

## **PART I**

### **OUTSIDE ENGINE DESIGN ENVIRONMENT: MARKET, VEHICLE, HYBRIDIZATION AND COMPONENTS OVERVIEW**

#### **I-I From worldwide market to the engine**

There is not tomorrow for car manufacturers will not have electric and hybrid models. This is funding of Audi's top manager, but similar speeches could be listened from all car makers who would have important role on international markets. Battery super cars, as Mercedes SLS AMG E-Cell or Audi R8 e-tron, serve mainly to have new image for customers that do not ask how much it costs, while electric city cars are turned to inhabitants and commuters of metropolis. Forecasts worldwide are not explosive but they could be in Asia. Anyway, car makers point out to sell hybrid vehicles but no one knows market dimensions. The matter is to be ready when customers will ask for hybrids. Because current forecasts for hybrid markets are reductive and misleading. Well, target of two millions Prius sold in fourteen years period, from 1997 until today, could appear modest. The key point is not average number per year that mean 140'000 vehicles per year but it is progression: three thousands in 1997; 400'000 in 2009; and 500'000 in 2010. A constant and sharply growth. This approach could extend to others brands. Of 70 millions vehicles sold worldwide in 2010, only one million, 750'000 in 2009, is about hybrid vehicles: marginal presence. However, according with J.D. Power analysis, in next five years, hybrid vehicles sold will reach 3 millions, rule of thumb 5 % of global market. It is not too much, of course, but real matter is another one: diffusion of bi-motor vehicles will happen at leopard spot and success will highlight in the richer markets as United

States, Europe and Japan, and in those ones with sharper growth as China. These, for several reasons, will be same key markets for car makers destiny. Just today, in same geographical areas, as California and Japan, bi-motor vehicles are not marginal presence. In fact, in Japan, Honda Insight and Toyota Prius are contend the best-selling vehicle title and they have just beaten, with government contribution, normal production vehicles. The rest, in country where diesel and methane vehicles are not able to brake market, hybrid vehicles represent only technological feasibility solution ready to be introduced in market that could deeply cut fuel consumption, or in others words, the famous CO<sub>2</sub> emission quantities. Anyway, future of hybrid vehicles in United States depend on crude oil price trend, because Americans buy hybrid vehicles when gasoline rocket increases price. If everything will follow forecasts of specialist, respect to 300'000 units in 2009, hybrid vehicles sold in United States will reach 1,5 millions in 2015. It means about 10 % of global market and almost double of diesel selling forecast. If from commercial point of view, situation is complicated, from technical one is more varied. Say hybrid, is not enough to define kind of vehicle is speaking about, because it ranges from minimum to maximum of adulteration and costs. For example, if one classifies the most famous hybrid vehicles, Smart MHD, Insight and Prius, first one belongs to micro hybrid, second one is mild hybrid and third one fits in full hybrid fold. In all micro hybrids, electrical traction system, with power of 2 – 3 kW, exclusively provides start & stop function for IC engine and advanced 12 V started battery charges, only electrical storage system on board, during deceleration and breaking phases. Nothing more. In fact, excluded commercial purpose, this kind of vehicles are not proper hybrid vehicles and they do not enter in hybrid market selling count. Majors are possibility of mild hybrid as Honda Insight: in this case electric motor transmits torque to wheels, so works together with IC engine and allows to reduce its dimension. Electric traction system, up to now it reaches 15 kW, does not allow solely traction, and as well as does not accelerate vehicle from stand situation. As micro, electric traction system provides start & stop function and regenerative breaking to charge battery. In mild hybrid, electrical storage system is not 12 V battery but it is able to supply and receive high power: it works with tension up 110 V. Only hybrid vehicles able to travel for 5 km at last up to now, in pure electric are full

hybrid as Citroen DS5 Hybrid4, Peugeot 508 RXH, Peugeot RCZ Hybrid4, Peugeot 3008 Hybrid4. For this fold, battery tension increase up to 200 – 270 V and increase electric machine power up to 20 – 50 kW. Full hybrids are the most completed, complex and expensive expression of hybrids and designer around world have made them in the most different ways.

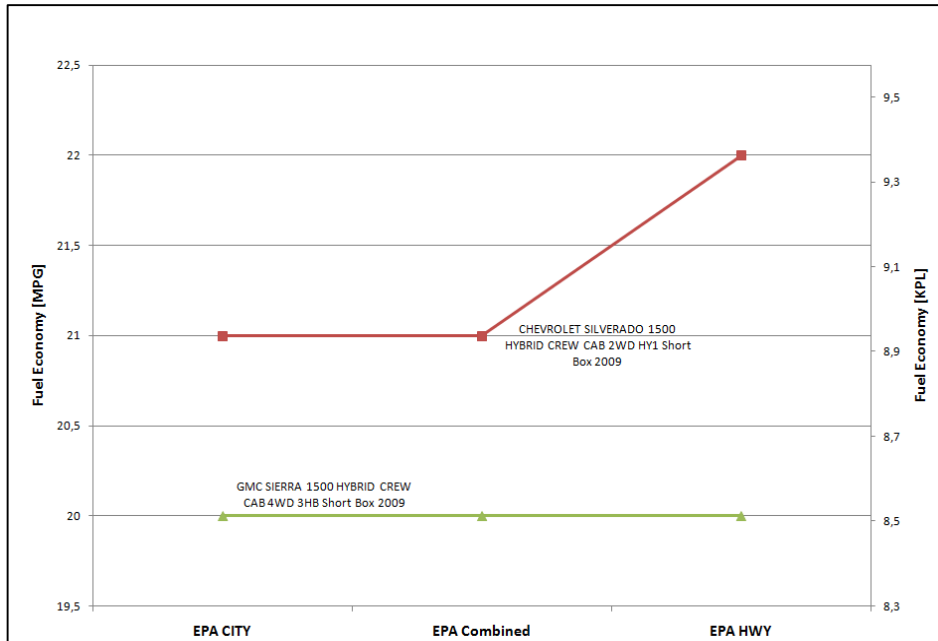
Nowadays, there are different hybrid solutions and they presents in every segment from compact cars as Citroen C-Cactus to super cars as Mercedes SLK Gullwing and Toyota Volta through to trucks as GMC Sierra Hybrid and Chevrolet Silverado Hybrid. On the bottom of this chapter there are some appendixes with pictures of all cars mentioned. There are different reasons to introduce hybrid version of existing model on the market, the most important one is for marketing purpose. Marketing is generic word that collects wide aspects and try both to read and lead market through customers. For examples, introduce “green” trucks on the market is strong controversy because they are the heaviest and have the bigger engine on the market. But this marketing strategy would collect “green” customers that love or need truck but they are eco-friend as well. In fact, as shown in the next chart, hybrid system on trucks, and in particular, on SUV match the biggest displacement, so hybrid does not have an environmental mean but it means trendy and cool. The same reason pushes to introduce hybrid super car on the market. Super cars, for principle, are top performance vehicles and to generate huge power and torque they have to burn high quantity of fuel and so have high fuel consumption. But hybrid super car is powerful, cool trendy and “green”: perfect combination to break the market. Always about marketing, inside every segments, every manufacturer has different positioning. This means there are leader, first follower, follower and so on. For example, market situation in the beginning of 2009 is leader manufactures proposed on the market mild hybrid solutions with only start & stop and torque assist functions on top segment cars as Mercedes M-class Hybrid, VW Touareg Hybrid, and Audi Q7 Hybrid. Ones again, behind this model there are only marketing purpose because these are top segment SUVs, with huge engine displacement that from technical point of view are on “green” antithesis. On the other hand, there are real “green” car on the market that means small – sedan cars that try to reset fuel consumption and work on mild – full hybrid propulsion

system, lightweight components, materials, aerodynamic resistance and so on. Examples of this kind of cars are VW Golf EcoHybrid, Honda Jazz Hybrid, Chevrolet Malibu Hybrid and Ford Fusion Hybrid. At moment, when hybrid market penetration is around 2,5 % and hybrid propulsion system means adding electric traction system, or in other words, not negligible extra cost that only top segment cars could withstand. In the end, it could defines two strategies to approach hybrid vehicle: one from the top to the bottom, and the other one from the bottom to the top. The first one is case of European and American car manufacturers that have started to hybridize big and expensive SUV with mild hybrid system only with torque assist and start & stop function. For example the first GM hybrid system is 36 V belt driven alternator starter, than an improved of this system and now, breakthrough hybrid propulsion system called Two-Mode with IC engine, two electric machines and three epicyclical gear trains. GM moves from SUVs and trucks with first system to sedan segment with last hybrid propulsion system as Chevrolet Volt and Opel Ampera. Second strategy is that used from Toyota and Nissan. Toyota have started in 1997 with first version Prius, sedan car for normal people and at moment, it moves hybrid know-how and technology on its top class brand: Lexus. Toyota case is outstanding because it uses two kind of hybrid propulsion systems: one for front traction on Toyota Prius, Auris and Lexus RX 450h; and other one for four wheels traction system uses on Lexus LS 600h. The same strategy is used by Nissan that started with sedan segment as Nissan Altima Hybrid and now it moves on top class brand Infinity M35h. Two exception are Honda and Volvo that develop and keep hybrid propulsion system only for sedan segment. As follow several segments are presented and discussed with respective charts. These charts will show fuel economy for different vehicles for every segment analyzed. Fuel economy is measured both in miles per gallon and kilometers per liter.

First segment shown in Figure 1 is truck, in particular, Chevrolet Silverado Hybrid and GMC Sierra Hybrid. These two trucks belong to same car company, in particular General Motors, and for this reason they have the same fuel economy. Figure 1 shows contribution of transmission. Differences from two wheels drive and four wheels drive are one mile per gallon on urban and combined cycle and two miles per gallon on

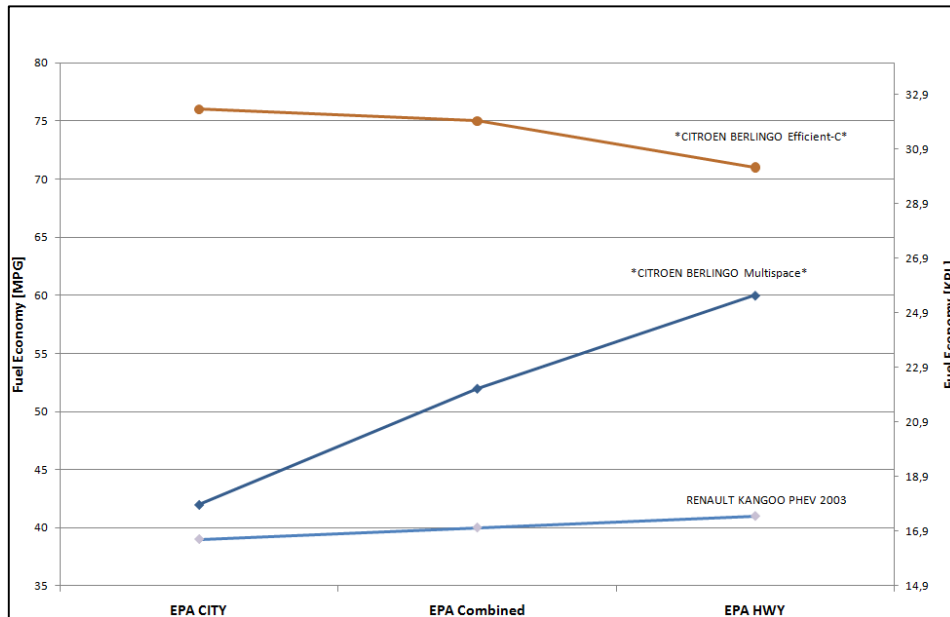
highway cycle. Anyway, average fuel economy for this segment is around 9 kilometers per liter. Comparison between normal production vehicle and hybrid one highlights that hybrid use 6 liter engine and normal 4.8 liter.

Fig. 1: truck segment fuel economy



Second segment is van one. The choose to use hybrid propulsion system for van comes to use advantage of reduction of fuel consumption, in the same way as hybrid vehicle for cab fleet. In Figure 2 there are three examples: Citroen Berlingo Efficient-C and Multispace; and Renault Kangoo PHEV 2003.

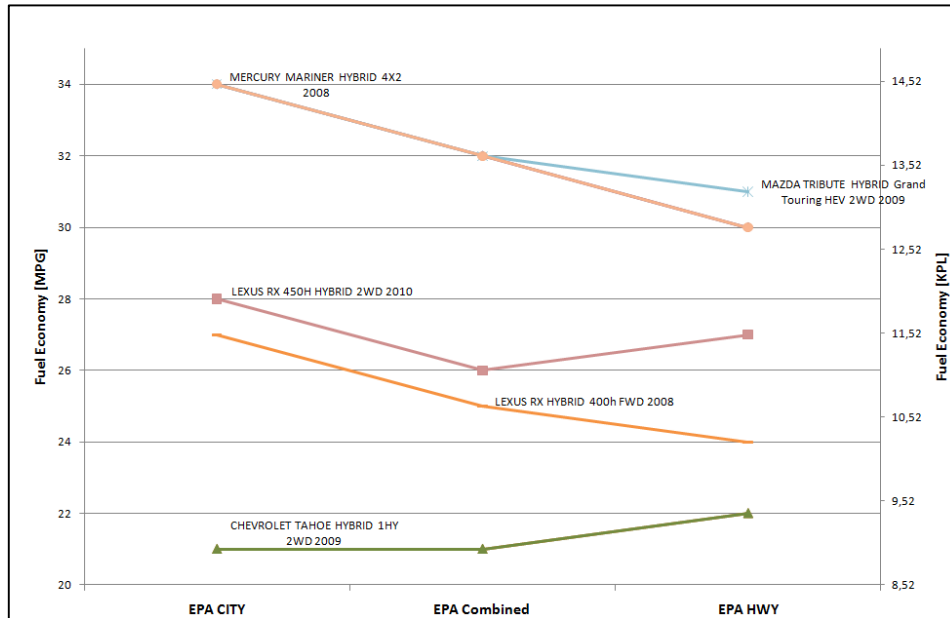
Fig. 2: van segment fuel economy



The Kangoo has full hybrid propulsion system with two cylinders engine of 500 cc with 11 kW at 5000 rpm. Citroen Berlingo is evaluated on European cycles. The Multispace is normal production 1,6 liter diesel engine with 66 kW. While Efficient-C is 1,6 liter diesel engine with 66 kW and 215 Nm that use SensoDrive automated gear box, high efficiency transmission develop by Qinetiq, a defense company, coupled with electric machine 23 kW and 130 Nm. This vehicle develops from Citroen, Ricardo and Qinetiq successful attempt the UK Department for Transport’s Ultra Low Carbon Car Challenge. The estimated extra cost for transmission and electric traction system is around 3000 GBP or 6000 dollars. The difference from Kangoo PHEV 2003 fuel economy and normal production Berlingo is that the fuel consumption of 2 cylinders engine is extremely high and so fuel economy sharply decrease. While difference between normal production and Efficient-C Berlingo are electric traction system and high efficiency transmission develops through QinetiQ. In this case, Citroen Berlingo keeps same IC engine of normal production using de-rating technique.

Figure 3 shows fuel economy of two wheels driveline SUV segment.

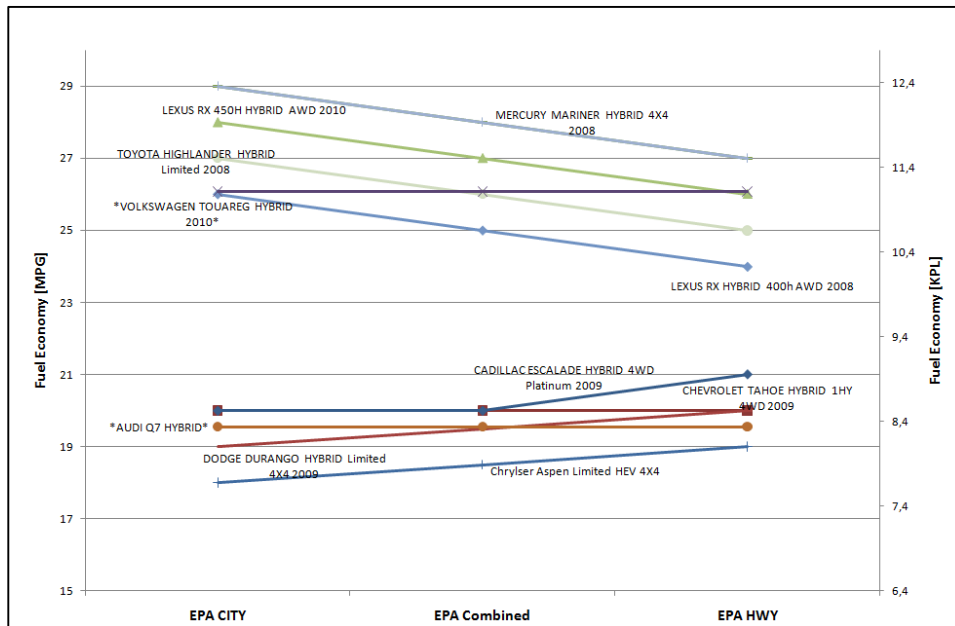
Fig. 3: SUV 2WD segment fuel economy



The best fuel economy is achieved through Mercury Mariner Hybrid 4x2 2008 and Mazda Tribute Hybrid Grand Touring 2WD 2009 but the second one has better break specific fuel consumption because fuel consumption on highway cycle is done mainly by thermal engine. Fuel economy of these two vehicles are about 14 km per liter. In the center of Figure 3 there are Lexus RX 450h Hybrid 2WD 2010 RX 400h Hybrid FWD 2008. The last evolution of Toyota Hybrid Synergy Drive propulsion system allows to gain fuel economy on city and combined cycles while on highway cycle there are contribution of both electrical and thermal improvements. About the Mercury Mariner, it uses same thermal engine but on hybrid version there are automated transmission in part of manual and electric traction system. These mean extra costs for 5000 US dollars. On the other hand, Mazda uses same thermal engine with de-rating technique. Moreover, Mercury Mariner weights 1666 kg while Chevrolet Tahoe weights 2393 kg. To sum up, the best combined fuel economy is 32 km per liter.

Figure 4 shows SUV 4WD fuel economy.

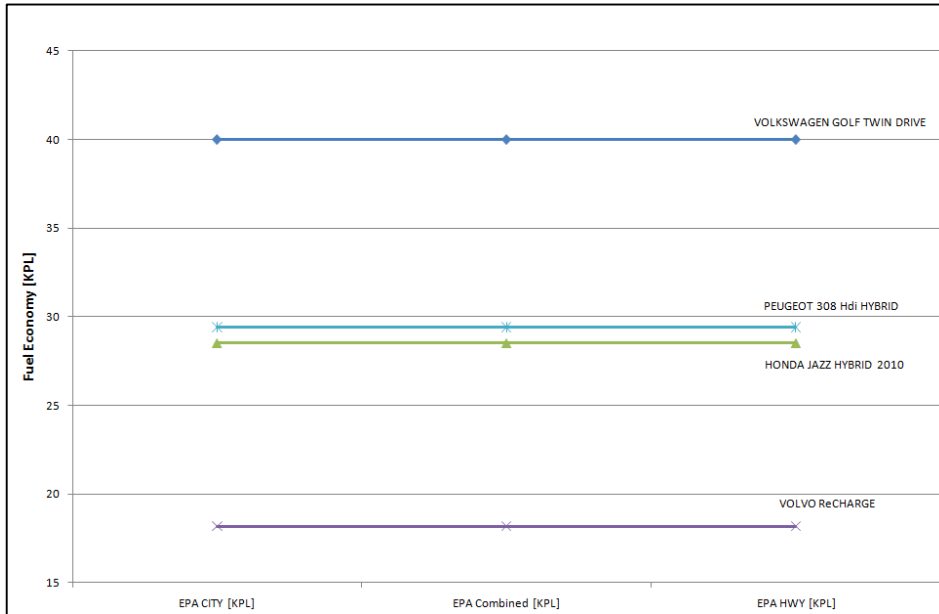
Fig. 4: SUV 4WD segment fuel economy



As well as SUV 2WD segment, the best in class is Mercury Mariner Hybrid 4x4 2008 that use Ford hybrid system. The main reason for this results is that the Mariner is most lightweight SUV and achieve about 28 km per liter. Then there are SUV using Toyota hybrid system as Lexus RX and Toyota Highlander. It is interesting how chart highlights fuel economy trend of Hybrid Sinergy Drive by Toyota. In particular this system has better fuel economy in city cycle than highway, because electrical traction system and transmission decrease efficiency of hybrid propulsion system at high vehicle speed. In the centre of chart there are the weightier vehicles and this generates worst fuel economy then Ford and Toyota SUVs. Moreover, there are VW Touareg Hybrid 2010 and Audi Q7 Hybrid. Fuel economy of these cars are only estimated and evaluated by European cycle, nevertheless these vehicle was not on the market when the research was conducted. Figure 5 shows compact segment fuel economy; unfortunately all follow vehicles are concept and data are not reliable.



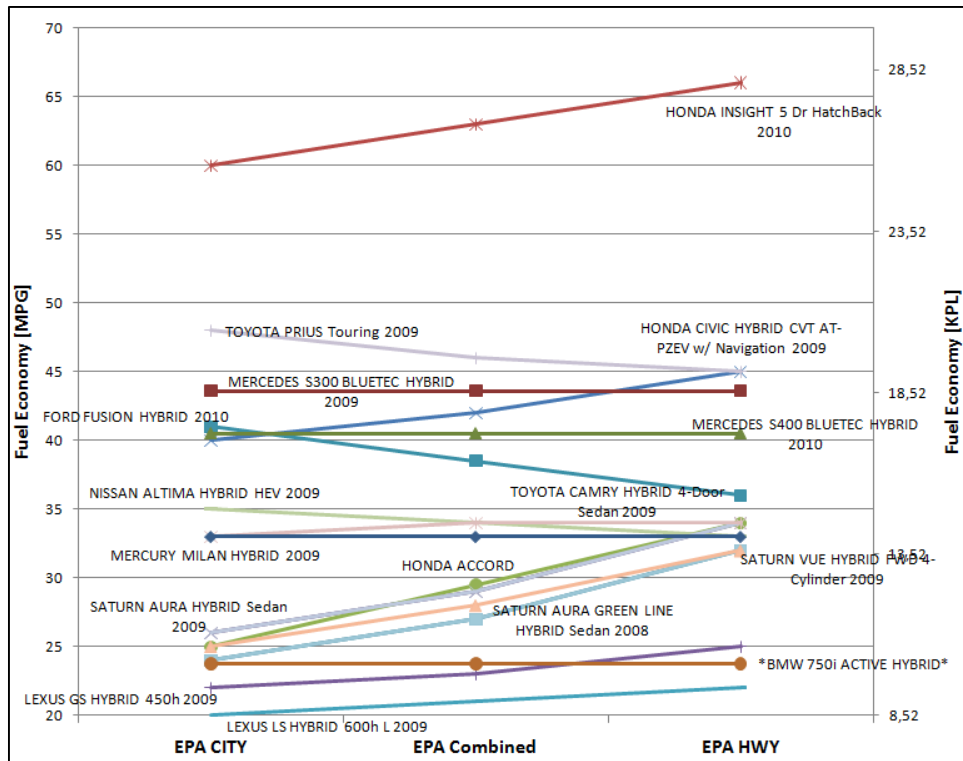
Fig. 5: compact segment fuel economy



VW Golf Twin Drive is plug-in parallel hybrid with 3 cylinders in line IC engine of 75 kW. Peugeot 308 HDI Hybrid is double drive hybrid vehicle, in particular, it has thermal traction system on the front axle using 1,6 liter HDI turbo-diesel engine and electric traction system on the rear axle with electric machine of 16 kW. Honda Jazz Hybrid 2010 has the last version of Integrated Motor Assist Honda hybrid system. Last one is Volvo Re-Charge, hybrid plug-in concept car based on Volvo C30 that use four wheels electrical machines, one per each wheel, and 1,6 liter FlexiFuel engine.

Figure 6 shows fuel economy for sedan segment.

Fig. 6: sedan segment fuel economy



The best in class is Honda Insight 5 Dr Hatchback 2010, where design approach to hybrid propulsion system reaches merged stage and go over to hug vehicle aerodynamic. It reaches over 26 km per liter. Then there is Toyota Prius 2009, the pre-last version with around 20 km per liter. It is interesting to see effects of Honda IMA system and Toyota HSD system. The first one is FAS mild hybrid that keep almost transmission of normal production vehicle: this lead advantages of better fuel economy at high speed vehicle where IC engine works at high efficiency point but disadvantage is low electrical power that force to use IC engine at low efficiency point at low vehicle speed. On the other hand, Toyota system has power split full hybrid propulsion system with dedicated transmission that lead advantage on urban cycle where IC engine works at low efficiency point but disadvantage at high vehicle speed where IC engine has to drive power split device. In the lower part of chart there are big and weight vehicles.

Figures 1 – 6 highlights the biggest fuel economy segment is sedan one and in particular, vehicles use IC engine in range of 1 – 3 liter. In particular vehicles choose are as follow and in brackets are reporting average fuel economy in km per liter, displacement in cc and weight in kg, where available: Honda Civic Hybrid CVT AT-PZEV 2009 (18, 1300, 1300), Insight 5 Dr Hatchback 2010 (27, 1300), Toyota Prius Base 2009 (20, 1500, 1300), Camry Hybrid 4 Dr Sedan 2009 (14, 2400, 1700), Chevrolet Malibu Hybrid HY 2009 (13, 2400, 1600), Ford Fusion Hybrid 2010 (16, 2500), Lexus HS 250h, Nissan Altima Hybrid HEV 2009 (14, 2500), Saturn Vue Hybrid FWD 4 Cyl 2009 (12, 2400, 1936), Saturn Aura Hybrid Sedan 2009 (13, 2400, 1600), Mercury Milan Hybrid 2009 (14), Mercedes S300 Bluetec Hybrid 2009 (19). Moreover, Figures 1 – 6 show market goes towards medium size vehicles and medium engine displacement. So, segment with higher number of hybrid vehicle is sedan one. About engines, market shows 4 cylinders in line is the most favorite engine configuration and hybridization level depends on engine displacement. Full hybrid propulsion system is chosen when thermal engine displacement up to 1500 cc where thermal performances are limited but high contribution of electrical traction system allows high vehicle performances. Mild hybrid propulsion system is used with IC engine displacement over 1500 and up to 2500 cc and it has only marketing purpose and it works as torque assist and starter & stop device. This trend suggests that IC engine for hybrid propulsion system will have less cylinders, low displacement depending on vehicle dimensions and in other words vehicle performances and so lighter thermal engines. Now, it is ready to go in details on IC engine architecture and make comparison with IC engine used on normal production vehicles.

About Honda Civic Hybrid respects with normal production one has small and simple engine: in particular it passes from 1800 cc 16 valves of normal production version to 1300 cc 8 valves of hybrid version. On the other hand, hybrid compression ratio is higher than normal one, it passes from 10,5 to 10,8. Bore x stroke of two engines are 72,90 x 80,01 mm and 81,03 x 87,38 mm. Two engines use i-VTEC, intelligent variable valve timing and lift electronic control, with Single Over Head Camshaft and Multi Ports Fuel Injection engine technologies. Both engines have cylinder block and head in aluminum alloy. In this case, there are two different base architectures but other features are the

same. In the end, hybrid system net power and torque are respectively 110 hp @ 6000 rpm and 167 Nm @ 2500 rpm, in these values come in electric motor of 20 hp @ 2000 rpm, while for normal production engine are 140 hp @ 6300 rpm and 174 Nm @ 4300. Toyota Prius uses 1500 cc 4 cylinders in line IC engine with bore x stroke 74,93 x 84,58 mm. IC engine has compression ratio 13 and 16 valves driven through Double Over Head Camshaft technology. Thermal engine uses VVT-i, intelligent variable valve timing, and MPFI technologies. Hybrid system net power and torque are respectively 76 hp @ 5000 rpm and 111 Nm @ 4200 rpm. Moreover, contribution of electric and thermal are severally 67 hp @ 1200 – 1540 rpm and 400 Nm @ 0 – 1200 rpm; and 110 hp @ 5000 rpm and 111 Nm @ 4200 rpm. Toyota Prius's engine uses aluminum alloy for block and head material.

Toyota Camry Hybrid uses exactly same engine, 2400 cc 4 cylinders in line with bore x stroke as 88,39 x 96,01 mm, but with higher compression ratio than normal production one, it passes from 9,8 to 12,5. Both vehicle versions have 16 valve driven through DOHC with VVT-i technology. Engines use Sequential Electronic Fuel Injection. In fact, Toyota strategy for Camry Hybrid is to provide explosive “green” vehicle with 192 hp @ 6000 rpm while for normal production engine is halted 158 hp @ 6000 rpm, so electric power is simply added to thermal one. Contribution of hybrid propulsion system between electric machines and IC engine are respectively as follow: 141 hp @ 4500 rpm and 269 Nm @ 0 - 1500 rpm; while IC engine 147 hp @ 6000 rpm and 187 Nm @ 4400. Camry's engine use aluminum alloy for block and head material.

Chevrolet Malibu Hybrid uses exactly same IC engine of normal production vehicle. Malibu's engine is 2400 cc 4 cylinder in line Ecotec engine developed by Opel – GM with bore x stroke as 86,36 x 96,52 and compression ratio 10,4. Ecotec engine has 16 valves driven through DOHC and uses SEFI technology. Malibu's engine performance in terms of power and torque are respectively 164 hp @ 6400 and 216 @ 5000 rpm; and uses 4 hp electric motor. Aluminum alloy is used for block and head.

As well as Chevrolet Malibu, Nissan Altima Hybrid uses exactly the same thermal engine for hybrid and conventional vehicles. Altima's engine is 2500 cc 4 cylinders in line with bore x stroke as 88,90 x 100,08 mm, compression ratio of 9,6. This engine uses 16 valves