EVS 24
Towards Zero Emission

Session 3F: Global Approach & Cost Analysis

2009-05-15, 13:50-15:50
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EVS24
Stavanger, Norway, May 13-16, 2009

Technical, Ecological and Economic Assessment of Electrified Powertrain Systems for Passenger Cars in a Dynamic Context (2010 to 2050)

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Abstract

Electrification of the powertrain to increase vehicle efficiency is probably the most important trend in automotive research and development today. In this paper partly and fully electrified propulsion systems for passenger vehicles are analysed from a technical, ecological and economic perspective. 8 powertrain systems with different degrees of electrification were investigated in detail starting from conventional drive with internal combustion engine to a pure electric drive. To identify the present and future potentials of each technology a detailed assessment of all propulsion systems was performed. Within this assessment the energy efficiency of each system was determined including detailed data on fuel consumption and greenhouse gas emissions of the vehicles (TTW-data). Furthermore the entire chains of energy conversion were investigated to receive overall energy- and greenhouse gas balances. For the analysis of their economic competitiveness an economic assessment of the aforementioned powertrain systems was performed considering investment costs for vehicles, fuel costs and taxes.

The whole assessment was performed for the present state and dynamically for the next decades (2010-2050). The latter was done in the form of development scenarios where shifts within both framework conditions and technological development were assumed. The results give an overview on the potential of the single vehicle propulsion technologies from technical, environmental and economic standpoints.

Keywords: list 3-5 keywords from the provided keyword list in 9,5pt italic, separated by commas

1 Motivation and Objectives

Passenger cars are the most important means of transport for individual mobility in industrialised countries [2] today. Moreover they massively gain importance in developing countries. The major problems of passenger vehicles today are that they currently show low efficiency and are characterised by a high dependence on fossil fuels [3].

The electrification of the vehicle's powertrain is seen as an appropriate approach to face these problems. On the one hand vehicle efficiency can be increased significantly and on the other hand dependence on fossil fuels can be reduced by using electricity from renewable sources [3].

1.1 Motivation

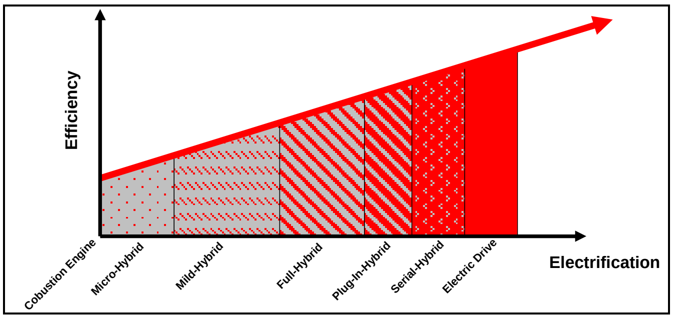
Today most major automotive manufacturers plan to introduce new hybrid electric vehicles in the market whereas some even plan to introduce pure electric vehicles.
This development raises the question which degree of electrification is achievable today and which degrees can be reached in a medium to long term.
The paper tries to answer this question by analysing the technical, ecological and economic performances of 8 different powertrain options with different degrees of electrification.
The paper is based on a research project realised for the Austrian ministry of traffic innovation and technology[1]. The project was realised in corporation with AVL List, an Austrian company specialised on R&D for car power train systems, and Joanneum Research, an Austrian research institute [1].

1.2 Objectives

The objective of this work was to analyse in a dynamic context from 2010 to 2050 how the electrification of vehicle powertrains can improve the energetic and environmental performance of passenger vehicles and how the development influences the economics of the vehicles.
The following types of powertrain systems were analysed in detail:

- Conventional Drive
- Micro hybrid
- Mild Hybrid
- Full Hybrid
- Plug in Hybrid
- Serial Hybrid
- Battery Electric Drive
- Fuel Cell Vehicle

Figure 1: Electrification of Vehicle Powertrain



2 Methodological Approach

For the investigation of the vehicle propulsion systems specified above technical, ecological and economical analysis were performed to obtain Well-to-Wheel data on energy consumption and greenhouse gas emissions and costs.
To be able to compare the different powertrain systems three reference vehicles were determined, representing compact, middle class and upper class vehicles. Each vehicles class was characterised by certain specifications (e.g. engine power, weight, range) typical for the Austrian passenger car sector. This paper will only discuss two of the three classes: compact class vehicles and middle class vehicles. Those two classes present more than 90% of the Austrian vehicle stock.

3 Technical Analysis

The technical analysis consists of two parts. Firstly the components of each propulsion system were determined so that the vehicle can meet the defined requirements. (see Table 1 & Table 2). Moreover the detailed properties of the single components had to be determined for the further steps of the investigation. For example the effects of additional components on the overall vehicle weight were an important factor for the calculation of the energy demand of the vehicle.

	Conventional Drive Gasoline	Conventional Drive Diesel	Mild Hybrid	Full Hybrid	Plug-In Hybrid	Serial Hybrid	EV	FCV
Vehicel Weight (kg)	1470	1522	1460	1488	1538	1623	1678	1799
Combustion Engine Power (kW):	75	75	65	50	50	40	0	0
Electric Motor Power (kW):	0	0	20	50	50	75	75	75
Li-Ionen Batteries (kWh)			1	2	10	20	50	20
Electric Range (km)				5	50	100	250	500
Overall Range	700	700	700	700	700	700	250	500

Table 1: Specifications of middle class vehicles

1 "Development of Sceanrios of the dissemination of vehicles with partly and fully electrified powertrain under different political framework conditions – ELEKTRA", Sponsored by the Austrian Federal Ministry of Transport, Innovation and Technology within the A3plus Technology Program

	Conventional Drive Gasoline	Conventional Drive Diesel	EV
Vehicel Weight (kg)	955	989	984
Combustion Engine Power (kW):	50	50	0
Electric Motor Power (kW):	0	0	50
Li-Ionen Batteries (kWh)			
Electric Range (km)			
Overall Range	400	400	100

Table 2: Specifications of compact class vehicles

The second step of the technical analysis was the determination of vehicles efficiency expressed by their fuel consumption and greenhouse gas emissions from a tank-to-wheel approach. The analysis was performed by experts from AVL, one of the partners within the project.
In the technical analysis the tank-to-wheel efficiency of the vehicles was determined for test cycles (a mix of NEDC and ARTEMIS).
Firstly the baseline vehicle with conventional drive was analysed using the simulation tool AVL-Cruise. Based on this data an additional software tool developed by Hybrid Experts within AVL was applied to determine the efficiency of all vehicle powertrain configurations. In this process all critical parameters (e.g. efficiency of power electronics and batteries, extra weight from hybridisation…) were considered to estimate the potentials different hybrid configurations.

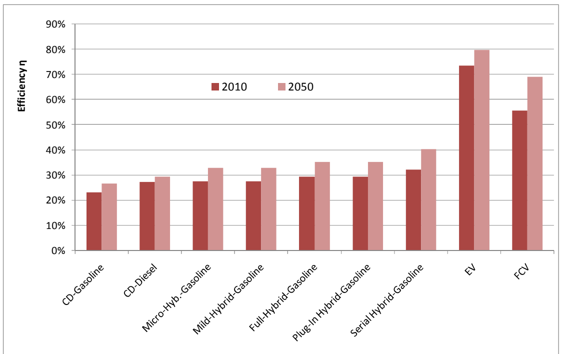


Figure 2: TTW Efficiency (middle class vehicle)

Figure 2 indicates that vehicle efficiency is increasing by the degree of electrification. The pure electric vehicle reaches a WTW-efficiency of over 70%.

4 Ecological Analysis

To obtain a detailed view on the ecological impact of each technology an ecologic analysis was performed by the project partner Joanneum Research. Within this analysis the greenhouse gas emissions and the energy balances of all pathways of energy conversion were determined. Different vehicle powertrain technologies can represent different pathways of energy conversion depending on the fuels they use.
To analyse those pathways in detail a Life-Cylce-Analysis (LCA) was performed which permitted to get Well-to-Wheel data of all pathways for both greenhouse gas emissions and the cumulated energy consumption (CED).
For the calculation the GEMIS software (Version 4.42) was used. The following greenhouse gases were considered: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)
The Methodology of the LCA refers to the ISO 14040 „Life Cycle assessment“, the standard methodology of IEA Bioenergy Task 38 and the recommendations of COST Action E9 „Life Cycle Assessment of Forestry and Forest Products“.
The Life Cycle Includes 5 steps („from cradle to grave“ respectively „well to wheel - WTW“).

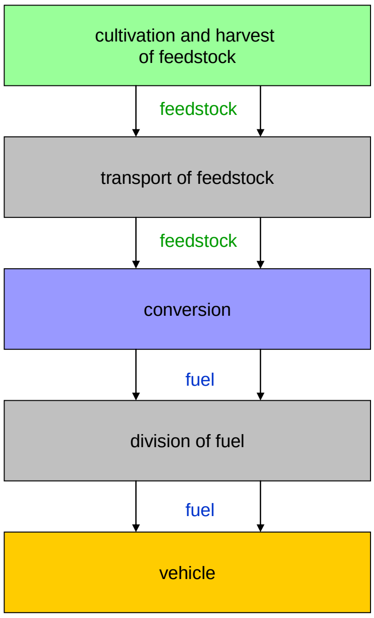


Figure 3: The 5 steps of the life-cycle-analysis

To measure the greenhouse gas effect of all gases the Global Warming Potential (GWP) was applied. In this method the effect of each gas on the warming of the atmosphere is expressed in equivalent amounts of CO_2. The concept was developed to make the different gases comparable in terms of their greenhouse impact giving them all factors that express their impact by CO_2 equivalent.

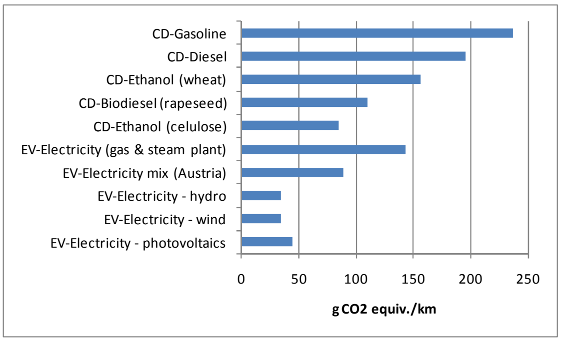


Figure 4: WTW-greenhouse gas emissions for middle class vehicle

Figure 4 shows the greenhouse gas balance of a middle class vehicle using different sources of energy. Above there are conventional diesel and gasoline internal combustion vehicles using fossil and renewable fuels. Below there is and electric vehicle using electricity from different fossile and renewable sources.

It is evident that electric pathway offer a high potential of green house gas saving especially when the electricity comes from renewable sources.

5 Economic Analysis

If a vehicle powertrain technology is supposed to gain a considerable share of the market and therefore be able to contribute to the reduction of energy consumption and greenhouse gas emissions it also has to be competitive from an economic point of view. To assess the economic competitiveness of the different powertrain systems a detailed analysis of their economics was carried out.

Within this analysis investment costs, fuel costs and taxes were considered. Maintenance costs and costs for insurances were not considered as they were assumed to be the same for all technologies.

5.1 Investment costs

The analysis of the investment costs is based on the costs of the single components. The costs of the components were taken form relevant literature in this field and from own investigations [4][5][6][7][8][9][10][11][12][13]. Figure 5 and Figure 6 show how the different component groups contribute to the overall cost of the each vehicle technology. It shows that the overall investment costs increases with the degree of electrification of the propulsion system. The main driver of the investment costs are the batteries that are required to permit the desired electric range.

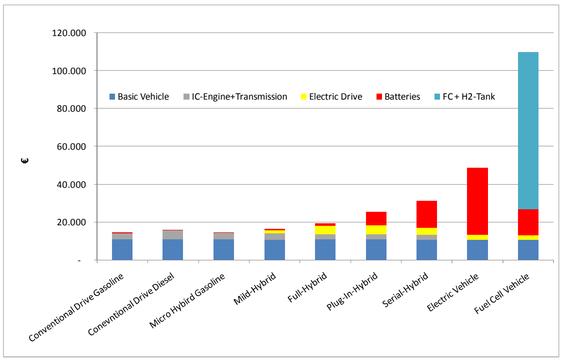


Figure 5: Costs of Vehicles 2010 (+ Fuel Cell Vehicle)

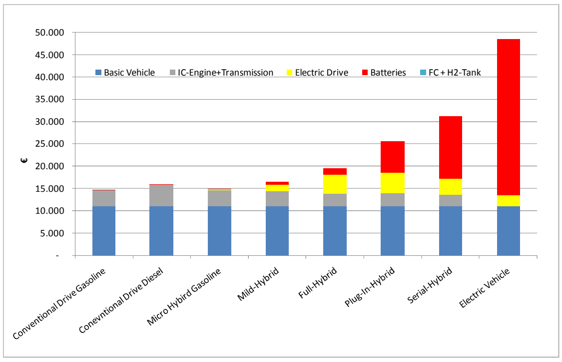


Figure 6: Costs of Vehicles 2010

Therefore the costs of batteries (Lithium Ion Batteries) can be seen as the crucial factor within the investment costs of electrified vehicles. Their specific costs in 2010 were assumed to be at 700€/kWh. For the mid- to long term development of the costs of batteries the concept of technological learning was applied. To estimate the cumulative production of lithium ion traction batteries the scheduled introduction of major automotive producers was used for the time 2010-2015. For the years 2011-2030 it was assumed that the lithium ion batteries become the standard technology for both electric and hybrid electric vehicles and therefore follows the characteristic S-shape of a technological substitution process. Furthermore it is assumed that the trend towards hybridisation of vehicles was a robust process and would continue within the following decades.

The mathematical description of the learning curve is given by the exponential function.

$$C(x) = a * x^{-b} \qquad (1)$$

C........cost per unit [EUR/unit]

a........cost of first unit produced [EUR/unit]
x........number of produced units
b........learning index [-]

It is evident that the cost reduction depends on the global cumulative production and the learning index. From the learning index the progress ratio p can be calculated. The progress ratio expresses what cost reduction would be caused by a doubling of cumulative production (percentage of former costs after a doubling of production).

$$p = 2^{-b} \qquad (2)$$

p........progress ratio [-]

For the case of lithium Ion batteries a progress ratio of 92,5% was assumed. The cost reduction of lithium Ion batteries from 2010 to 2030 is depicted in figure Figure 7.

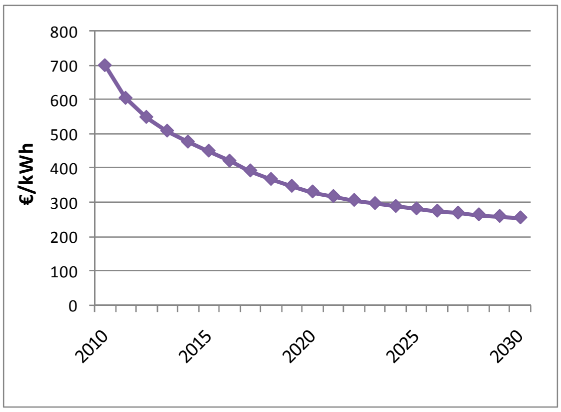


Figure 7: Costs of Li-Ion Batteries 2010-2030

The reduction of battery costs effect a significant reduction of overall vehicle costs of hybrid and electric vehicles up to 2030 (see Figure 8 & Figure 9).

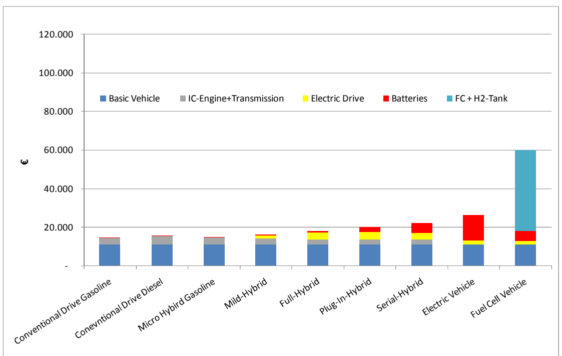


Figure 8: Costs of Vehicles 2030 (+ Fuel Cell Vehicle)

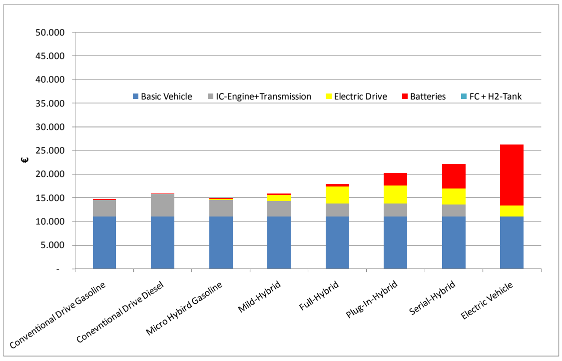


Figure 9: Costs of Vehicles 2030

5.2 Annual Costs

For the calculation of the annual costs the levelized costs of investment were used from chapter 5.1. assuming a life span of the vehicles of 10 years.
The fuel costs could be calculated from the fuel consumption determined in the technologic analysis (see chapter 3) and the fuel prices. For the 2010 fuel price status market prices in Austria were taken (spring 2009). For the 2030 price status it was assumed that the fossil fuel prices increase to level of 50% beyond the one of 2010.
Another important factor for the costs of vehicles is taxation. Within the analysis three types of taxes were considered.

- Tax on Acquisition
- Tax on Ownership
- Tax on Motoring

For the status 2010 the Austrian taxation level of spring 2009 was assumed. For the development until 2030 it was assumed that taxes would be adapted with regard to an increase in energy efficiency and a reduction of greenhouse gas emissions.
The service costs of each vehicle consists of it's energy costs and it's capital costs. The mathematical definition is expressed by the following equations:

$$SC_j = EC_j + CC_{SP\_j} \text{ [EUR/km]} \qquad (3)$$

SC................service costs [EUR/km]
EC…..……..energy costs [EUR/km]
CC_{SP_j}……..specific capital costs of vehicle j [EUR/km]

$$EC_j = FC_j * FP_j \text{ [EUR/km]} \qquad (4)$$

FC_j.........energy consumption of vehicles j [kWh/km]
FP..........fuel price [EUR/kWh]

$$CC_{SP\_j} = (\alpha * (IC_j + TA_j) * (1 + VAT_j)) / S_{km} + TO_j$$
[EUR/km] (5)

α ....Annuity factor
IC_j......Investment costs of vehicles j (EUR/vehicle)
TA_j .....tax on acquisition
TO_j......tax on ownership
VAT_j...Value added tax
S_{km}.......driven kilometres by year

In the calculation an annual kilometrage of 20000km was assumed for middle class vehicles and 15000km for compact vehicles.

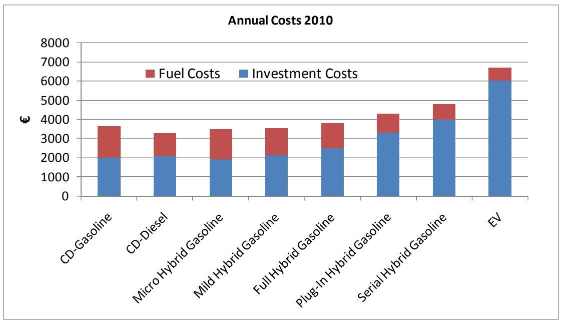


Figure 10: Annual costs of middle class vehicles 2010

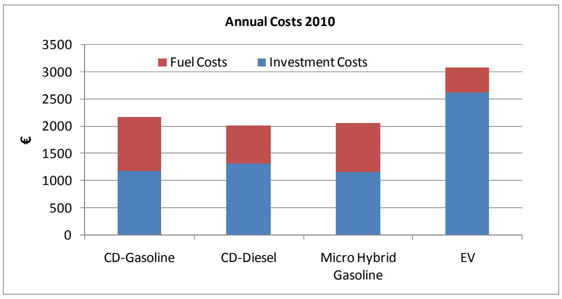


Figure 11: Annual costs of compact class vehicles 2010

Figure 10 and Figure 11 indicate that today hybrid and electric vehicles are not competitive from an economic point of view, neither in the middle class segment nor in the compact class. Their high investment cost cannot be compensated by the fuel savings.

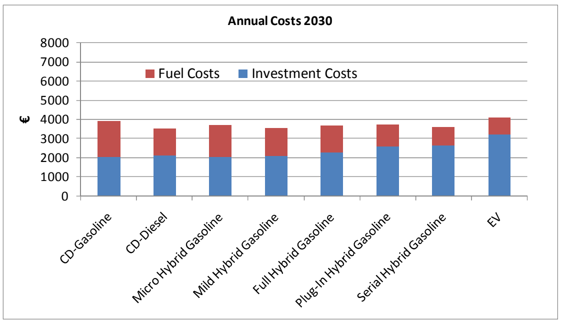


Figure 12: Annual costs of middle class vehicles 2030

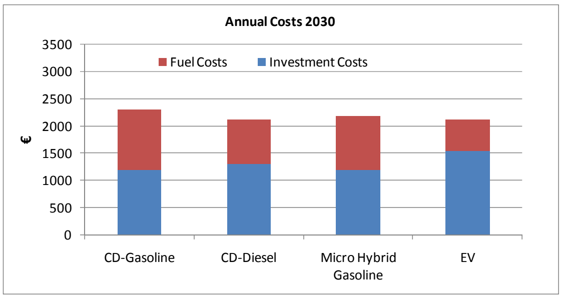


Figure 13: Annual costs of compact class vehicles 2030

Until 2030, due to the reduction of the investment costs and the shift within the political and economic framework condition, the competitiveness of electrified vehicles improve strongly. By that time they are more or less catching up with conventional technologies and some become even better.

6 Conclusions

The results point out that there is a high potential for energy savings in the passenger vehicle sector by using partly and fully electrified powertrain systems. It has to be considered however, that even though electrified vehicles save energy during the use, their production needs more energy (embodied energy). Therefore, for the whole lifecycle, the savings depend on the milage of the vehicle.

The reduction of greenhouse gas emissions strongly depends on the source of electricity used. However, even if fossil energy carriers are used for its production, the emissions can be reduced considerably by the use of electrified vehicles.

The economic analysis shows that electrified vehicles are not competitive under the present framework conditions. Their high costs cannot be compensated by the fuel saving within the vehicle life time.

Within the next decades due to the reduction of investment costs their competitiveness improves dramatically. Together with favourable political

and economical framework conditions this development can make hybrid and electric vehicles an equal option for the customer from an economic perspective.
This perspective and the fact that electrified propulsion systems are superior in terms of their ecological impact make them a very promising option for becoming the future standard for passenger vehicles.

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