Hybrid Electric Vehicle (HEV) Concepts - Fuel Savings and Costs

Holger Jené, Ernst Scheid and Hans Kemper

ABSTRACT

Hybrid vehicles offer a further chance to reduce fuel consumption and emissions. Some vehicles are on the market already, and many companies are working on different solutions. The chosen technology influences very much the overall result for actual operation, because differences in efficiency and weight have to be considered. Also the vehicle investment cost depending on the chosen complexity should be taken into account. The question about the degree of complexity will be discussed with regard to additional manufacturing costs, by evaluating and highlighting the technical as well as the commercial background.

INTRODUCTION

Today's discussion about sustainable technologies concerning emission reduction, fuel saving potential and carbon dioxide reduction (CO_2) respectively, treats often two subjects: alternative fueled ICEs, especially compressed natural gas (CNG), and hybrid electric vehicles (HEV), which besides the high fuel saving potential, bring further benefits for our society.

Throughout the motored vehicle evolution, there have always been concept and prototype cars combining the advantages of two different propulsion systems, which include a second power source and energy storage device to supplement the fuel tank.

MAIN SECTION

ELECTRIC HYBRID VEHICLE EVOLUTION

Two centuries ago, in 1881 the first electric vehicle (EV) was already in use by Gustave Trouvé, shortly after Nikolaus August Otto invented the four-stroke internal combustion engine (ICE) in 1876. In 1902, the first Gasoline Electric Hybrid "Mixte" was built up as a range extender principle. The first manufacturer to market HEVs in any great volume was Toyota by launching the Prius I in 1997.

In 2010, HEV sales forecast for Europe is expected to be more than 400.000 units per year (Frost & Sullivan, B126), nearly 40 times higher than today's figures.

MOTIVATIONS FOR HEVs

Because of pricing by the petroleum exporting countries, HEVs are under discussion concerning fuel consumption benefit and therefore lower running costs. But also higher manufacturing costs by HEV related components need to be considered. From the technical point of view, the combination of an ICE with an electric machine appears to make sense because of their different torque characteristics. Therefore the power assisting by the electric motor in forms of high low-end torque results in a win in comfort as well as in increased "Fun-to-Drive" behavior, and in addition an improved noise-vibration-harshness (NVH) behavior can be achieved. Such an advanced technology could also make a contribution for a better public image.

Environmental aspects

The environmental aspects could be the main drivers for such a sustainable technology. Besides the protection of natural resources, several commitments from the "Association des Constructeurs Européens d'Automobiles" (ACEA), the "Japan Automobile Manufacturers Association" (JAMA), the "Korea Automobile Manufacturers Association" (KAMA) and California legislation, limit the CO_2-emission of the vehicle fleet to 140 g/km and further future reduction steps. Automotive manufacturers have to comply with these commitments. The question should be posed, which kind of technology has to be applied. Undisputable seems to be, that not even a 100-percent share of Diesel engines can meet this target. Against this background, HEVs should be discussed concerning their suitability for a sustainable solution.

However, there are some more environmental aspects, like the reduction of air pollution, especially in metropolitan area, where a hybrid electric vehicle can function as an "Advanced Technology Partial Zero Emission Vehicle" (AT-PZEV). Despite the limited electric operating range, the "California Air Resources

Board" (CARB) ensures credits for the AT-PZEV. The European government is just now discussing an initiative, which covers a 50 percent reduction of the current traffic noise by 2020. To comply with these regulations, partly electric driven vehicles could be one acceptable solution.

HEV CONCEPTS

In respect of the technical realization, there are several concepts possible, whose classification are given by serial, parallel and split HEVs. The serial HEV concept is characterized for the exclusive purpose of electric driving (Konstantin Neiß, 2004). That means no direct drive between ICE and wheels. The ICE power is transformed into electrical power by the electric alternator. Because of the corresponding losses, the total efficiency for the entire power train is low. A significant potential for fuel saving is given by the parallel hybrid concept. The co-axial adjustment of electric machine and ICE allows a vehicle drive by both, separately or in combination. High efficiency can be realized with split HEV, a concept which combines the serial and the parallel system. The ICE power can be used for both, vehicle and electric alternator drive. The advantage comes from the optimized ICE operating strategy. Generally, operating the ICE under low load causes inevitably bad efficiencies, especially for gasoline engines. Such engine map areas can be avoided by increasing the load and therefore the power output. The excess power can be used for powering the electric machine and charging the batteries.

HEV FUNCTIONS

Not only the concept decision is of relevance for fuel saving but also the degree of hybridization and functions respectively. Discussion is started with the "Micro HEV", which is applied for the purpose of power supply for the electric accessories concerning the increasing on-board demand and for realizing a start-stop function, which allows fuel saving during idle sequences - Figure 1 (Dr. D. Kock, 2004). Further more, a limited recuperation by regenerative braking is possible. Compared to the micro HEV, torque smoothing and launch assist will be allowed by mild HEVs. Those functions are not focused on higher propulsion system efficiencies, but show their importance with view on the NVH behavior and on the driving comfort, like shift assist, which ensures permanent traction without interruption during switching operations. To acquire higher recuperation potential, an increase of the electric machine power and therefore of the system voltage up to 288 Volt and more is necessary. That means only "Medium-" and "Full HEV" systems can offer these functionalities. Medium hybridization also includes power assistance and optimized ICE operation strategies, which enable higher efficiencies. The maximum possibilities can be realized by full hybridization - Figure 2 - allowing electric drive - all electric range (AER) higher than 20 miles - and full power assist and power split respectively. Another motivation for the electric drive is the "Local Zero Emission" requirement by the California emission legislation, offering special credits for advanced technological vehicles.

But besides these mentioned benefits, the higher variability implicates also some drawbacks like additional vehicle weight and increased manufacturing costs. Because of this, the question has to be posed, if the maximum possible technical solution shows always the best choice for the customer.

HEV BENCHMARK

Today, several prototype and series production HEVs are known with electric motor power up to 80 kW. That means, the whole range of hybridization is covered and there is not a clearly leading technology detectable. With regard to vehicles with increased inertia weight like sports utility vehicles, medium and full HEVs seem to be preferred systems, where most of them are operated by an electric motor power between 30 and 70 kW and an ICE power between 90 and 130 kW. Gasoline concepts are still dominating the HEV technology, supposing that the higher manufacturing costs and weight are the main arguments against the self ignition concept.

FUEL SAVINGS WITH HYBRIDS

The potential for fuel saving is given by start-stop functionality, optimized engine operation, brake energy recovery and electric drive. Fuel saving potential in test cycles strongly depends on the cycle characteristic, and there mainly on three parameters: the average speed, the idle share and the recuperation share. Significant potential for fuel saving is given by high proportion of idling and recuperation, and by a low average speed in the test cycle, adding some more benefit.

<u>Average speed versus idle share</u>

A comparison of test cycles shows significant differences in the idle share in spite of nearly same average speed, e.g. NEDC and FTP75. High fuel savings potential can be reached with the ECE cycle, which shows the lowest average speed with nearly 19 km/h, quite similar to the J10-15 cycle. In general, there is a clear correlation detectable between the average speed and the idle share - Figure 3.

Average speed versus recuperation share

With a view to the brake energy recovery, a correlation with the average speed is not detectable. Test cycles with higher average speeds also show significant potential for brake energy recovery, because increased vehicle speeds cause longer brake sequences. In spite of nearly similar average speed and idle share for ECE and J10-15 mode, these tests do not comply with each other in terms of recuperation share. That means, test cycles with identical average speed and idle share have different potential for fuel saving, because of the impact of recuperation share by brake energy recovery - Figure 4.

Fuel economy versus electrical power

As mentioned before, functions like torque smoothing and power assist as well as brake energy recovery require sufficient electric machine power and therefore adequate system voltages and battery capacities. The technical realization results in an unavoidable increase of vehicle weight. This means, there is an optimum for the fuel saving potential, given by the adverse parameters, energy win by recuperation and additional weight - Figure 5. An exceeding of the energy win by brake energy recovery over a certain level will not lead to further benefits, because of over compensation by the additional weight. Referring to the impact of additional weight on fuel saving, a significant “All Electric Range” (AER) causes somewhat lower benefits.

Average speed in metropolitan area

Relating to the fuel saving potential with hybrid concepts, which is mentioned above, the question about the real potential has to be posed. HEVs should be primarily used in crowded areas, where the average speed is quite low. Because of the hybrid functions, the fuel saving will be significant. The average speed in metropolitan area like London, Rom, Shanghai, Tokyo, etc. is lower than 20 km/h. If the real potential of hybrid concepts shall be evaluated under this boundary condition, the characteristic of the ECE test cycle seems to be appropriate, because of its average speed of nearly 20 km/h.

Fuel savings with HEV technology

In the following, the fuel consumption benefit by hybridization for the Toyota Prius II and the Honda Civic IMA will be benchmarked compared to conventional Gasoline and Diesel fueled vehicles, especially with the Audi A2 1.4 TDI, which is best of its class and because of this, the reference for the two benchmarked HEVs - Figure 6. The scatter band is generated by 50 vehicles with a displacement between 1,2 and 2,0 liter and a performance of 44 up to 108 kW. The relation between fuel consumption and vehicle weight is shown for Gasoline as well as for Diesel fueled vehicles. An increase in vehicle weight of 100 kg results in a higher fuel consumption of approximately 0,4 liter per 100 km for Gasoline engines and 0,3 Liter for Diesel engines respectively. The advantage in fuel consumption for Diesel engines against Gasoline ICEs is approximately 2 liters. The Honda Civic IMA shows nearly similar fuel consumption, as the average of all measured Diesel engines with same inertia weight, approximately 4,8 liter per 100 km. This is still higher than the value of the Audi A2. The Toyota Prius has an additional weight of 100 kg, but needs around 12 percent less fuel consumption than the Honda and is on the level of the Audi A2. However, the fuel saving potential of Gasoline HEVs is nearly identical to that of Diesel engines. Only a slight improvement can be recognized. Considering the additional measures of the Toyota Prius II, e.g. the light-weight and the special aerodynamic design, the question is, whether Gasoline HEVs show sufficient benefits against the Diesel fueled vehicles or not.

Fuel economy potential and test cycle characteristics

The answer to above question is given by considering the fuel consumption benefit of HEVs for the ECE test cycle. The reduction in fuel consumption between the Toyota Prius II and an adequate powered vehicle with same inertia weight is approximately 50 percent. Referring to another, high speed test cycle like the US Highway cycle, the benefit shrinks to only 20 percent - Figure 7.

HEV SYSTEM COSTS

Besides the fuel saving potential, the additional manufacturing costs are important for the system definition, and even more for the mass production decision by the OEM. Estimations for different degrees of hybridization are presented for a gasoline vehicle with 1.300 kg and 75 kW ICE power - Figure 8. The increase of vehicle costs for micro hybrids, belt driven systems, can be estimated to approximately 250 € and integrated systems on the crank shaft up to 500 €. Higher degree of hybridization can be achieved with mild systems and extra expenses up to 1.500 €. Medium and full hybridization demands additional 1.000 € for each step. The most advanced HEV system, which allows an all electric range of more than 20 miles, can be realized with additional costs of up to 12.000 €. All mentioned costs are average figures and strongly depend on mass production numbers. HEV systems, showing similar fuel saving potential as Diesel engines, generate approximately two times higher incremental costs than Diesel engines.

AMORTIZATION OF ADDITIONAL HEV SYSTEM COSTS

Regarding the cost-benefit ratio, the amortization of the extra expenses for HEV systems could be a criteria for the system decision. Referring to the NEDC cycle and an annual driving performance of 15.000 km, the additional manufacturing costs for the micro HEV would be compensated by fuel savings after approximately 2,5 years - Figure 9. The amortization period for mild HEVs is calculated to be nearly 6 years, and for medium and full HEVs, it can be assumed to be finalized after 8 and 10 years respectively. This result seems to be far away from customer acceptance concerning a positive decision for the advanced HEV technology. But, as mentioned above, the high potential for fuel saving in the ECE cycle will lower this amortization period significantly. In addition with an annual driving performance of 20.000 km, the amortization time will be only 4 years. Furthermore, a reduction of prices for the HEV component costs can be expected soon, because several automotive manufacturers have announced their HEV market launch. This would lead to a large reduction of amortization times. A further parameter, which is still under consideration, is the fuel price. The current trend of permanent rising prices also has a positive impact on amortization time.

CONCLUSION

There are several motivations for hybrid electric vehicles, but the main drivers are given by environmental aspects, especially fuel consumption and CO_2-reduction. The potential for fuel savings depends on:

- HEV concept
- Degree of HEV functions
- Test cycle characteristics.

Because of the very low average speed of motored vehicles in metropolitan area, one possibility for a more realistic evaluation of HEV potentials in terms of fuel saving is given by the ECE cycle with an average speed of nearly 20 km/h. Calculations for the ECE test cycle results in a fuel saving potential of around 50 percent.

The permanent increase of fuel costs and the demand for more environmental vehicles, which have a sustainable impact on the environment, will lead to significant higher production numbers of HEVs, supported by a decrease of the additional HEV component costs.

Even the most complex, full hybrid systems, can reach an acceptable amortization period of the additional purchasing costs, only by fuel saving without any tax incentives.

Also Diesel HEVs are likely to come into the market, because of their enormous potential in fuel savings.

TABLES AND FIGURES

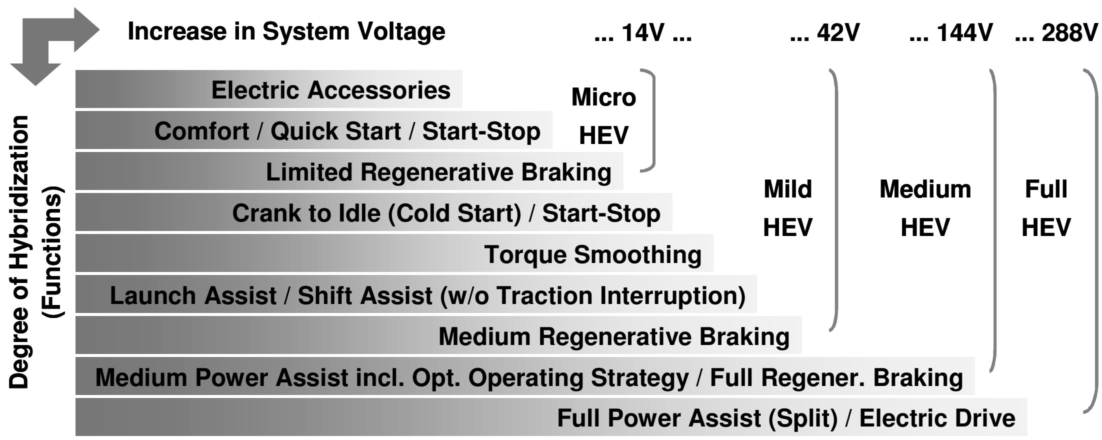

Figure 1 - Hybrid Functions (Source: Dr. Daniel Kok, FFA, July 2004, modified)

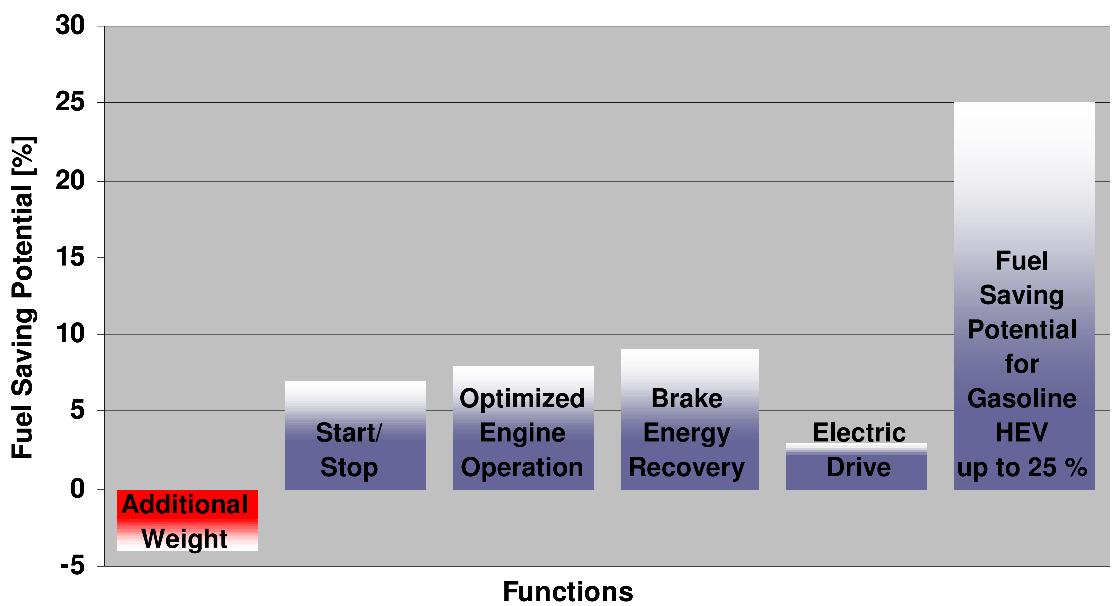

Figure 2 - Fuel Savings by Hybrid Functions

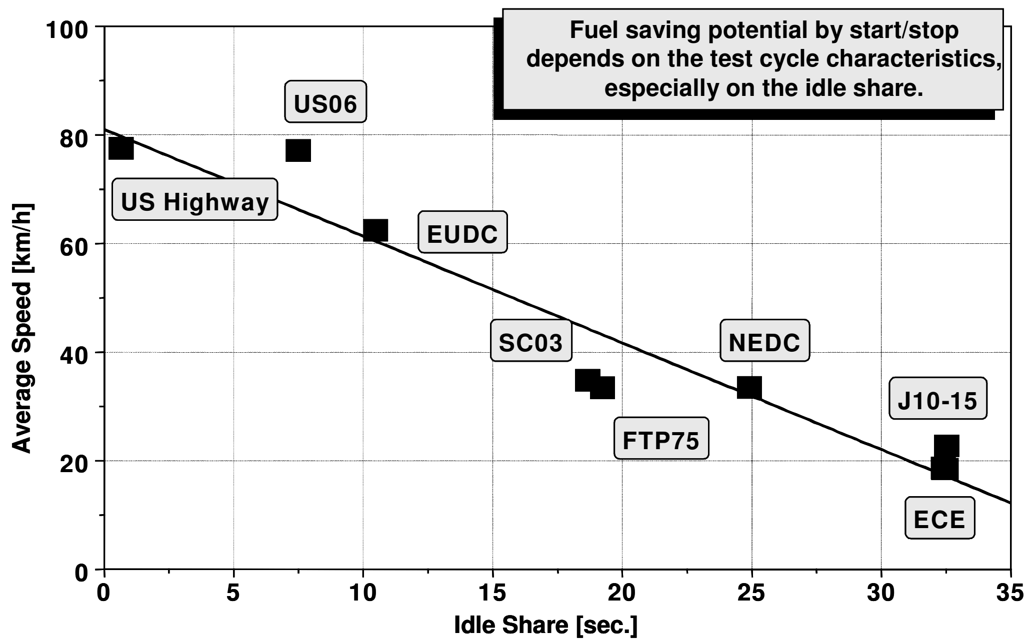

Figure 3 - Average Speed versus Idle Share

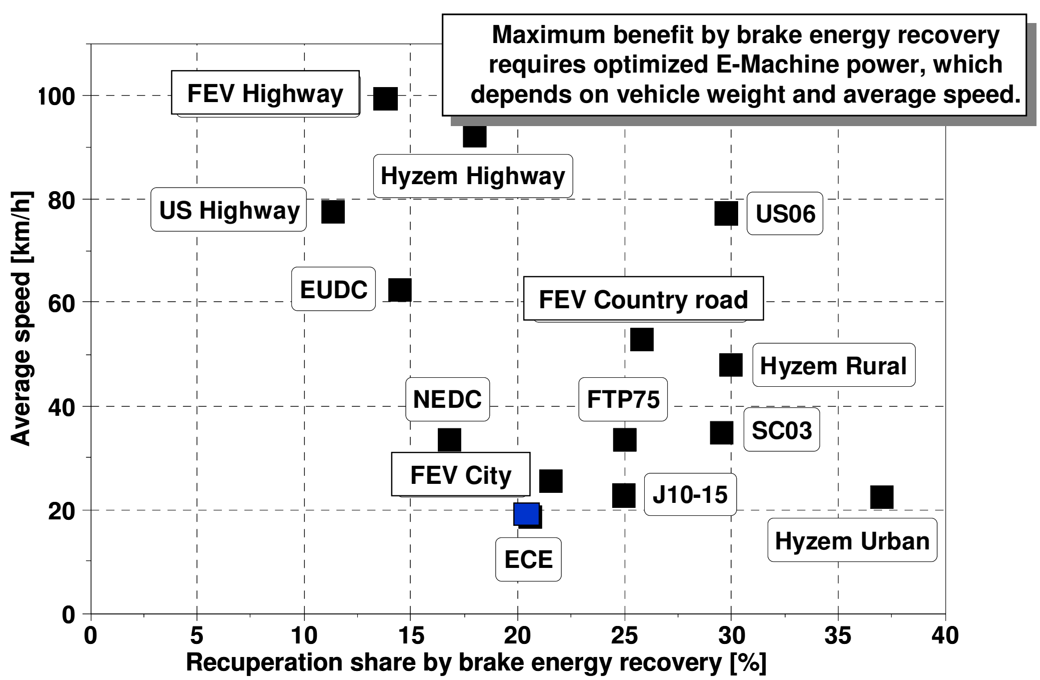

Figure 4 - Average Speed versus Recuperation Share

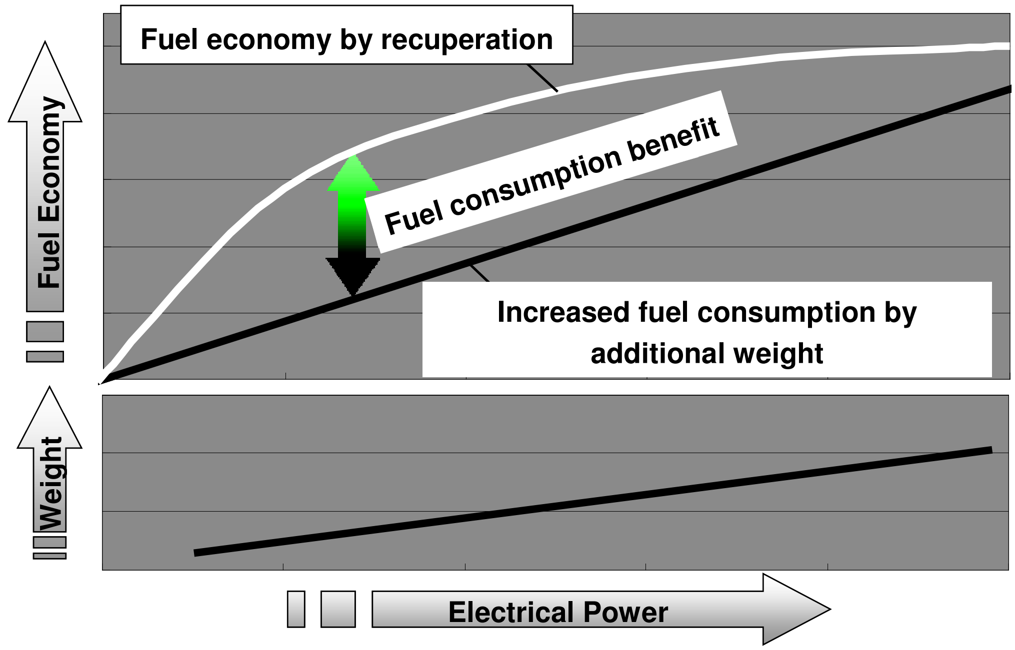

Figure 5 - Fuel Economy versus Electrical Power

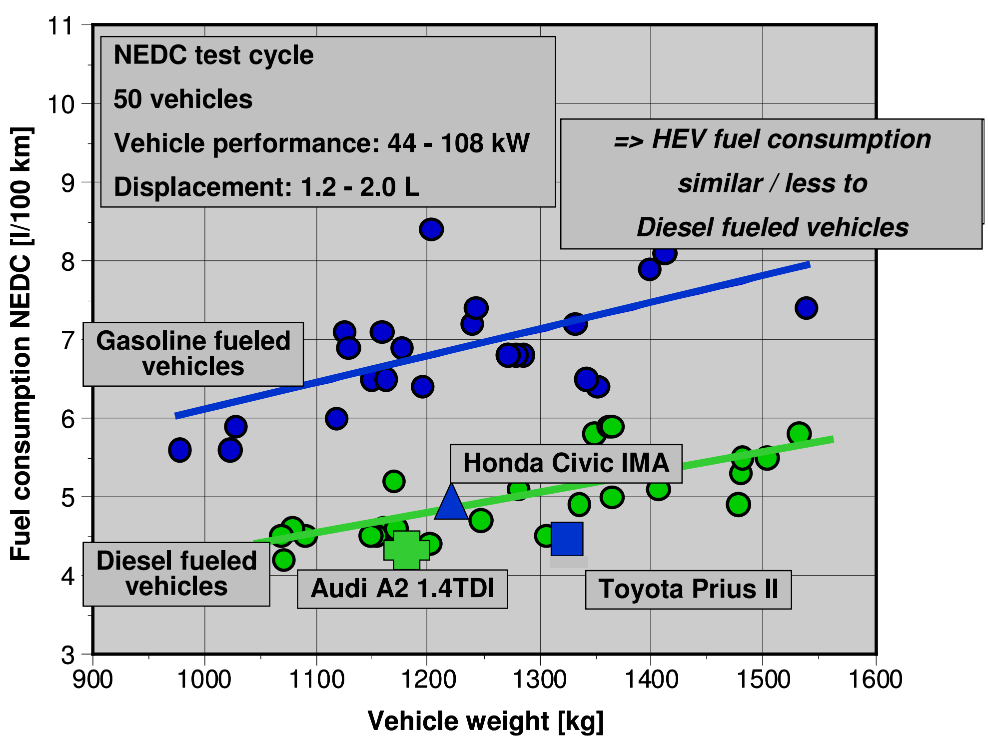

Figure 6 - Fuel Consumption (NEDC) versus Vehicle Weight

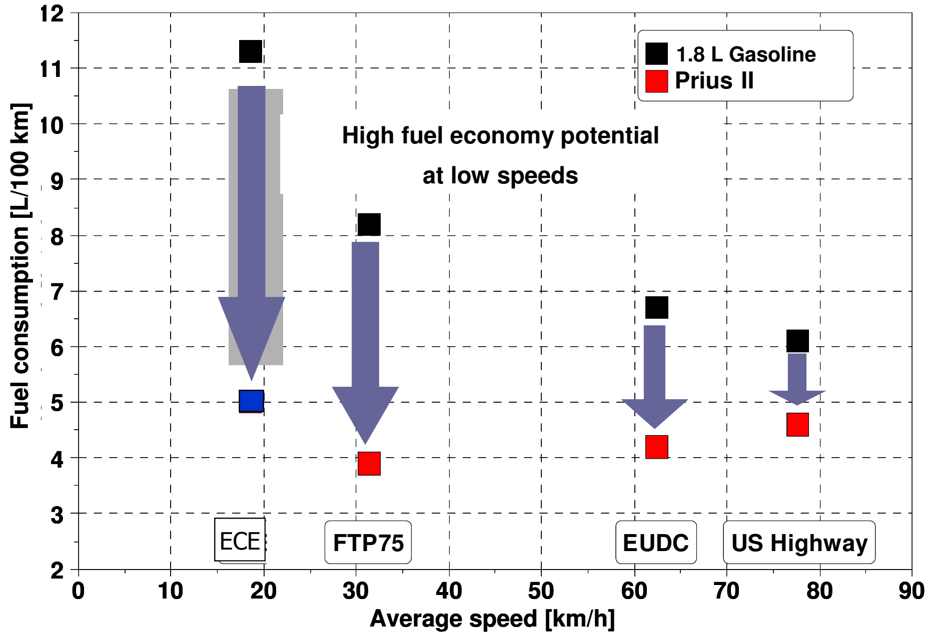

Figure 7 - Fuel Economy Potential (NEDC) versus Average Speed

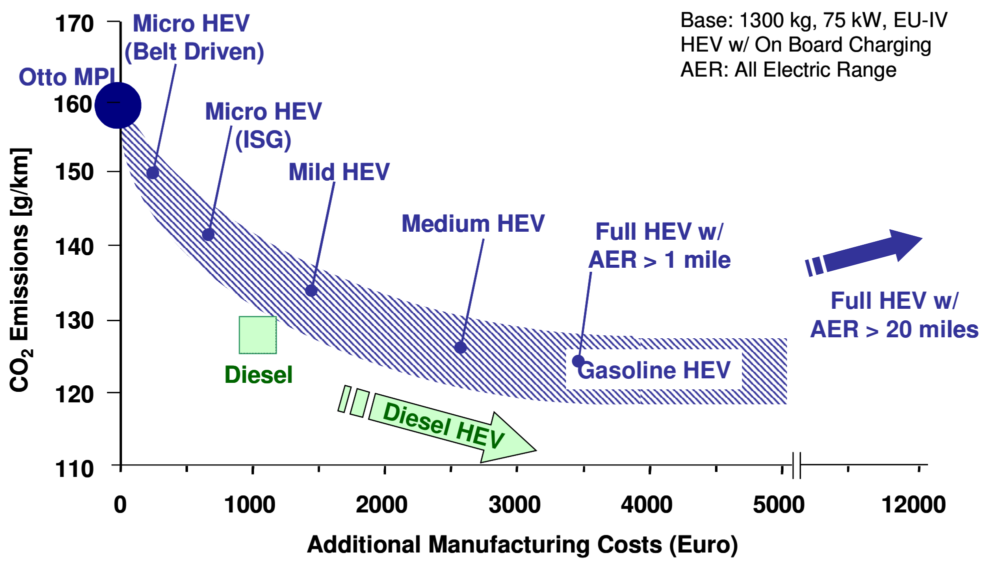

Figure 8 - CO_2-Emission Savings (NEDC) versus Costs

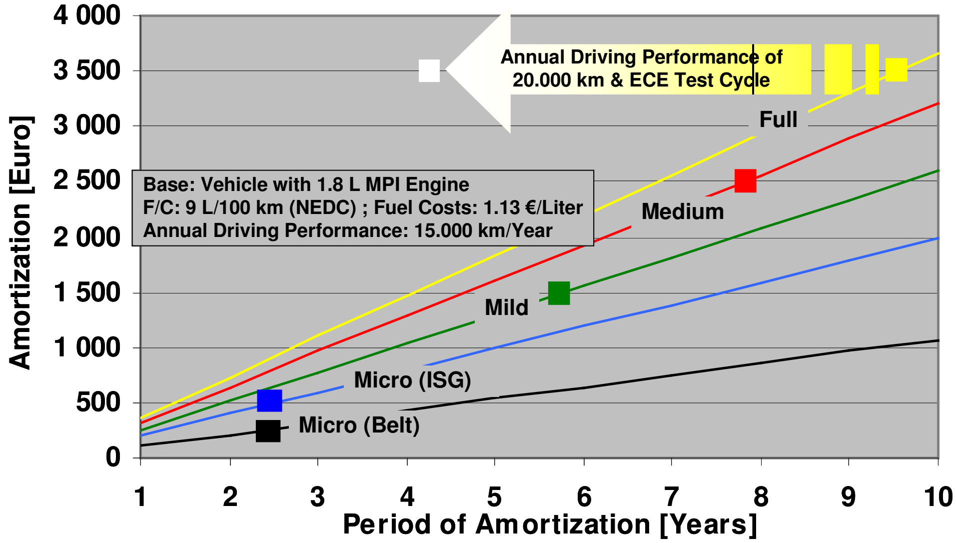

Figure 9 - Amortization of Additional HEV Costs by Fuel Saving

REFERENCES

Konstantin Neiß, 14/15 June 2004, Hybridfahrzeuge auf dem Vormarsch, Management Circle
Dr. Daniel Kock , 14/15 June 2004, “Hybridfahrzeugtechnologie am Beispiel von Ford”, Management Circle
Frost & Sullivan, B126