table 2-1.

Criteria for powertrain design:

1) Maintain or enhance the performance of power system.
2) Safety issues with fuel cell, hydrogen storage and motor operation.
3) Consideration of the weight change of vehicle.
4) Cost of driving using new system with hydrogen as fuel.
5) Energy efficiency and energy saving strategy during driving.

2.1 Replacement of Electric Motor

1) Power output requirement for electric motor:

From the Table 2-1. We can find that 59kW power from electric motor (EM) only make up part of hybrid system net power (100 kW). Thus, when IC engine is removed, it is necessary to replace present electrical motor with a more powerful one with at least power putout of 100kW to maintain the present performance of Toyota Prius v.

TABLE 2-1
SPECIFICATIONS OF POWER SYSTEM IN TOYOTA PRIUS V

Technical Specifications	
Curb Weight	1485 kg
IC Engine	1.8 Litre, 4-Cylinder, DOHC, 16-Valve, VVT-i
IC Engine Max Power Output	73 kW (98 hp) @ 5200 rpm
Engine torque	105 lb-ft @ 4,000 rpm
Fuel consumption (combined driving)	4.6 L/100km
Fuel Tank Capacity	11.9 gals/45.0 liters
Electric Motor	3-phase high voltage AC permanent magnet electric motor
Electric Motor Power	59kW (80 hp) /153 lb-ft torque
NiMH Battery	201.6 Volt Sealed NiMH Battery
Power output of NiMH battery	36 hp (27kW)
NiMH battery pack dimensions	15 x 40 x 9 in (387 x 1011 x 225 mm)
NiMH battery pack weight	90 lbs (41 kg)
Hybrid System Net Power	100 kW (134 hp)

2) Electric motor operation model selection:

Electric vehicles use two types of electric motors to provide power to drive the wheel: the direct current (DC) motor and the alternating current (AC) motor. DC engine was applied first in electric vehicles in the past; because they are simple to operate directly from the battery current without complex electronics system in control unit. The DC motor/controller system is still used today on some electric vehicles. AC motor systems are smaller, lighter, more efficient and lower cost than the DC systems. The permanent magnet type motor is the better choice for small and moderate power (25-150 kW) systems in passenger cars. The permanent magnet (PM) motors tend to be smaller and easier to control than the induction motors at moderate powers [9].

The features of DC and AC electric model are listed in Table 2-2.

Considering the cost, weight, efficiency and requirement for maintenance and power output, our overall operation on EM is to replace it with a permanent magnet AC motor, which provides the max power output of 100kW.

2.2 Powertrain Design and PEMFC Selection

Nuvera Product has the following advantages [11] :

1) Low Pressure Operation: The Nuvera stacks are able to operate with very low pressure drop allowing for the use of a lower cost air blower instead of a standard compressor.
2) No External Humidification: Nuvera has pioneered the use of a fuel cell stack technology that uses dry air and hydrogen as inputs, which reduces the heat exchange loops from three to one.
3) Metallic Bipolar Plates: Metallic stacks are suitable for transportation applications due to their resistance to shock and vibration and are significantly lower in manufacturing cost than graphite stacks.

TABLE 2-2
COMPARISON OF DC AND AC ELECTRIC MOTOR [10]

Features	AC Motor	DC Motor
Transmission	Single-speed	Multispeed
Weight	Light	Heavier for same power
Cost	Less expensive	More expensive
Efficiency	95% at full load	85-95% efficiency at full load
Controller	Complex	Simple
Design	Motor/controller/inverter more complex	Motor/controller less complex
Maintenance	Little or no maintenance required	Require periodic maintenance
Heat generation	More heat generated	brushless DC motors generate less heat
Safety	AC inverter fails and the car stops at shut-circus	short-circuit battery and cause fire

TABLE 2-3
SPECIFICATIONS OF ANDROMEDA FUEL CELL

Specifications	150 Cell	272 Cell	384 Cell
Stack Power	50kW ± 4	90kW ± 4	127kW ± 4
Stack Operating Voltage	130 – 90V ± 10	235 – 165V ± 10	335 – 235V ± 10
Transient Response	10% - 90% < 2 sec	10% - 90% < 2 sec	10% - 90% < 2 sec
Stack Dimensions	210(h) x 300 x 570 mm	210(h) x 600 x 535 mm	210(h) x 900 x 515 mm
Stack Weight	58kg ± 10kg	107kg ± 10kg	155kg ± 10kg
Energy density	0.86 kW/kg	0.84 kW/kg	0.82 kW/kg

A. Powertrain design 1 with secondary battery:

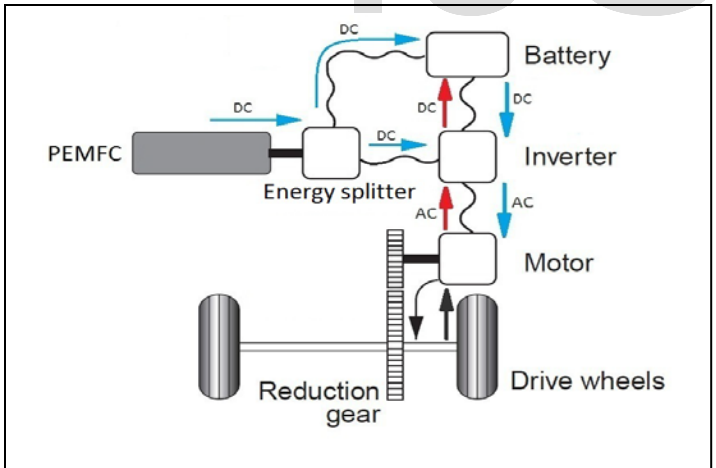


Figure 2-1: New Power System with Present Battery and Recharge Pathway.

In our new system design 1 (shown in Figure 2-1), we keep the battery and charging pathway from PEMFC to battery. The power produced by PEMFC is distributed by energy splitter, of which one part goes to invertor-motor; the other part is used to recharge battery. When the power demand is low, the fuel cell provides the required power. The battery allows the fuel cell system to perform more efficiently [12]. Many different kinds of battery can be applied in hybrid or electric vehicle, including NiMH, NaAlCl, NiCad, Li-ion and lead–acid. Their characteristics are compared with each other in Table 2-4. It is obvious to find out that lithium–polymer battery exhibits the best performance among all types. Anyhow, NiMH, which is presently used in Prius v, has the higher volume power density. It means that using NiMH will save space in vehicle, and it has the same life cycle with lithium–polymer battery. Try to simplify our design; we decided to maintain the present Nickel–metal hydride battery.

TABLE 2-4
CHARACTERISTICS OF BATTERY APPPLIED IN HYBRID AND ELECTRIC VEHICLES

Technology	Specific energy (Wh/kg)	Energy density (Wh/l)	Specific power (W/kg)	Power density (W/l)	Initial cost (US$/kW)	Life-cycle
Advanced lead-acid	35	71	412	955	180	500–1000
Nickel–metal hydride	80	200	220	600	450	1000
Lithium–polymer	155	220	315	445	400	1000
Sodium–nickel chloride	90	150	100	200	—	—
Nickel–cadmium	50	150	—	—	—	—

According the research results shown in Figure 2-2, the hybrid fuel cell system with a hybrid ratio of 1/3 exhibits the highest fuel efficiency [12]. With this hybrid ratio, the vehicle can cover the maximum driving distance with the same amount of hydrogen fuel. With 27kW battery in 100 kW total power out-put system, the hybrid ratio is 0.2, not as favourable as the optimized ratio, but still can maintain relative high fuel efficiency. It conforms that the design of fuel cell power system with 27kw battery is an economic choice.

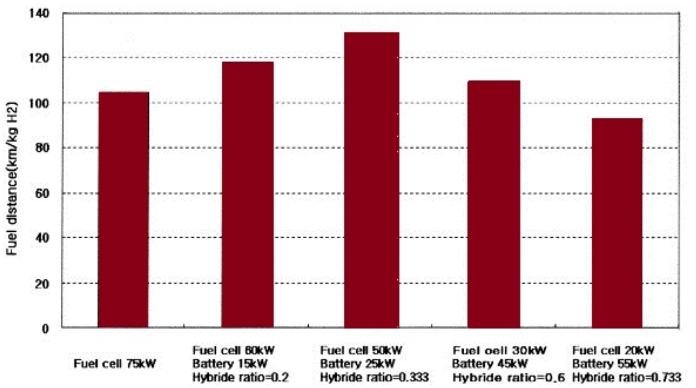


Figure 2-2: Comparison of Fuel Economy for Fuel Cell and Fuel Cell Hybrid Vehicles.

With a battery power output of 27kW, in order to obtain total 100kW net power output, the feasible and reliable design is to substitute present IC engine with a PEMFC offering at least 73kW power. Under this condition, 272 cell PEMFC and 384 cell PEMFC are applicable.

Take the energy density and weight into account, 272 cell PEMFC is the best choice for several reasons:

a. It has less weight, smaller volume and higher power density.
b. Its max power output is quite closed to required power capacity without too much waste of hydrogen and energy.
c. The excessive power generated can be used to charge battery through energy splitter.

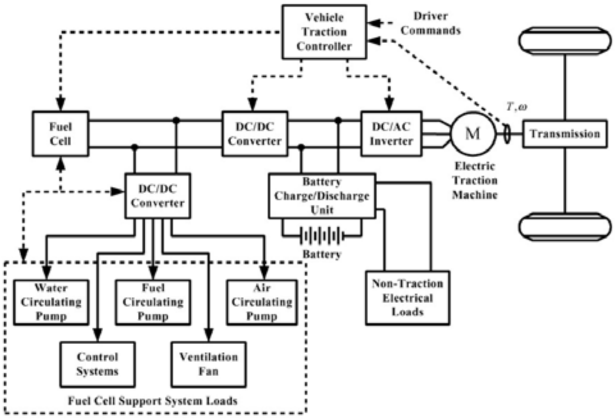


Figure 2-3: Topological Overview of Hybrid Electric and Fuel Cell Vehicular Power System Architectures and Configurations [13].

The operation mechanism for hybrid fuel cell and battery vehicular power system:

a. At normal cruising speed, PEMFC generates electric power to drive the motor.
b. When accelerating, the battery supplies more power to electric motor with PEMFC together to give better driving performance.
c. At start-up and low cruising speed, vehicle runs only with the power produced by battery.
d. At braking and deceleration, the motor acts like a generator and the excessive energy is turned into electricity power to charge battery.

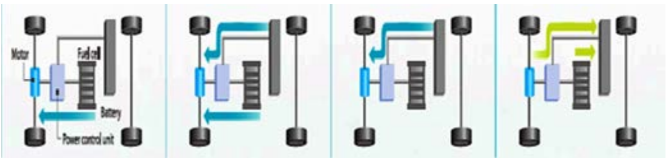


Figure 2-4: Topological Overview of Hybrid Electric and Fuel Cell Vehicular Power System Architectures and Configurations [13].

There are several advantages of using PEMFC together with battery.

a. The size of fuel cell is reduced.
b. Performance of fuel cell system under high power demand is improved.
c. Allow fast start-up of the fuel cell.
d. The capture of excessive and regeneration energy make it more energy efficient.
e. The required amount of hydrogen on-board storage is decreased.

The disadvantages of hybridization of fuel cell and battery are complexity of the control system, weight increase, and extra cost of battery manufacture.

B. Power train design 2 without secondary battery

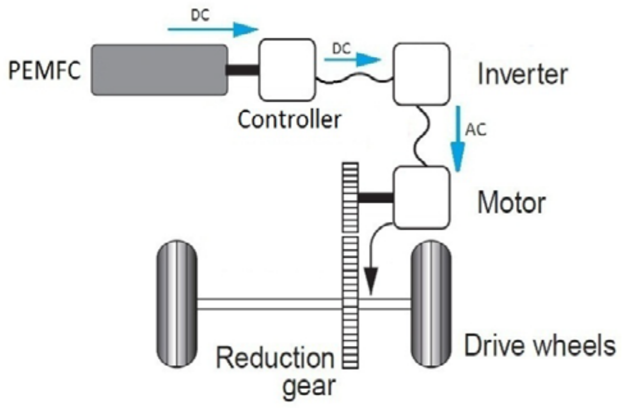


Figure 2-5: Power System Without Battery and Recharging Pathway.

There is another option for powertrain design in which the powertrain is built up without secondary battery. It becomes very simple after removing battery and charging pathway from the powertrain Figure 2-5. Without battery, the PEMFC becomes the only power source. Then more than 100kW power from PEMFC is required and only 384 cell product is suitable for this system. Although it doesn't require complex electric control system, this design still has several disadvantages.

a. It increases the total weight of vehicle. Although the removal of battery decreases the vehicle weight by 41kg, 384 cell PEMFC is 48 kg heavier than 272 cell PEMFC.
b. The excessive energy generated from PEMFC and by braking is both wasted without energy storage capacity.
c. More hydrogen on-board storage is required, which further increases vehicle weight.

Consider all these factors, we concluded that the removal of battery from power system is not favourable compared to the design with present battery. Thus we adopt the design with present 27kW battery.

3 CALCULATION OF HYDROGEN CONSUMPTION

3.1 Energy Consumption of IC Engine

1) Assumptions in calculation:

a. The required driving distance in this project is 400 km.
b. The vehicle is used for combined driving (4.6 L/100km gasoline consumption)
c. Gasoline's density is measured at temperature of 25 ºC (298.15 K).

d. All the energy stored in gasoline is released through combustion in IC engine.
e. IC engine the water produced exist in the form of vapor.
f. The fuel energy efficiency η of the engine of Toyota Prius v is indicated as 37.2% [15].

2) Calculation:

- The volume of consumed gasoline:

$$V = 4.6\ L/100km \times 400km = 18.4\ L \qquad (1)$$

- Lower heating value of gasoline[16] is used in calculation: $H_L = 12.07\ kWh/kg$.
- Density of gasoline [17]: $\rho = 0.72\ kg/L$
- Calculate the weight of gasoline consumed for 400km driving:

$$W = 18.4\ L \times 0.72 kg/L = 13.2\ kg \qquad (2)$$

- Energy stored in gasoline consumed for 400km driving :

$$E_{fuel} = 13.2\ kg \times 12.07\ kWh/kg = 159.324\ kWh \qquad (3)$$

- The net energy put into driving the car is calculated in equation (4).

$$E_{eff} = E_{fuel} \times \eta = 159.324\ kWh \times 37.2\% = 59.27\ kWh \qquad (4)$$

3.2 Energy Efficiency of PEMFC

TABLE 3-1
GIBBS FREE ENERGY AND MAXIMUM 'ETA' FOR WATER FOR VARIOUS TEMPERATURES AND STATES

Form of water product	Temp °C	ΔG° kJ/mol	Max E°	Max Efficiency η°
Liquid	25	-237.2	1.23V	83%
Liquid	80	-228.2	1.18V	80%
Gas	100	-225.3	1.17V	79%
Gas	200	-220.4	1.14V	77%
Gas	400	-210.3	1.09V	74%
Gas	600	-199.6	1.04V	70%
Gas	800	-188.6	0.98V	66%
Gas	1000	-177.4	0.92V	62%

In calculation, there is an assumption that the reaction occurs at a temperature of 80°C[18], actual operation temperature is between 50°C - 70°C [19]. The theoretical maximum efficiency for fuel cell in Table 3-1 is obtained using the following equation (5).

$$\eta_{max} = \frac{\Delta G^\circ}{\Delta H^\circ} \qquad (5)$$

ΔG°, Gibbs free energy. $\Delta G^\circ = -228.2$ kJ/mol (353K, refer to Table 3-2).

ΔH°, enthalpy change of water formation. $\Delta H^\circ = -284.2$kJ/mole (353K), corresponding to the produced H_2O in the liquid state. This value is known as the higher heating value (HHV).

The actual energy efficiency η_{act} can be calculated via equation (6) [20]:

$$\eta_{act} = \frac{\Delta G}{\Delta H^\circ} \qquad (6)$$

TABLE 3-2
FREE ENERGY, ENTHALPY (HIGHER HEATING VALUE) AT DIFFERENT TEMPERATURES [21]

Temp (K)	ΔG° (kJ/mol)	Δ H° (kJ/mol)
298	-237.3	-285.8
333	-231.6	-284.8
353	-228.4	-284.2
373	-225.2	-283.5

ΔG, the actual Gibbs free energy used in fuel cell.

ΔG could be calculated with equation (7).

$$\Delta G = -ZFE \qquad (7)$$

- *F*, Faradays constant, F= 96485 C/mole
- *E*, the electromotive force for single battery cell
- *Z*, the number of electrons that pass through the system per molecule of reactant. For hydrogen, Z = 2.

In order to evaluate the best performance of battery, the top value of electromotive force available is adopted in calculation. Assume that each fuel cell produce the same voltage. For 272 cell battery, $E_{act} = 235/272 = 0.864$ V.

Theoretical electromotive force E^o = 1.18V and the maximum efficiency $\eta_{max} = 80\%$.

Combine the equation (5) (6) and (7), we got the actual energy efficiency η_{act} for fuel cell expressed from the following equation (8):

$$\eta_{act} = \eta_{max} \times \frac{E}{E^\circ} \qquad (8)$$

Substitute in $\eta_{max} = 80\%$, E = 0.864 V, E^o = 1.18V, we got the actual energy efficiency of $\eta_{act} = 58.58\%$. This value agrees with the efficiency reported by ECW, refer to Table 3-3 [22].

TABLE 3-3
LIST OF VARIOUS HYDROGEN FUEL CELLS AND THEIR PROPERTIES [22]

Fuel Cell Type	Mobile Ion	Operating Temp./ °C	Efficiency
Alkaline	OH−	50-200	N/A
Proton exchange membrane	H+	50-100	35-40%
Phosphoric acid	H+	≈ 220	35-40%
Molten carbonate	CO32-	≈ 220	50-55%
Solid oxide	O2-	500-1000	45-50%

3.3 Hydrogen Consumption of PEMFC

1) Assumptions in calculation:

a. The net energy we got from fuel cell should equals to the net energy put into driving the car from gasoline (59.27 kWh).
b. All the enthalpy change of H2O formation is converted into electricity in fuel cell.
c. Hydrogen is stored at 298.15K, at pressure of 70 MPa.
d. No hydrogen loses during storage and transportation from storage reservoir to fuel cell.

2) Calculation:

- Energy stored in gasoline consumed for 400km driving:

$$Et = E_{eff} / \eta_{act} = 59.27kWh / 58.85\% = 100.71kWh = 362556kJ \quad (9)$$

- The weight of H_2 consumed:

$$W_H = Et / - \Delta H° \times M_{mol} = 362556\ kJ / 284.2kJ/mol \times 2g/mol = 2.55kg \quad (10)$$

- From a case study, it is indicated that the electrical path has only 70% efficiency in second generation of Toyota hybrid vehicle. Then we got the actual weight of H_2 c consumption:

$$W_{act} = W_H / 70\% = 2.55kg/70\% = 3.64kg \quad (11)$$

- Hydrogen is not ideal gas (refer to Figure 3-1). Calculation of compressibility factor of hydrogen at 70Mpa:

$$Z = 0.99704 + 6.4149 \times 70 \times 10^6 \times 10^{-9} = 1.45 \quad (12)$$

To verify the accuracy of the result from equation (11), we adopt another more accurate method to calculate the compressibility factor of hydrogen [24]. This method is based on equation (12). It has been proved that result from this formula agree with the current standard to within 0.01 % from 220 K to 1000 K with pressures up to70 MPa.

$$Z(p,T) = \frac{p}{\rho RT} = 1 + \sum_{i=1}^{9} a_i \left(\frac{100\ K}{T}\right)^{b_i} \left(\frac{p}{1\ MPa}\right)^{c_i} \quad (13)$$

The value of a, b, c were given in Table 3-4. After calculation, Z (298.15K, 70Mpa) = 1.4459. Compared with the value from (11), it only has 0.3% error, which could be ignored.

- the density of Hydrogen is:

$$\rho = P/ (ZRT) = 70 \times 10^6\ Pa/(1.45 \times 4157\ Nm/kg \cdot K \times 298.15\ K) = 38.95\ kg/m^3 \quad (14)$$

- Actual volume of H_2:

$$V = W/ \rho = 3.64kg / 38.95\ kg/m^3 = 0.09353\ m^3 = 93.53L \quad (15)$$

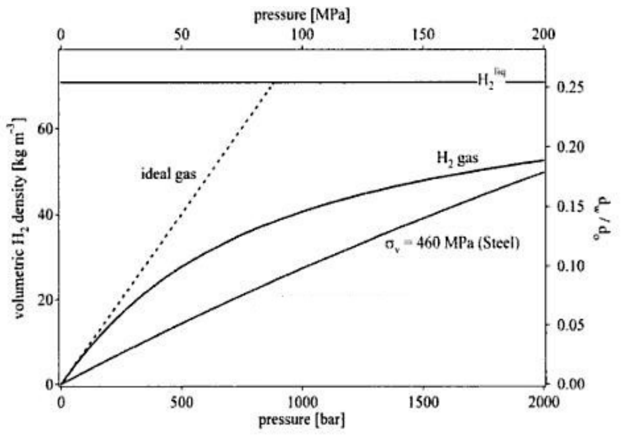


Figure 3-1: Hydrogen volumetric density changes with pressure[23].

TABLE 3-4
CONSTANTS ASSOCIATED WITH THE DENSITY EQUATION FOR NORMAL HYDROGEN

i	a	b	c
1	0.0588846	1.325	1.0
2	-0.06136111	1.87	1.0
3	-0.002650473	2.5	2.0
4	0.002731125	2.8	2.0
5	0.001802374	2.938	2.4
6	-0.001150707	3.14	2.6
7	9.58853E-05	3.37	3.0
8	-1.10904E-07	3.75	4.0
9	-1.2644E-10	4	5.0

4 ECONOMIC ANALYSIS OF FCHV

It is necessary to evaluate the efficiency, fuel economy and characteristics of power output in hybridization of fuel cell vehicles.

4.1 Cost of Hydrogen Supply

From Table 4-1, the average cost of hydrogen is proximately $4 to $12 per kilogram, which is equivalent to gasoline at $1.60 to $4.80 per gallon. Combining the calculation results, the cost for 3.64kg hydrogen is approximately $15-$44. The price of gasoline in Canada is around$5 per gallon, which means that hydrogen fuel with lower price is competitive in

Canada vehicle market. However, looking at figure 3-2, we can find that gasoline price varies in a wide range around that world. In many countries with slower industry development, gasoline price can be as low as around $1 per gallon. On contrary in some European countries, gasoline price is around $8-$10. It is predictable that in those countries where gasoline price is lower than hydrogen fuel, fuel cell hybrid vehicle is not competitive to conventional IC engine vehicle. But in America, Canada, China and certain European countries, FCHV have considerable market potential due to the low price of hydrogen fuel.

If the cost of hydrogen fuel could be reduced in some way, the FCHV could be more economic and popular in market. The cost of hydrogen supply can be reduced in several ways:

- Reduce the cost of producing hydrogen from natural gas.
- Reduce the cost of producing hydrogen from renewable resources.
- Reduce the cost of delivering hydrogen to the end-user.
- Improve the capacity of hydrogen storage systems.
- * each include $1.25 for taxes.

TABLE 4-1
THE COST OF HYDROGEN SUPPLY FROM DIFFERENT SOURCES, PRODUCTION AND DELIVER METHOD [25]

Hydrogen sources	Production and deliver method	Cost / $/kg*
Hydrogen from natural gas	produced via steam reforming at fueling station	4-5
	produced via steam reforming off-site and delivered by truck	6-8
Hydrogen from wind	via electrolysis	8-10
Hydrogen from nuclear	via electrolysis	7.5-9.5
	via thermochemical cycles –in a large scale	6.5-8.5
Hydrogen from solar	via electrolysis	10-12
	via thermochemical cycles – in a large scale	4.5-9.5

4.2 Cost of Fuel Cells and Vehicle Manufacture

The application of durable membrane electrode assemblies (MEAs) with low platinum group metal (PGM) content reduced the manufacture cost of automotive fuel cells from $275/kW in 2002 to $49/kW in 2011. In 2006, the maximum durability of fuel cell in vehicles was demonstrated as 950 hours. In 2011, this magnitude achieved more than 2,500-hour (75,000 miles) with less than 10% degradation under real-world conditions. Development of a solid-oxide fuel cell for micro-combined heat and power applications introduced an almost 25% increase in system power density with more than a 30% reduction in stack volume and a 15% reduction in stack weight [27]. Developed advanced manufacturing methods and materials that enabled a 50% decrease in the cost of gas diffusion layers since 2008 [28].

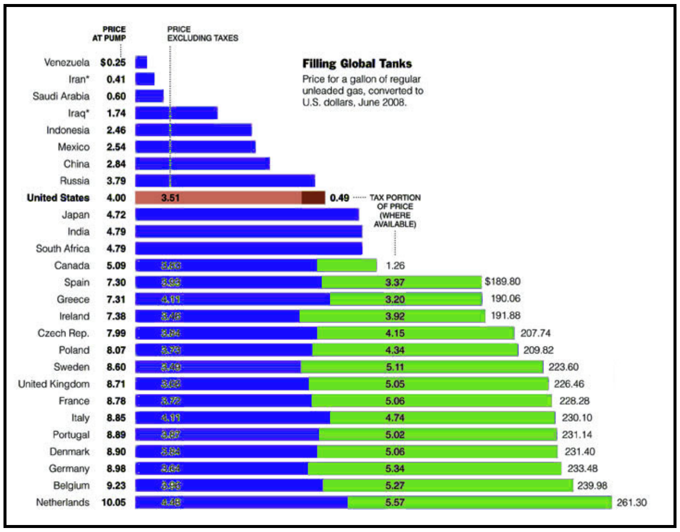


Figure 4-1:**The gasoline price at pump in different countries around the world [26].**

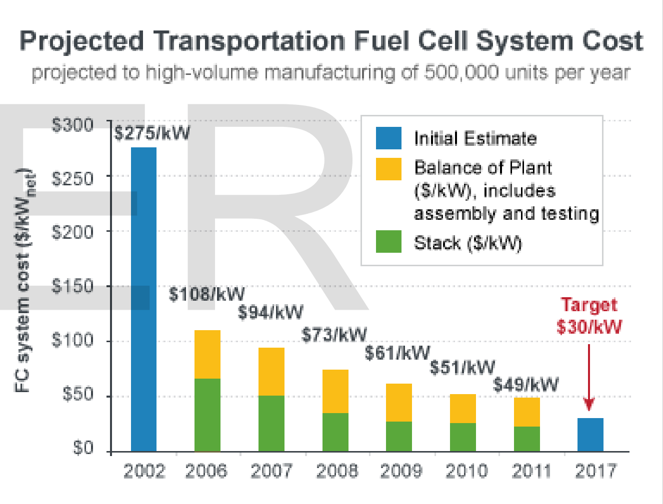
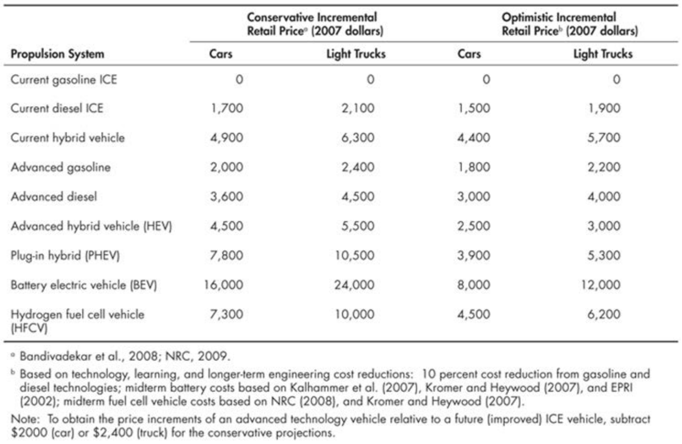


Figure 4-2: **FC system cost estimation and prediction [29].**

The cost of whole vehicle system changes with different power system, and the prediction is shown in Table 4-2 [30]. It is obvious that although the manufacture cost of hydrogen fuel cell vehicle is not as low as fossil fuel or hybrid fossil fuel vehicle, but is still lower than pure electric vehicle and competitive to plug in hybrid vehicle. It should be notice that this data was obtained in 2005. Along with the development of fuel cell manufacture technology, there is possibility for further reduce of HFCV manufacture cost nowadays and in future.

TABLE 4-2
ESTIMATED INCREMENTAL COST OF ADVANCED VEHICLES IN THE NEXT 25 YEARS RELATIVE TO A BASELINE 2005 STANDARD GASOLINE VEHICLE.



	Conservative Incremental Retail Price[a] (2007 dollars)		Optimistic Incremental Retail Price[b] (2007 dollars)	
Propulsion System	Cars	Light Trucks	Cars	Light Trucks
Current gasoline ICE	0	0	0	0
Current diesel ICE	1,700	2,100	1,500	1,900
Current hybrid vehicle	4,900	6,300	4,400	5,700
Advanced gasoline	2,000	2,400	1,800	2,200
Advanced diesel	3,600	4,500	3,000	4,000
Advanced hybrid vehicle (HEV)	4,500	5,500	2,500	3,000
Plug-in hybrid (PHEV)	7,800	10,500	3,900	5,300
Battery electric vehicle (BEV)	16,000	24,000	8,000	12,000
Hydrogen fuel cell vehicle (HFCV)	7,300	10,000	4,500	6,200

[a] Bandivadekar et al., 2008; NRC, 2009.

[b] Based on technology, learning, and longer-term engineering cost reductions: 10 percent cost reduction from gasoline and diesel technologies; midterm battery costs based on Kalhammer et al. (2007), Kromer and Heywood (2007), and EPRI (2002); midterm fuel cell vehicle costs based on NRC (2008), and Kromer and Heywood (2007).

Note: To obtain the price increments of an advanced technology vehicle relative to a future (improved) ICE vehicle, subtract $2000 (car) or $2,400 (truck) for the conservative projections.

5 PRESSURE VESSEL DESIGN

5.1 Introduction

A pressure vessel is a closed contained that is able to store many types of gases and liquids that are pressurized above the ambient temperature. In the industry there are many uses of pressure vessels. Some of the industries that use it are oil refineries and power plants for storage of crude oil, nitrogen, ammonia and hydrogen. Homes have pressure vessels for hot water storage as well as diving cylinders/ scuba tanks that are used to hold breathing gas. One of the important applications that will be discussed is the storage of hydrogen for the use of hybrid vehicles.

Pressure vessels can come in many shapes and sizes depending upon the application that it has to serve. Some of the most popular shapes are cylindrical with hemispherical heads and spherical as shown in Figure 5-1. Cylindrical tank was chosen for this project as it is easy to manufacture thus reducing the cost.

Due to high pressure storage inside the pressure vessels, the types of materials chosen are very critical to make the tanks lightweight and pressure resistant. The pressure vessel design is regulated by many codes and standards. In the industry ASME has a design guides containing types of materials and design formulas that is used to aid in the design of pressure vessel. Many pressure vessels are made of steel and composite material such as carbon fiber with epoxy resin. Composite materials are very good in strength to weight ratio but one of the drawback are that they are very expensive and are difficult to manufacture.

Pressure vessel is held together against the tensile forces exerted from the compressed gas/ liquid. As the tensile stress is proportional to pressure and radius and inversely proportional to thickness of the wall we should be very careful in choosing the radius and wall thickness as to limit the stresses inside the pressure vessel. Stresses exerted on pressure vessel are hoop stresses (stresses in circumferential direction) and axial stresses (longitudinal direction). For a cylindrical tank with hemispheric heads the hoop stresses and axial stresses are shown in Figure 5-2.

Theoratically spherical pressure vessels are twice the strenth as cylinderical but are hard to manufacture and the manufacturing price increases drastically so the best choice is the cylindrical tank with hemispheric heads.

Figure 5-1: **Cylindrical and spherical pressure vessel used in the industry [31, 32]**

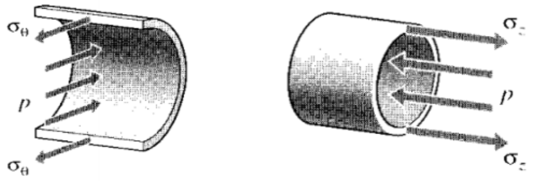


Figure 5-2: **Hoop stress (Left) and Axial stress (right) for a thin walled pressure vessel [33].**

5.2 Tank Design Constraint

For the design of a 70 MPa hydrogen storage pressure vessel for a hybrid car there are many design constraints that should be taken into account such as feasibility of manufacturing, weight of the reservoir, cost, thermal expansion and permeation rate to name a few.

For the hydrogen tank to be feasible, cylindrical pressure vessel with hemi-sperical heads was chosen as they are easier to construct then the spherical pressure vessel. The manufacturing cost also decreases for the cylindrical pressure vessels as they are easier to construct. Strength and weight is critical for a pressure vessel because higher strength of material translates into less thickness of tank walls which reduces the cost of manufacturing and makes the pressure vessel lighter.

5.3 Type of Pressure Vessels

There are 4 types of pressure vessels that are used for storing 70 MPa hydrogen and can be seen below in Figure 5-3.

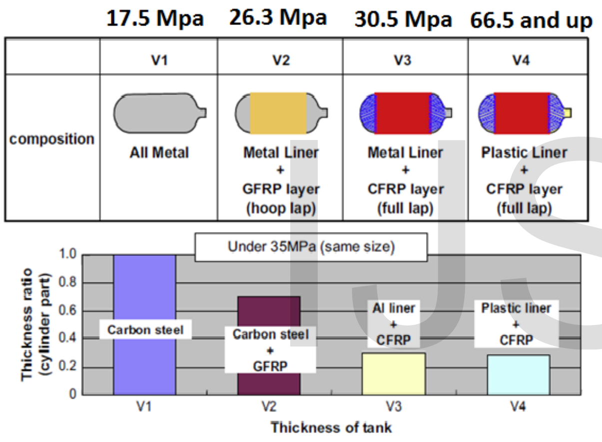


Figure 5-3: **Types of hydrogen storage pressure vessels available [34]**

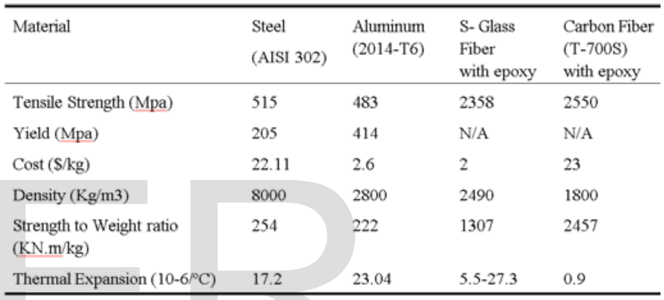
From Figure 5-3 it can be seen that type I pressure vessel on the far left is made of carbon steel. The pressure that type I tank can withhold is approximately 17.5 MPa. Type II tank on the other hand is made out of metal liner (carbon steel) with glass fiber reinforced polymer. The advantage of type II tank is that it can hold higher pressure than type I (26.3 MPa) and the thickness ratio of the tank decreases which results in lighter tank. Type III tank is made of metal liner that consists of aluminum and it has a carbon fiber reinforced polymer wound fully around the tank. This tank can hold pressure up to 30-40 MPa and the weight decreases relative to type I and type II tank. However, the 3 tanks are not feasible for the storage of 70 MPa hydrogen gas so type IV tank is introduced. Type IV tank consists of plastic liner and carbon fiber reinforced polymer. This tank is able to withhold pressure higher than 66.5 MPa which makes it feasible for the storage of hydrogen gas at 70 MPa.

5.4 Material Comparison / Selection

One of the important aspects of pressure vessel design is the material selection. Material is selected based on its tensile strength, thermal expansion, density and cost. When comparing some of the material used in pressure vessel design as seen in Table 5-1, we can see that carbon fiber has the highest strength to weight ratio, lower thermal expansion and density. The only downside of carbon fiber is the cost. For automotive applications the weight and strength are considered the most important aspect. Lower weight of vehicle can provide higher fuel efficiency while the strength can help improve the safety of the passengers in the car. Due to these reasons the tanks wrapping is done using carbon fiber composite instead of other materials.

TABLE 5-1

LIST OF VARIOUS PROPERTIES OF MATERIAL THAT ARE USED TO CONSTRUCT THE PRESSURE VESSEL



Material	Steel (AISI 302)	Aluminum (2014-T6)	S- Glass Fiber with epoxy	Carbon Fiber (T-700S) with epoxy
Tensile Strength (Mpa)	515	483	2358	2550
Yield (Mpa)	205	414	N/A	N/A
Cost ($/kg)	22.11	2.6	2	23
Density (Kg/m3)	8000	2800	2490	1800
Strength to Weight ratio (KN.m/kg)	254	222	1307	2457
Thermal Expansion (10-6/°C)	17.2	23.04	5.5-27.3	0.9

5.5 Stresses in Pressure Vessels

When designing a pressure vessel it is critical to worry about stresses that will be induced. Some of the most important stresses included cyclic stress (fatigue stress). The 70 MPa pressure vessels will be fueled many times during the operation of the pressure vessel inside a car. SAE J2579 rules dictate that the pressure vessel should be able to withhold 5500 refueling cycles. However, other organizations have different refueling cycles. This can be observed inTable 5-2. The EIHP (European Integrated Hydrogen Project) and ISO 15869.3 have higher refueling cycles. Since the tank is for automotive application the SAE J2579 rules were followed.

High shock and vibrations from the vehicle should also be taken into account. The tank has to be protected during car crashed and vibrations. When vibrations are induced to the pressure vessel, the agitation of compressed hydrogen gas inside pressure vessel will cause static charge. The static charge can lead to catastrophic failures in the pressure vessel. To reduce the agitation of tank and vibrations, the Impact resistant dome is used to protect the pressure vessel from high shock and vibrations as well the tank is firmly tightened to the car. The resistant dome is usually made of rubber and it fits on the caps of the pressure vessel as can be seen in the below Figure 5-4.

Tests such as gunfire test, drop test and pressure test are done to observe the safety of the pressure vessels. Many manufacturers like Quantum Technologies have added extra features such as reinforced external protective shell to increase the safety of the pressure vessel and to protect from impact, cuts and gunfire.

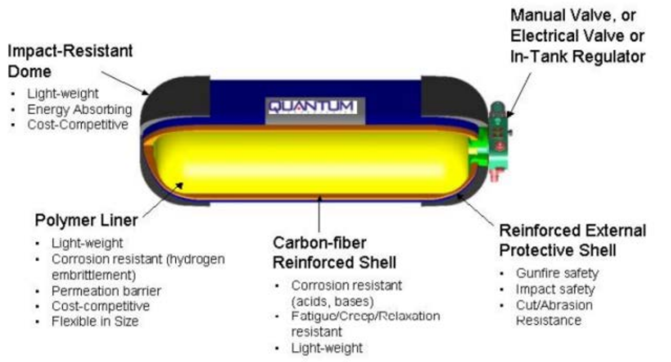


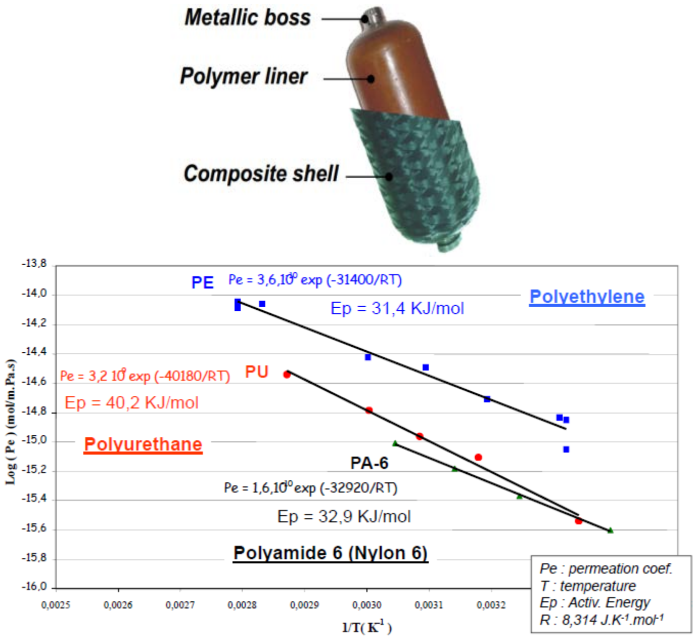
Figure 5-4: **Type IV pressure vessel components built by QUANTUM technology [36]**.

5.6 Type IV Tank

From thorough analysis of all 4 types of tank available, it was decided that only type IV tank is feasible for 70 MPa hydrogen storage tank. Type IV tank is a composite overwrapped pressure vessel which consists of a non-structural liner wrapped with fiber composite. Figure 5-5 depicts the type IV tank and the construction material. The composite shell is made of carbon fiber and the function is to provide strength for the tank. The liner can be made of different materials such as polyethylene, polyurethane and Nylon-6 (PA 6). The function of the liner is to provide barrier between the gas and the composite to prevent leaks and chemical degradation of fiber composite. When the hydrogen gets mixed with the carbons in the carbon composite, the outside material becomes brittle and is prone to failure. To prevent hydrogen leaks, Nylon-6 was used as it provides enhanced barrier properties as can be seen in the below Figure 5-5.

5.7 Fueling Criteria

The pressure vessel will be fueled at a hydrogen fueling station. The fueling rate, pressure and temperature are dependent on each other so when fueling at a certain rate and pressure, the temperature in the tank shouldn't exceed the set temperature or else the tank will be overfilled. Overfilling of pressure vessel can cause catastrophic failures. SAE J2601 has set refilling criteria and it states that the fueling stations will operate at 25% higher pressure above nominal pressures to allow gas to flow from the station into the vehicle at an acceptable rate and fill pressure. For a nominal working pressure of 70 MPa the fuel pump will be discharging hydrogen gas at 87.5 MPa which is the maximum allowable working pressure. When fueling at 40.2 g/l gas density and 87.5 Mpa, the temperatures shouldn't exceed 85 degrees Celsius. This is clearly depicted by the belowFigure 5-6. For fueling at other pressures, the straight line in the figure should be followed.



Polyamide-6 and Polyurethane have enhanced H2-barrier properties compared to Polyethylene (not suitable for hydrogen application)

Figure 5-5: **Type IV pressure vessels main components (Left) and Permeation rate of different liner materials (right) [37]**.

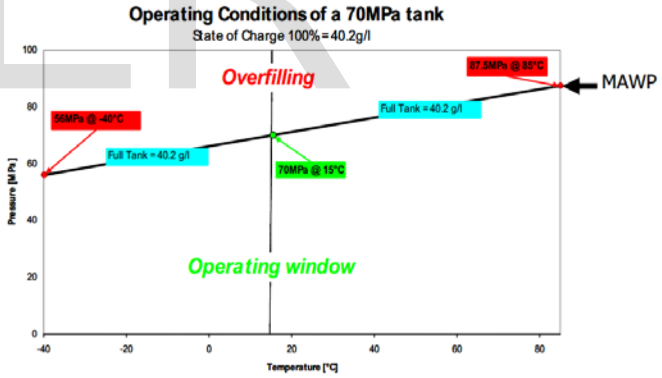


Figure 5-6: **Hydrogen fueling rate, temperature and pressure chart [38]**.

5.8 Tank Design

For the tank design there are criteria that have to be met as described above. Table 5-3 portrays the requirements of the tank and the construction material to be used. Two designs for the pressure vessels are designed. Design 1 consists of 1 tank of 94 L while design 2 consists of 2 tanks of 47 L. In this paper we will only look at Design 1 since it weighs less, it's less costly and takes up less space in the trunk. The criteria listed in Table 5-3 are for design 1.

For the design of the tank the length of the pressure vessel was arbitrarily chosen to be 75cm because of the Toyota Prius design constraints. Some of the constraints imposed on the pressure vessel are that the overall length of pressure vessel should not increase the length of the Toyota Prius which is 115 cm. Since 94 L of hydrogen gas at 70 MPa is needed, it is critical to find the internal diameter as well as thickness of the composite and the thickness of the liner. It is assumed that the pressure vessel will be a thin walled pressure vessel so to meet this requirement the ratio of radius to thickness has to be greater than 10.

TABLE 5-3
CRITERIA AND MATERIAL SELECTION TABLE FOR THE TYPE IV PRESSURE VESSEL DESIGN

Criteria		Material Selection	
max fuelling pressure	87.5 MPa	**Tank Liner Material**	PA6
max gas temp in vehicle tank	85 degrees	**Tank Liner Thickness**	4 mm
Nominal Working pressure	70 MPa	**Carbon Fiber Type**	T700 C.F
Minimum Working Pressure	0.3- 2 MPa	**Carbon Fiber Tensile strength**	2500 MPa
Number of cycles	>5500	**Overwrap Thickness**	
Burst Safety Factor	2.25		
Number of Tanks	1		
Volume of Tank	94 L		
Length to Diameter Ratio	3		
Cylinder Length	115 cm		

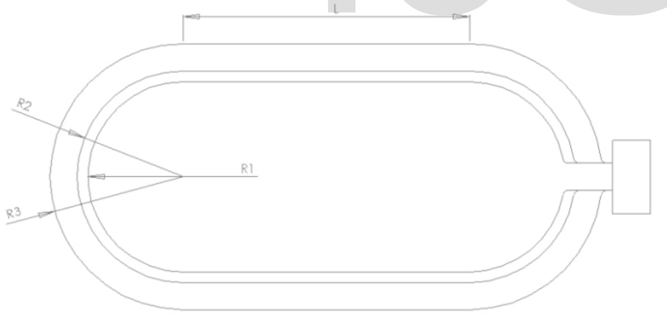


Figure 5-7: **Pressure vessel design where R1, R2, R3 and L need to be determined.**

From the above criteria, the volume of the tank, liner and carbon fiber was found using the calculations shown below. The mass of the linear as well as the mass of carbon fiber were found.

$$V_{Inside} = \frac{4}{3} * \pi * r_1^3 + \pi * r_1^2 * l \qquad V_{Inside} = \frac{4}{3} * \pi * 0.1785^3 + \pi * 0.1785^2 * 0.7$$

$$\boldsymbol{V_{Inside} = 94\,L}$$

$$V_{liner} = \frac{4}{3} * \pi * (r_2^3 - r_1^3) + \pi * (r_2^2 - r_1^2) * l \qquad \boldsymbol{V_{liner} = 4.8\,L}$$

$$m_{liner} = \rho_{liner} * V_{liner} \qquad \boldsymbol{m_{liner}} = 1150 * 0.0048 = \boldsymbol{5.52\,kg}$$

$$\boldsymbol{V_{carbon} = \frac{4}{3} * \pi * (r_3^3 - r_2^3) + \pi * (r_3^2 - r_2^2) * l} \qquad \boldsymbol{V_{carbon} = 17.9\,L}$$

$$m_{carbon} = \rho_{carbon} * V_{carbon} \qquad \boldsymbol{m_{liner}} = 1750 * 0.0179 = \boldsymbol{31.325\,kg}$$

From above calculation it can be concluded that the final dimension shown below satisfy the thin wall criteria as well as it fits in the Toyota Prius.

$$\boldsymbol{l = 70cm}$$

$$\boldsymbol{r_{out} = 0.1965\,m}$$

$$\boldsymbol{r_{in} = 0.1785\,m}$$

To determine the mass of the pressure vessel, we find the weight of the H_2 gas, carbon fiber, foam and balance of plant which includes pressure regulator, control valves, fill port and pressure gauge. The Table 5-4 below depicts the overall mass of the pressure vessel as well as the mass of the materials. From the overall weight we can find the gravimetric density of the pressure vessel. The gravimetric density for this design comes out to be 5.8 wt% H_2. The gravimetric density fulfills the 2010 requirements set for the 70 MPa pressure vessel.

TABLE 5-4
TYPE IV PRESSURE VESSEL WEIGHT WITH ITS COMPONENTS

Parts	Weight (kg)
H2 gas	3.64
PA6 Liner	5.52
Foam (protective end caps)	4
Carbon fiber	31.325
Balance of Plant	18
Weight w/o H2	**58.845**
Weight with H2	**62.485**

Stresses induced in the pressure vessel that was designed above should be found. With the tank dimensions and thickness, the hoop stresses and axial stresses for this pressure vessel can be calculated using the formulas shown:

$$\sigma_H = \frac{P\,D}{2\,t} = \frac{70 * 2.25 * 0.357}{2 * 0.018} = 1561.875 \text{ Mpa}$$

$$\sigma_L = \frac{P * F.O.S * D}{4\,t} = \frac{70 * 2.25 * 0.357}{4 * 0.018} = 781\,Mpa < 2500\,Mpa$$

The stresses from the calculations depict that the hoop stress and the axial stresses at rupture are below the tensile strength of the carbon fiber composite. It is assumed that the liner transfers 85% of the axial and hoop stresses. Even with this assumption it can be seen that the stresses induced in the pressure vessel as way below so this design is feasible and can be manufactured.

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5.9 Placement of Tank

The pressure vessel will be placed in the trunk of the Toyota Prius. The dimensions of the Toyota Prius are as shown below. The tank was designed in accordance with the dimensions shown for proper placement of the tanks. The tank placement is shown by the picture on the right (shown in Figure 5-8).

Figure 5-8: **The trunk space for the tank (Left) and tank placement in the Prius (Right) [39]**

The Toyota Prius has a trunk capacity of 445 L and the carbon fiber tank is 116.7 L in capacity. When the tank is placed inside the trunk there is still a decent amount of space available. To be exact the available volume is 328.3 L. The tank occupies 26.2% of the overall trunk capacity so there is still space available and no changes to the trunk have to be made to fit the pressure vessel.

5.10 Tank Manufacture

The liner and the carbon fiber composite are made by two different processes. The liner needs to be a hollow plastic part that is of constant thickness. The method of creating the plastic liner is by reactive rotational molding. The process of rotational molding can be seen in Figure 5-9**.** The first step in production of the liner is that the mold is heated and Nylon-6 charged particles are shot into the mold. The mold is then rotated which causes the material to stick to the walls of the mold. The mold rotates constantly during heating and cooling phase to avoid sagging or deformation. The final part is of constant thickness when it is taken out after it has cooled.

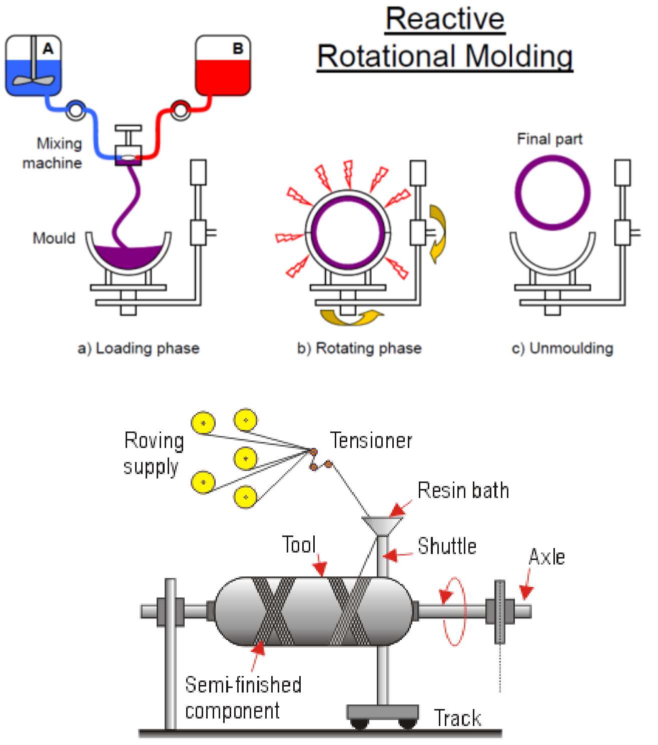


Figure 5-9: **Liner molding (left) and Carbon fiber winding (right) [37, 40].**

On the other hand, the carbon fiber is wound using the filament winding process as shown inFigure 5-9**.** The linear is placed on an axle that rotates at a constant speed. The strand carbon fiber rolls are placed on the roving supply and are connect to a shuttle that can move back and forth in the y direction. The carbon fiber strands get soaked in resin bath and then are wrapped onto the linear at winding angle of 54.7 degrees. At this winding angle the strength is twice the strength in the circumferential direction to the longitudinal direction. Above it was seen that stresses in circumferential direction were two times greater than the longitudinal direction so it is necessary to strengthen the composite wrapping in the circumferential direction to withstand the stresses and increase the strength of the overall composite tank.

5.11 Summary of Tank Design

This section looked at the design of pressure vessel design. The first step was to determine the types of tanks available for 70 MPa hydrogen storage. It was determined that type IV tank was the most feasible out of all the tanks. Then the types of materials that are used to design the pressure vessel are analyzed to see why the strength of type IV pressure vessel increases while the weight reduces. There were many constraints that the hydrogen storage had to meet such as the constraint on Toyota Prius, weight, pressure storage as well as induced stress. The fueling criterion of the tank was also analyzed as well as some of the regulations that are set by different organizations such as ASME and SAE. The pressure vessel was designed and the overall weight of the tank as well as gravimetric densities was analyzed. The gravimetric density of the designed pressure vessel met the 2010 requirements so the tank was feasible. The hoop stresses and longitudinal stresses were calculated. The stresses were way below the tensile stress of carbon fiber so the tank would be able to withstand a pressure of more than 157.5 MPa. The tank placement in the Toyota Prius was determined. The tank could fit in the trunk of the Prius without taking much space. To be precise the tank occupied 26.2% of the space so there is still more trunk space for storage of other items. In the end, the tools and processes that are used to construct the type IV tank are shown and are very feasible for manufacturing purposes. In the end, the designed pressure vessel was type IV pressure vessel that can withhold 94 L of H_2 gas at 70 MPa of pressure. The stresses and the space taken by the pressure vessel are minimal which makes type IV tank very attractive to use in the storage of H_2 gas for future cars.

6 WEIGHT ANALYSIS OF TOYOTA PRIUS V

6.1 Parts Removed and Added

In the new design the part removed are Engine Assembly, Gearbox, Radiator, Fuel Tank Exhausts system assembly, so the total weight is 281 kilogram. However, the new estimation of design part added are Fuel cell, Tanks with hydrogen, NiMH Battery peck, Electric motor, Cooling system, Power control unit (accessories), Pressure valves, regulators, so the total weight is 311 kilogram. The weight of fuel cell is 107 kilogram according the Andromeda 272 fuel cells. The tank design is 58.84 kilogram plus the weights of hydrogen 3.6 kilogram so the weight of thank is 62.48 kilogram. The weight of 59 kilowatt over Power-to-weight ratio is 1.37 to get the electric motor weight of 43 kilogram. The other weight such as NiMH Battery peck, Cooling system, Power control unit (accessories), and Pressure valves, regulators had taken from Toyota Motor Corporation category. Therefore, the total weight is 303.48kilogram of the new weight. However, the weight difference between the two vehicles is 22.48 kilogram. In the end the new vehicle is 1507.4 kilogram, which is listed in Table 6-1.

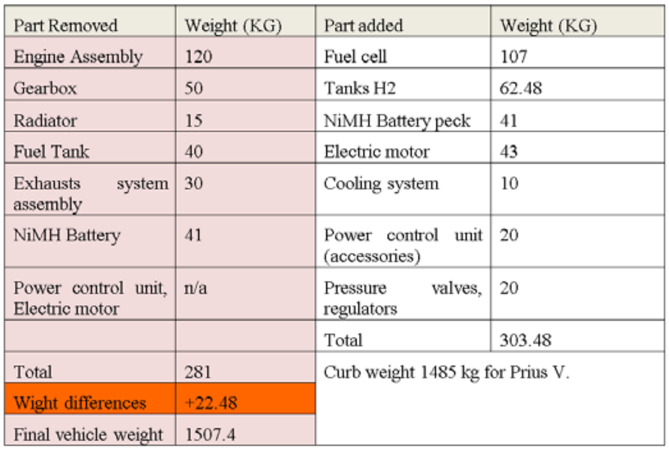
6.2 Department of Energy

The Department of Energy (DOE) is focusing on the PEMFC as the most likely candidate for transportation applications. The U.S. Department of Energy introduced a number of targets for on board hydrogen storage systems within the framework of its Freedom CAR program for the years 2010, and 2015[41], which are listed in Table 6-2.

In the design Toyota Pius v design:

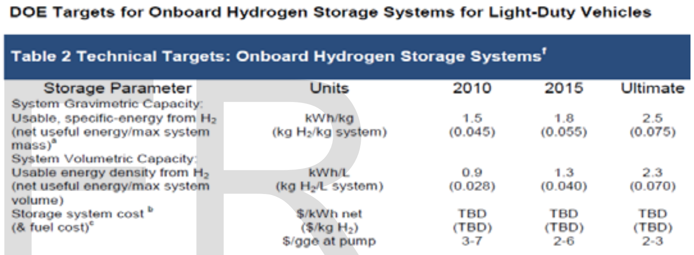
- Gravimetric Capacity (H2/kg), 3.64 kg / (70.1kg) = 0.051, so the new design is approximately meeting 2010 target Volumetric Capacity (H2/L)
- 3.64 kg / 94 L external tank volume = 0.038 the new design is approximately meeting 2010 Target

TABLE 6-1
ANALYSIS WEIGHT OF TOYOTA PRIUS V



Part Removed	Weight (KG)	Part added	Weight (KG)
Engine Assembly	120	Fuel cell	107
Gearbox	50	Tanks H2	62.48
Radiator	15	NiMH Battery peck	41
Fuel Tank	40	Electric motor	43
Exhausts system assembly	30	Cooling system	10
NiMH Battery	41	Power control unit (accessories)	20
Power control unit, Electric motor	n/a	Pressure valves, regulators	20
		Total	303.48
Total	281	Curb weight 1485 kg for Prius V.	
Wight differences	+22.48		
Final vehicle weight	1507.4		

TABLE 6-2
ANALYSIS OF TARGET 2010 AND 2015



DOE Targets for Onboard Hydrogen Storage Systems for Light-Duty Vehicles

Table 2 Technical Targets: Onboard Hydrogen Storage Systems[f]

Storage Parameter	Units	2010	2015	Ultimate
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass)[a]	kWh/kg (kg H_2/kg system)	1.5 (0.045)	1.8 (0.055)	2.5 (0.075)
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume)	kWh/L (kg H_2/L system)	0.9 (0.028)	1.3 (0.040)	2.3 (0.070)
Storage system cost [b] (& fuel cost)[c]	\$/kWh net (\$/kg H_2) \$/gge at pump	TBD (TBD) 3-7	TBD (TBD) 2-6	TBD (TBD) 2-3

- Cost is much higher than DOE target, so the new design is not meeting 2010 target.

6.3 Range Analysis Results

This is an estimation of hydrogen consumed for total range 400 kilometers. As shown in Table 6-3 that the vehicle may go up to 288.8 kilometers because it is only consumed 3.6 kilogram of hydrogen; therefore, the remaining for range trip is 111.2 kilometers, and the remaining of hydrogen is 0.7 kilogram. In the end we need an approximately 4.3 kg of hydrogen to go for 400 kilometers. This assumption estimated from National Renewable Energy Laboratory and Savannah River National Laboratory who evaluation two cars were driving on road ranges of 400 miles announced by Toyota for its new advanced Fuel Cell Hybrid Vehicle (FCHV-adv) utilizing 70 MPa compressed hydrogen [42].

6.4 Fuel Cells Need Clean Hydrogen

Researchers are looking for couples of ways to avoid carbon emission because of free hydrogen does not exist naturally:

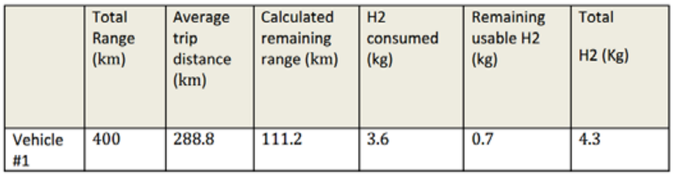
- Hydrogen is an energy carrier, not a source.
- It has to be generated from naturally occurring compounds.

- Implies energy use and hence GHG emissions.

Hydrogen can be delivered to the vehicle in two ways [43]:

- Direct hydrogen supply to the vehicle.
- On-board the vehicle using a hydrogen containing fluid.

TABLE 6-3
RANGE ANALYSIS INTERMEDIATE VALUES AND FINAL RESULTS



	Total Range (km)	Average trip distance (km)	Calculated remaining range (km)	H2 consumed (kg)	Remaining usable H2 (kg)	Total H2 (Kg)
Vehicle #1	400	288.8	111.2	3.6	0.7	4.3

TABLE 6-4
RISK ASSESSMENT OF HYDROGEN FUELLING STATIONS FOR 70 MPA FCVS [46]

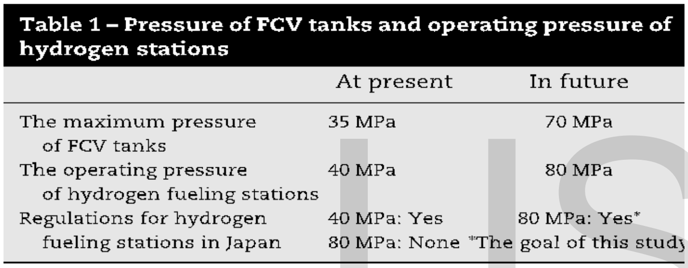


Table 1 – Pressure of FCV tanks and operating pressure of hydrogen stations

	At present	In future
The maximum pressure of FCV tanks	35 MPa	70 MPa
The operating pressure of hydrogen fueling stations	40 MPa	80 MPa
Regulations for hydrogen fueling stations in Japan	40 MPa: Yes 80 MPa: None	80 MPa: Yes* *The goal of this study

6.5 Renewable Hydrogen

Renewable source is nature method to product clear carry hydrogen without using fossil energy sources. In the world, the production of hydrogen is probably in excess of 50 million tonnes per a year that uses in industrial and vehicles [44].

There are couples of methods to have free clean hydrogen energy such as biomass, wind, geothermal hydro, and solar. Each of these devices called an electrolyser, which uses electricity to separate water into hydrogen and oxygen [45]. Electrolysis is separating water into hydrogen and oxygen using electricity from one of the many renewable sources. However, biomass conversion is thermochemical or biochemical conversion to intermediate products that can then be separated or reformed to hydrogen. Also, solar conversion is using solar generated heat for high temperature chemical cycle hydrogen production or photolysis, in which solar photons are used in biological or electrochemical systems to produce hydrogen directly. There are many challenges to producing Hydrogen from renewables and the major one is reducing the cost [44].

6.6 Risk Assessment of Hydrogen Fueling Station for 70 Mpa FCVs

Fueling stations where pressure is no higher than 40 MPa were established in 2005 in Japan. However, recently, there is not enough information about concerning hydrogen leakage, ignition, and explosions at 70 MPa, as well as high-pressured hydrogen equipment. Therefore, researchers estimate their assumption based on 35 MPa hydrogen data. There are two options for compressed hydrogen refueling. One is the cascade storage system. In this system, the rated pressure of the station storage is higher than that of the vehicle tank after refuelling. The other one is the booster filling system where the station storage has a rated pressure below that of the vehicle tank. However, the tank is 35 MPa and the pressure of hydrogen fuelling stations using the cascade storage system is 40 MPa in Japan. Japan stations are using 40 MPa because "The pressure of the stations therefore is 1.1+ a higher than the pressure of the vehicle tank, and this is referred to as the operating pressure"[46]. In addition, researchers showing at Table 6-4 the maximum pressure of FCV tanks and the operating pressure of hydrogen stations. Also, The sequence of the verification procedures undertaken in the risk assessment is shown in Figure 6-2 [46].

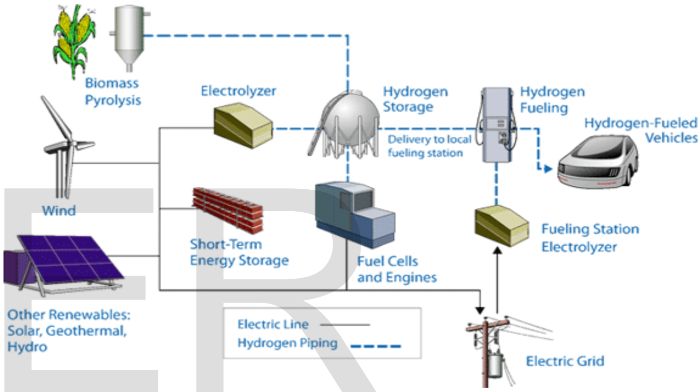


Figure 6-1: **How Renewable Hydrogen and Fuel Cells Integrate with the Grid [45].**

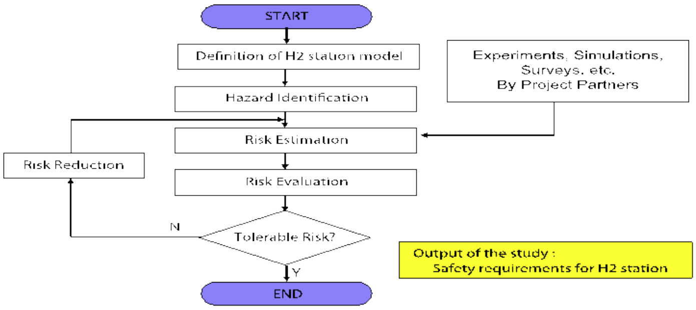


Figure 6-2: **Sequence of verification procedures in the risk assessment [46].**

6.7 Hydrogen Storage Challenges

There are many challenges for hydrogen storage to driving range (400 kilometer) such as [47]:

- Weight and Volume
- Efficiency
- Durability

- Refuelling Time
- Cost
- Codes and Standards
- Life-Cycle and Efficiency Analyses

6.8 Unique Hazards of Compressed Hydrogen Vehicles

Hazards such as: Combustion hazards, High pressure hazards, Electrical hazards, Crash hazards, Fire hazards.

Advantages at 70 MPa:

- High strength.
- Excellent hydrogen permeation prevention performance.
- Increased tank capacity.
- Reduced weight.
- Minimizing wall thickness.

Disadvantages at 70 MPa:

- The cost of the carbon fibre materials for this purpose is expensive.
- There is also the added complexity of supplying H2 (g) at this high level of pressure. Multiple-stage compression systems will be necessary, and this is expensive from an energy-input perspective.

7 SUMMARY

The main goal of this paper is to provide a detailed research report on “Design of gaseous hydrogen storage at 70 MPA” for Toyota Prius and to analyse their effects on global energy consumption, energy efficiency and global warming as well as to see their environmental impact. In addition to this, their socio-economic impact with respect to design, cost, convenience and maintenance has also been discussed. Adoption rate/future trends of these vehicles in addition to recommending ways which lead to increased efficiency, lowered costs and a positive impact on the overall environment are also included.

The scope of this paper is mainly limited to design and characteristics of hybrid and electric vehicles. Some of the information may be leaning towards a North American perspective but majority of them apply to Asia, Europe and other continents. The recommendations provided are fairly general to automobile manufacturing industry.

A hybrid vehicle is one which uses two or more power sources to move the vehicle while electric vehicle is one which uses one or more electric motors to provide propulsion to the vehicle. Power sources can be numerous like natural gas, gasoline, fuel cells and hydrogen (H_2).

The main conclusion is both hybrid and electric vehicles consume much less energy and are much more energy/fuel efficient as compared to gasoline cars. Both hybrid and electric vehicles provide low emissions and better cost benefits as compared to gasoline powered cars. Lower emissions reduce atmospheric concentration of greenhouse gases and hence counter the effects of global warming. As compared to electric vehicles, hybrid vehicles have certain benefits in many consumer and auto-makers. Hybrid cars have better mileage, better infrastructure for refuelling/recharging, and a better adaption rate to different weather situation, result in higher overall cost saving for consumers and auto-makers.

The design of hybrid and electric vehicles can be improved by different ways to make them more energy efficient, help in their commercialization etc. Alternate forms of hybrid power should be looked into; batteries should be combined with electrical storage devices and new prototype materials for the vehicle body should also be researched.

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