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Fuel cell power trains for road traffic

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Abstract

Legal regulations, especially the low emission vehicle (LEV) laws in California, are the driving forces for more intensive technological developments with respect to a global automobile market. In the future, high efficient vehicles at very low emission levels will include low temperature fuel cell systems (e.g., polymer electrolyte fuel cell (PEFC)) as units of hydrogen-, methanol- or gasoline-based electric power trains. In the case of methanol or gasoline/diesel, hydrogen has to be produced on-board using heated steam or partial oxidation reformers as well as catalytic burners and gas cleaning units. Methanol could also be used for direct electricity generation inside the fuel cell (direct methanol fuel cell (DMFC)). The development potentials and the results achieved so far for these concepts differ extremely. Based on the experience gained so far, the goals for the next few years include cost and weight reductions as well as optimizations in terms of the energy management of power trains with PEFC systems. At the same time, questions of fuel specification, fuel cycle management, materials balances and environmental assessment will have to be discussed more intensively. On the basis of process engineering analyses for net electricity generation in PEFC-powered power trains as well as on assumptions for both electric power trains and vehicle configurations, overall balances have been carried out. They will lead not only to specific energy demand data and specific emission levels (CO_2, CO, VOC, NO_x) for the vehicle but will also present data of its full fuel cycle (FFC) in comparison to those of FFCs including internal combustion engines (ICE) after the year 2005. Depending on the development status (today or in 2010) and the FFC benchmark results, the advantages of balances results of FFC with PEFC vehicles are small in terms of specific energy demand and CO_2 emissions, but very high with respect to local emission levels.

Keywords: Fuel cell systems; Internal combustion engine; Power trains; Road traffic

1. Introduction

In development work, benchmark and prototype tests as well as process engineering and systems analyses, efforts are made worldwide to improve the balances of full fuel cycles (FFCs) for power trains in road traffic. This is done including secondary energy carriers in the vehicle tank other than gasoline and diesel. The different solution approaches all serve to reduce the vehicles' specific energy demand and fuel supply as well as to minimize specific vehicle and fuel cycle emissions. As far as the emissions are concerned, it is also important to optimize the quality (i.e., the composition) of the hydrocarbon emissions in the sense of minimizing the secondary pollutants, such as ozone [1].

The development of passenger cars for the future is currently focused on conventional car power trains. However, among the novel power trains with low specific energy demand and emissions compared to conventional power trains with internal combustion engines (ICE), electric power trains with fuel cell systems undoubtedly represent a great challenge. The present analysis of such electric power trains and a comparison with future conventional power trains with ICEs can provide information about the options of novel power trains with fuel cell systems for passenger cars of the future [2].

2. New energy carriers and power trains in road traffic

If advanced power trains with ICEs based on conventional fuels will fulfill future energy demand and emission standards and if sufficient gasoline and diesel will be

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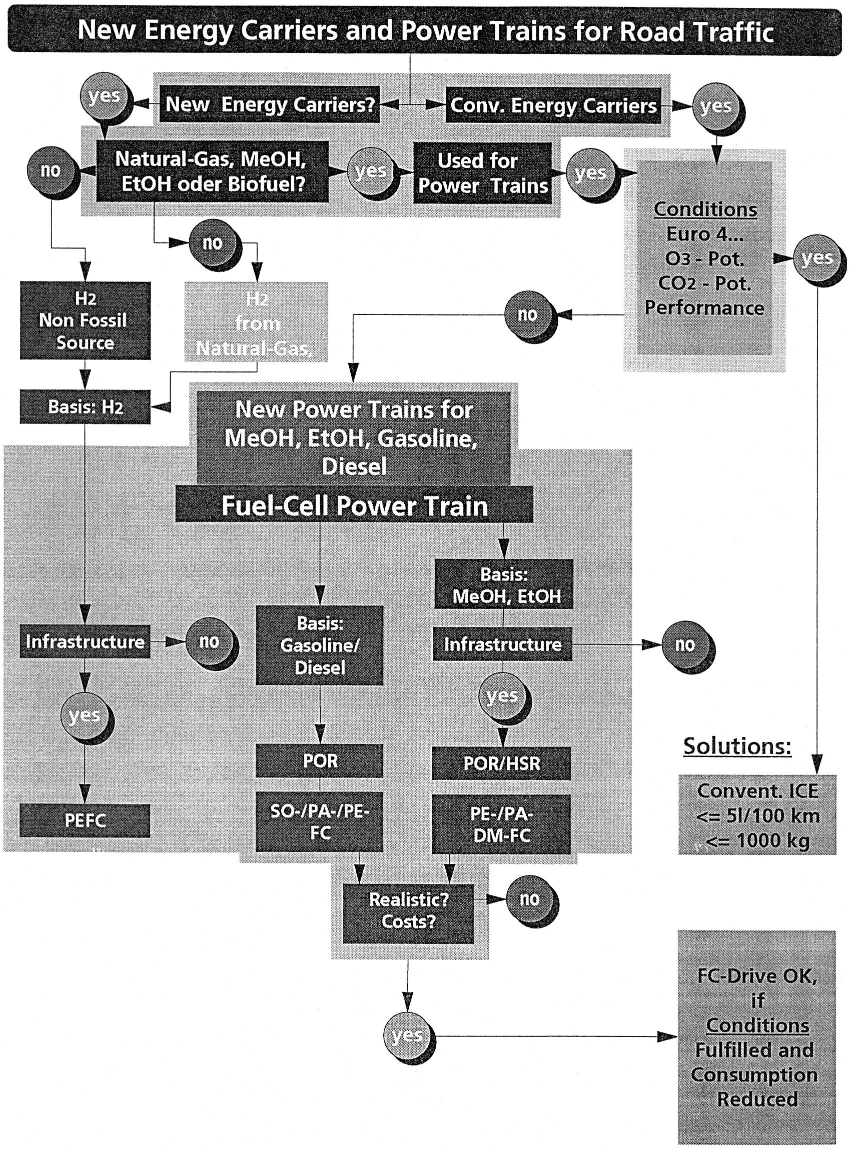


Fig. 1. New energy carriers and power trains for road traffic. PEFC, Polymer electrolyte fuel cell; PAFC, phosphoric acid fuel cell; SOFC, solid oxide fuel cell; ATR, autothermal steam reformer; POR, partial oxidation reformer; DMFC, direct methanol fuel cell; CO_2-Pot., global warming potential; O_3-Pot., ozone formation potential; HSR, heated steam reformer; ICE, internal combustion engine; FC, fuel cycle; MeOH, methanol; EtOH, ethanol.

available on a long-term basis worldwide with globally increasing mobility, then industry will cling to these ''conventional'' systems for the mass market of passenger cars. Since it is more likely, however, that not all boundary conditions (see Table 2) can be fulfilled simultaneously, it is already necessary today to discuss the short-, medium- and long-term introduction of new power trains and energy carriers in the global passenger car mass market of the future (see Fig. 1).

3. State of the art

Worldwide projects on fuel cell power trains especially in Europe (F, D, NL, I, S, CH), USA and Japan suggest that the development status of the solution approaches involving different energy carriers and fuel cells is very different. Great efforts at improving the efficiency and emission data of vehicles are currently devoted to conventional vehicles with ICEs for diesel and gasoline as conventional energy carriers and natural gas or biofuels as renewables. At the same time, nearly all car manufacturers develop vehicles with electric power trains and batteries for energy storage. Development is currently focused worldwide on fuel cells combined with electric motors as new power trains, supplying the fuels under discussion either directly or indirectly to the fuel cells systems (see Fig. 2).

Based on project reports available from the literature, seven different FFCs including fuel cycle and power train

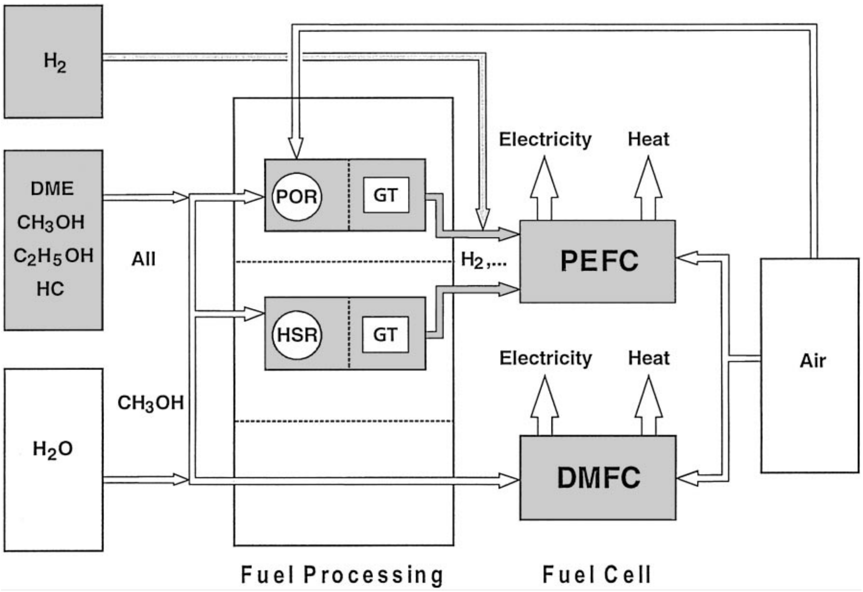


Fig. 2. Different solutions including energy carriers and fuel cell systems. POR, Partial oxidation reformer; HSR, heated steam reformer; GT, gas treatment; PEFC, polymer electrolyte fuel Cell; DMFC, direct methanol fuel cell; HC, hydrocarbons.

(as defined below) can be described at present and used for a state of the art comparison (see Table 1).

The power train includes the following energy carrier processing and energy conversion and/or storage steps: fuel on-board processing (if necessary) — energy conversion from chemical energy to mechanical energy (ICE) or to electrical energy (fuel cell) — energy conversion from electrical energy (fuel cell) to mechanical energy (electric motor) (if necessary); in addition, possible storage of (recovered) energy as chemical energy or as electrical energy or as mechanical energy. If a fuel cell is included into a power train it will be referred to a *fuel cell power train*.

Worldwide progress in hydrogen-fueled polymer electrolyte fuel cells (PEFCs) and the power-train systems and prototypes with compressed hydrogen storage, PEFC and electric motor already developed [3–5], different EU-JOULE-3 programs) permit FFC 4 with a currently feasible hydrogen production on the basis of natural gas and an assumed infrastructure to be included in the comparison with future conventional FFCs (1, 2 and 3). For FFC 5 with methanol (based on natural gas) in the tank, on-board hydrogen production by reforming, PEFC and electric motor, there are numerous projects under way worldwide [6] and DOE/PNGV-USA programs and EU-JOULE-3 programs). Work at the Research Center Jülich (FZJ) for on-board hydrogen production and PEFC [7,8] is pursued as well as initial car prototype and concept developments [9–11]. For such a system, the introduction of a new infrastructure for methanol as the secondary energy carrier would be required. The results of technical work on the components of the system are complemented in comparative analyses by studies with separate process engineering analyses [1,12–14]. FFC 6 is currently only based on development work on the direct use of methanol in a direct methanol fuel cell (DMFC) system without hydrogen pro-

Table 1
Full fuel cycles
CNG, compressed natural gas; CH_2, compressed hydrogen; ICE, internal combustion engine; PEFC, polymer electrolyte fuel cell; DMFC, direct methanol fuel cell.

FFC no.	Fuel cycles	Power train
FFC 1	Oil: refinery — gasoline	ICE
FFC 2	Oil: refinery — diesel	ICE
FFC 3	Natural gas: compressor — CNG	ICE
FFC 4	Natural gas: reformer–compressor — CH_2	PEFC + electric motor
FFC 5	Natural gas: reformer–synthesis — methanol	Reformer[a] + PEFC + electric motor
FFC 6	Natural gas: reformer–synthesis — methanol	DMFC + electric motor
FFC 7	Oil: refinery — gasoline	Reformer + PEFC + electric motor

[a] Reformer: fuel processor with catalytic converter and gas separating membrane; see Table 5.

Table 2
Requirements for passenger cars of the future

Group of interest	Target	Goal
Customer	Overall costs	Low
	Performance and safety	High
Society	Energy demand	Low
	Environmental pollutants	Low
	Greenhouse gases (CO_2, O_3, ...)	
	Regulated pollutants (CO, NO_x, VOC, PM)	
	Availability of fuels and materials	Good
	Life cycle analysis	
Manufacturer	Acceptance by customer and society	High
	Acceptance by global market	High

duction in reformers [15,16]. FFC 7 presents a solution approach producing a hydrogen-rich fuel gas for a PEFC from gasoline on board the vehicle. This new variant of possible fuel cell power trains has so far only been described in the literature in the form of process engineering analyses or initial gasoline reformer results [13,17–21].

At the Research Center Jülich, comparative analyses for FFCs in road traffic for passenger cars have been investigated using the FFC balancing tool ‘‘KRAKE’’ [1,22–25] with respect to the following criteria: specific primary energy/passenger car demand, specific fuel cycle/passenger car emissions as well as secondary pollutant potentials. Essential prerequisites are process engineering analyses for the power trains including experimental results and data from the literature, also concerning the fuel cycles.

4. Definition of reference systems: power-train variants and energy carriers

This chapter pertains to the definition of power train variants for passenger cars with respect to the FFCs and is complemented by data on the vehicle specifications (calculation of energy demand at the wheel in the New European Driving cycle (NEDC)) and on the specific emission data of regulated pollutants (CO, NO_x and VOC)). In total, a *worst case/best case* evaluation is obtained with a more conservative (worst) and a more optimistic (best) assumption for the proposed power-train variants based on currently available selected process engineering analyses, technical data from the literature and assumptions or working hypotheses and working goals. The absolute, specific energy demands (per 100 km) to be derived from these data for passenger cars in the NEDC must then still be correlated with the energy demand and emission data for the fuel cycle — from primary energy production to the filling station — of the respective energy carriers used.

4.1. General requirements for passenger cars

The general requirements for passenger cars of the future, i.e., until the year 2005 and thereafter, to be discussed here can be described in Table 2.

The passenger cars with ICE and gasoline or diesel as energy carriers serving as reference vehicles in the present analysis are constantly improved, but also increasingly challenged — assuming comparable requirements — by passenger cars with ICE and natural gas as energy carrier, electric vehicles with batteries or fuel cells or vehicles

Table 3
Key challenges for fuel cell power trains

Goals	Means, limits
Low costs	Fuel cells, fuel processing < 100 DM/kW_{el}
Light and compact construction	Specific mass < 6 kg/kW_{el}
Efficient energy management	Optimization of pressures, air ratio, current/voltage values
Efficient water management	
Efficient gas treatment	Usage of membranes, CO oxidation
Optimized material balances	Minimized mass of catalysts (Pt, Pd, Ag, Cu, Zn, ...)
Quick start-up and dynamic system	
Efficient energy management of hybrid systems	Energy storage, regenerative braking energy recovery
Reduction of Light Duty Vehicle’s emissions	Emissions $<$ SULEV (California standard) CO_2 emissions < 120 g/km (EU standard)

Table 4
Technical conditions for FFC
Worst case: values without brackets; best case: values in brackets (assumptions for future developments > 2005).
Demand wheel: energy demand at the wheels of the LDV; Eff. LDV: efficiencies of LDV power trains; Energy LDV: energy demand of LDVs; Energy FFC: energy demand of FFCs; POR: partial oxidation reformer; HSR: heated steam reformer; (see also Table 1 and Fig. 2).

FFC	Fuel/Power train	Demand wheel (MJ/100 km)	Eff. LDV (%)	Energy LDV (MJ/100 km)	Energy FFC (MJ/100 km)
FFC 1	Oil (gasoline)/ICE	35.0 (35)	21 (23)	166	189
FFC 2	Oil (diesel)/ICE	35.0 (35)	24 (27)	146	160
FFC 3	Natural gas (CNG)/ICE	35.6 (35)	21 (23)	170	214
FFC 4	Hydrogen (CH_2)/PEFC + electric motor	36.6 (35)	32 (40)	113	182
FFC 5	Methanol/HSR + PEFC + electric motor	38.1 (35)	30 (37)	125	214
FFC 6	Methanol/DMFC + electric motor	38.1 (35)	25 (31)	154	264
FFC 7	Gasoline/POR + PEFC + electric motor	38.1 (35)	22 (27)	177	200

with hybrid power trains. Since electric vehicles with batteries do not satisfy current range requirements for a vehicle not only to be used in towns, they are not discussed here. Hybrid vehicles as a combination of ICE or electric power train with batteries or electric power trains with fuel cells and a second energy storage system will not be analyzed here either, which is not meant to be a negative assessment.

4.2. Key challenges for fuel cell power trains

The challenges listed below apply to the passenger cars with fuel cells based on different energy carriers such as hydrogen, methanol or gasoline/diesel (or other energy carriers such as ethanol, dimethyl ether or various crude oil fractions) to be analyzed here in comparison to conventional passenger cars (see Table 3).

4.3. Definition of power-train variants

In Table 4, the technical data for the selected FFCs of Table 1 are listed as they enter in an analysis based on the current state of the art. In addition to the data on fuel gas production and fuel cells, the efficiencies determined from analyses or assumptions for the fuel cell and net electricity generation from the tank to net power production are defined as well as the efficiencies of the electric power trains behind the fuel cell up to the wheel. The weights of

Table 5
Specific passenger car emissions in comparison
European emission standards of organic gases are not given as non-methane organic gases (NMOG) but as volatile organic compounds (VOCs), including methane.

Source	Emissions (mg/km)			
	CO	NO_x	NMOG	PM 10
European emission standards (NEDC)				
EURO 2005 gasoline	1000	80	100[g]	–
EURO 2005 Diesel	500	250	50[g,h]	25
California emission standards[a] (US-FTP-75-Cycle)				
ULEV at 50,000 miles (old)	1062	124	25	6
ULEV at 120,000 miles (new)	1312	43	34	6
SULEV at 120,000 miles (new)	625	12	6	6
HONDA emissions[b] (Driving cycle unknown)				
CNG + ICE at 100,000 miles	71	11	1	0
Pilot-scale experiments[c] (Constant driving cycle)				
Fuel processor[d] + PEFC + electric motor[e,f]	0.8–1.2	0.10–0.15	0.8–1.2	0

[a] California emission standards following Ref. [27].
[b] HONDA emission data following Ref. [26].
[c] Research Center Jülich [28].
[d] Catalytic converter and gas separating membrane.
[e] Emission data following [28].
[f] Corresponding to 1.0–1.4 MJ/km.
[g] VOC, not NMOG!
[h] Total (VOC + NO_x) = 300 mg/km.

Table 6
Efficiencies of energy supply from well to filling station in Germany
HP = High pressure.

FFC	Path 1	Efficiency (%)	Path 2	Efficiency (%)
FFC 1 + 7	Crude oil to refinery	97	Gasoline at filling station	88
FFC 2	Crude oil to refinery	97	Diesel at filling station	91
FFC 3	Natural gas to HP grid	90	CNG (250 b) at filling station	81
FFC 4	Natural gas to HP grid	90	CH_2 (300 b) at filling station	63
FFC 5 + 6	Natural gas to HP grid	90	Methanol at filling station	58

the vehicles are defined by their energy demand at the wheels (see Table 4). The mechanical power at the wheels is fixed at 40 kW and the range of the vehicle at 500 km. These data are also suitable for determining the specific CO_2 emissions. These assumptions lead to an energy demand for the passenger car and, using the efficiencies for the fuel cycle from the well to the filling station according to the FFC tool KRAKE, a total primary energy demand relative to 100 km (based on the lower heating value) is obtained. As far as regulated pollutants are concerned, the EURO 2005 emission standard is assumed for FFC 1 and FFC 2 (gasoline/diesel ICE), the HONDA emission values are taken for FFC 3 (CNG-ICE) and emission data determined from pilot-scale experiments are used for FCC 5 (methanol–reformer–PEFC–electric motor).

5. Emission potentials of the power-train variants

The emission potentials of the vehicles defined in Table 5 are specified for FFC 1, 2 (EURO 2005 standard) and FFC 3 [26] as well as for FFC 5 according to the data known from pilot-scale experiments. For FFC 6 and 7, there are not even emission data from pilot-scale tests available so that those of FFC 5 were assumed here as feasible in the future and adopted.

The comparison in Table 5 shows the advantages of the fuel cell power train with catalytic converter and a gas separating membrane for a passenger car consuming about 1–1.4 MJ/km of methanol with only part of the energy being converted in the catalytic converter. These values for the specific regulated pollutants were used for the passenger cars of FFC 5 and assumed for FFC 6 and 7.

6. Evaluation

The energy and emission balances are based on the defined passenger cars and fuel cycles as obtained according to the FFC balancing tool KRAKE (as of April 1998; European electricity production data after UCPTE; CNG passenger car emission data following Ref. [26]). The efficiencies of energy carrier supply from well to filling station in Germany are given in Table 6.

A first survey (Figs. 3 and 4) shows the energy and CO_2 balances for the seven selected FFCs with the conservative passenger car specifications until 2005 (worst case; values without brackets in Table 4) (see also Ref. [25]). At

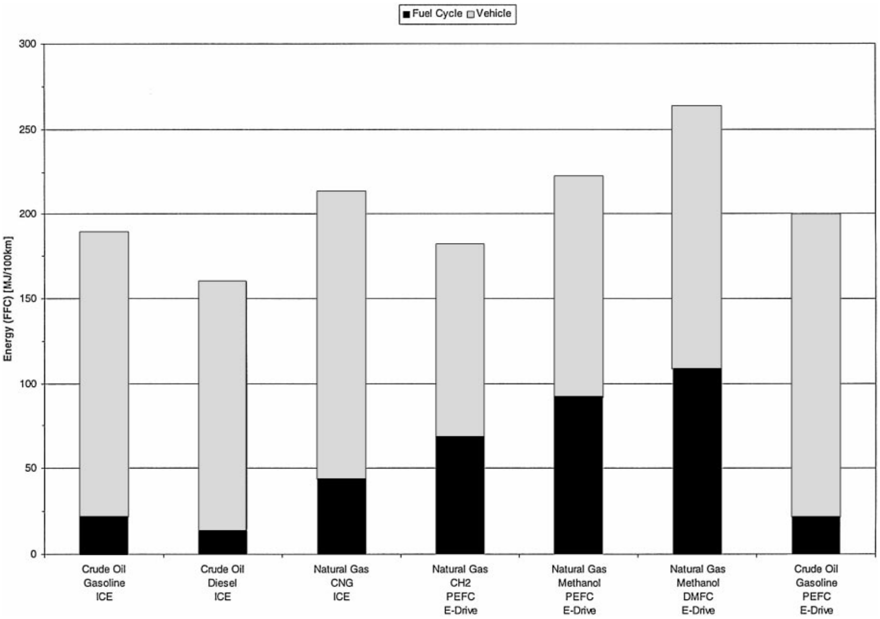


Fig. 3. Energy demand for the supply of different energy carriers and for different types of power trains < 2005 (worst case).

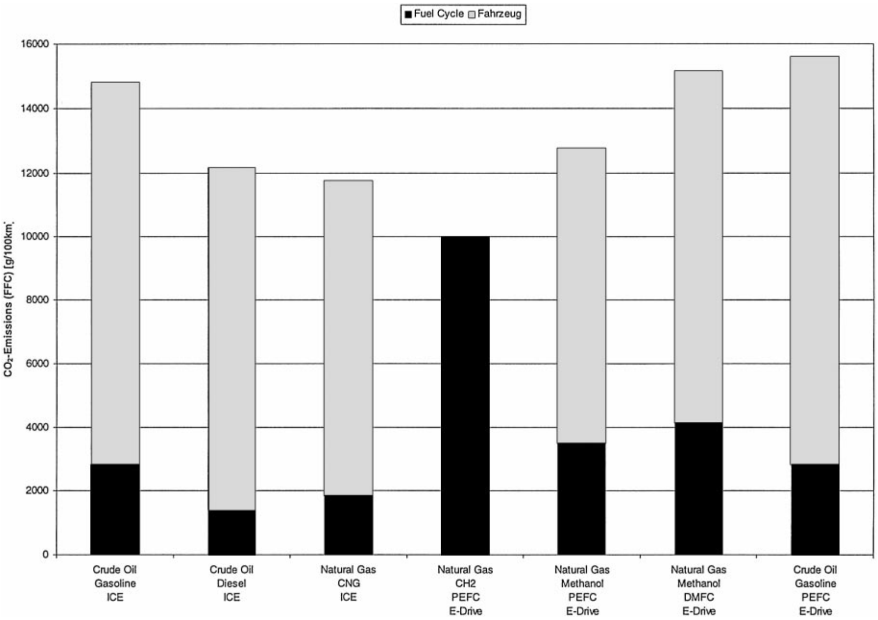


Fig. 4. CO_2 emission values for the supply of different energy carriers and for different types of power trains < 2005 (worst case).

this point it should be taken into account that the basis of these balances include the following settings, uncertainties and assumptions:

- Considerable additional weights compared to conventional gasoline/diesel-ICE power trains have been assumed for the fuel cell passenger car.
- The efficiency analysis is still unclear especially for the DMFC electric power train and the gasoline-reformer-PEFC electric power train; the corresponding emission balances are even unclear.
- All passenger car specifications exhibit a different development status despite the comparative evaluation performed here.
- New production facilities and infrastructures have to be installed for methanol and hydrogen supply.

6.1. Primary energy expenditure

Primary energy savings can hardly be achieved for FFCs with PEFC power trains compared to FFCs with

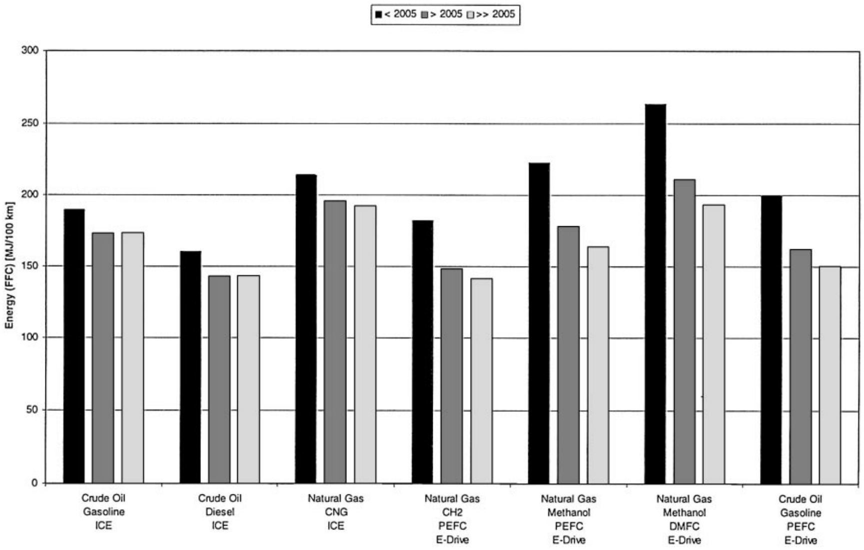


Fig. 5. Energy demand for the supply of different energy carriers and for different types of power trains < 2005 up to ≫ 2005 (worst case/best case).

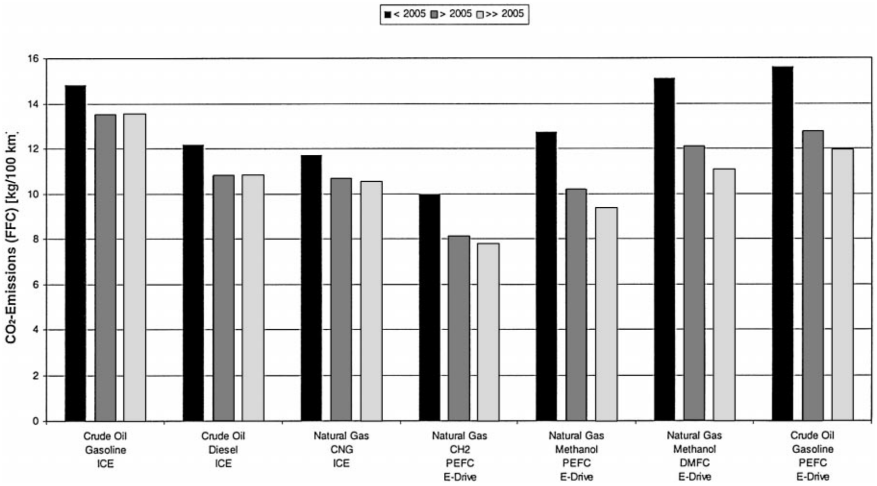


Fig. 6. CO_2 emission values for the supply of different energy carriers and for different types of power trains < 2005 up to $\gg 2005$ (worst case/best case).

advanced ICE power trains in mobile applications on the assumptions of a worst case study made here.

6.2. Passenger car and local emissions

Clear advantages would result for all fuel cell passenger cars taking account of the above-described assumptions and restrictions for regulated vehicle pollutants and thus for the local emission situation especially in conurbations (Table 5). These advantages also imply a considerable reduction of local secondary pollutant formation in the so-called summer smog scenario especially due to the different VOC emissions with their low ozone formation potentials in comparison to ICE exhaust gases. In the FFCs with PEFC-powered passenger cars, the regulated pollutants (CO, NO_x and NMVOC as well as methane) of the fuel cycles are much higher than the car emissions. These fuel supply emissions from well to tank are also described very differently in the literature.

6.3. Global CO_2 emissions

For the CO_2 emissions of all FFCs advantages of about 30% are only found for FFC4 with CH_2–PEFC power train compared to the FFC with gasoline-ICE power train and of 15% compared to the FFC with diesel-ICE power train. The FFC with MeOH–PEFC power train only shows advantages of about 13% compared to the FFC with gasoline-ICE power train (Fig. 4).

6.4. Outlook

The first columns (< 2005) of Figs. 5 and 6 contain the same overall information about the primary energy and CO_2 balances of the seven selected FFCs as in Figs. 3 and 4. They are complemented by the second columns ($>$ 2005), containing passenger car specifications assumed as *optimistic* (best case power train efficiency values put in brackets in Table 4). The third columns ($\gg 2005$) show the same conditions as the second columns but on the assumption of identical energy demand at the wheels of 35 MJ/100 km for the vehicles.

This worst case/best case comparison of specific energy demand and CO_2 emissions clearly shows that a power train variant with a CH_2/PEFC system would exhibit advantages over conventional types of passenger car power trains if natural gas were used as the primary energy carrier for hydrogen production. This applies in the best case vs. the FFC with diesel ICE not to the primary energy demand (Fig. 5) but to the CO_2 emissions of the FFC (Fig. 6).

7. Summary

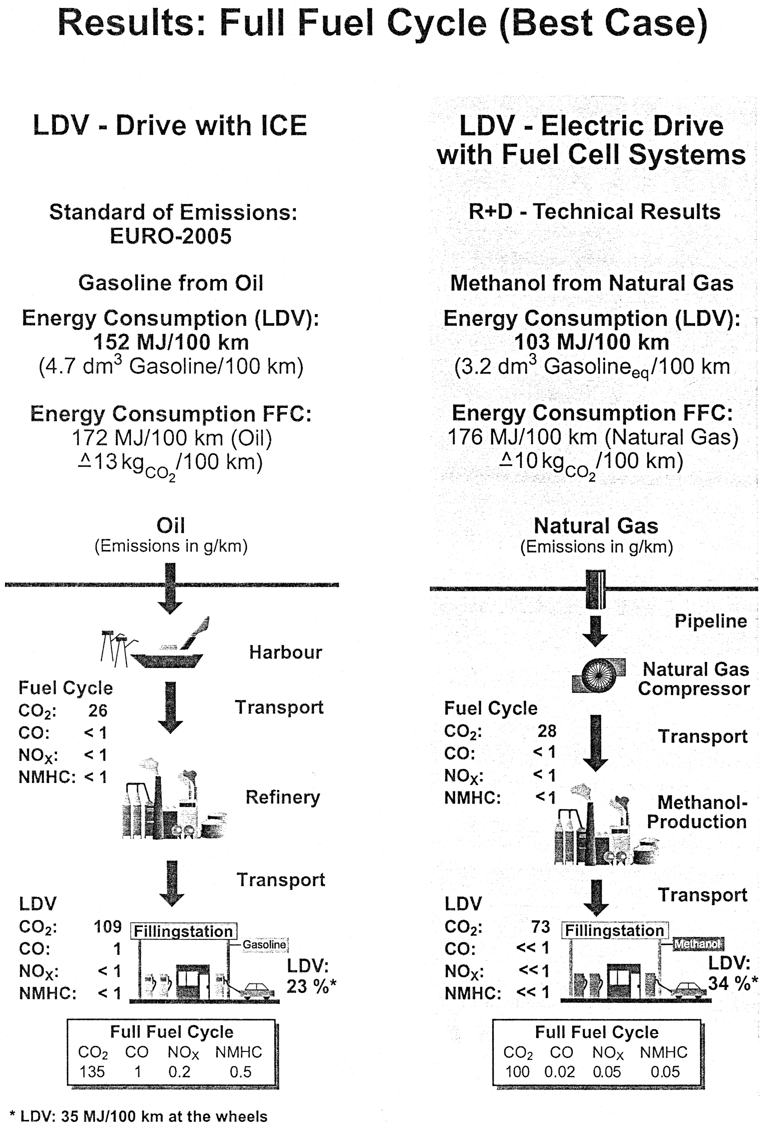
In the present analysis, the use of hydrogen, methanol and gasoline fuels is described from the aspect of electricity generation by means of fuel cells for passenger car power trains. On the basis of simulation calculations, system efficiencies of energy conversion were determined and integrated into the corresponding FFCs. The current and the already recognizable future development status were shown both for FFCs with conventional ICEs and for FFCs with fuel cell power trains based on different energy carriers.

Medium-term options for the energy supply of fuel cell power trains with PEFC systems and electric motors are methanol, ethanol from biomass and gasoline or diesel (ethanol and diesel were not analyzed here). They all exhibit a high energy density with adequate handling and possible available infrastructure. A long-term option would be hydrogen as the energy carrier for PEFC systems based on renewable primary energy sources.

Methanol, ethanol and gasoline or diesel must be converted into hydrogen or a hydrogen-rich synthesis gas in front of the fuel cell system. This will not only require a reformer, but also a gas treatment unit (for minimizing the carbon monoxide harmful for PEFC systems) and for some processes a catalytic burner as an energy source for the reformer. The catalytic burner may be chiefly responsible for the emissions of the entire fuel cell power train.

The development status of the different power trains analyzed here is very different. As a function of the development status and from the present perspective or based on the possibilities assumed for the future the following statements can be made using the example of a comparison of fuel cell power trains and gasoline-ICE power trains (see Appendix A: FFC best case): The advantages of FFCs with fuel cells for light duty vehicle power trains are small with respect to specific energy demand and CO_2 emissions, but are very high with respect to local passenger car emissions. Other criteria as energy demand and emissions have not been discussed in this study.

Appendix A. Results: full fuel cycle (best case)



Results: Full Fuel Cycle (Best Case)

LDV - Drive with ICE

Standard of Emissions:
EURO-2005

Gasoline from Oil

Energy Consumption (LDV):
152 MJ/100 km
(4.7 dm^3 Gasoline/100 km)

Energy Consumption FFC:
172 MJ/100 km (Oil)
≙13 kg$_{CO_2}$/100 km)

Oil
(Emissions in g/km)

Fuel Cycle
CO_2: 26
CO: < 1
NO_X: < 1
NMHC: < 1

LDV
CO_2: 109
CO: 1
NO_X: < 1
NMHC: < 1

Full Fuel Cycle			
CO_2	CO	NO_X	NMHC
135	1	0.2	0.5

* LDV: 35 MJ/100 km at the wheels

LDV - Electric Drive with Fuel Cell Systems

R+D - Technical Results

Methanol from Natural Gas

Energy Consumption (LDV):
103 MJ/100 km
(3.2 dm^3 Gasoline$_{eq}$/100 km

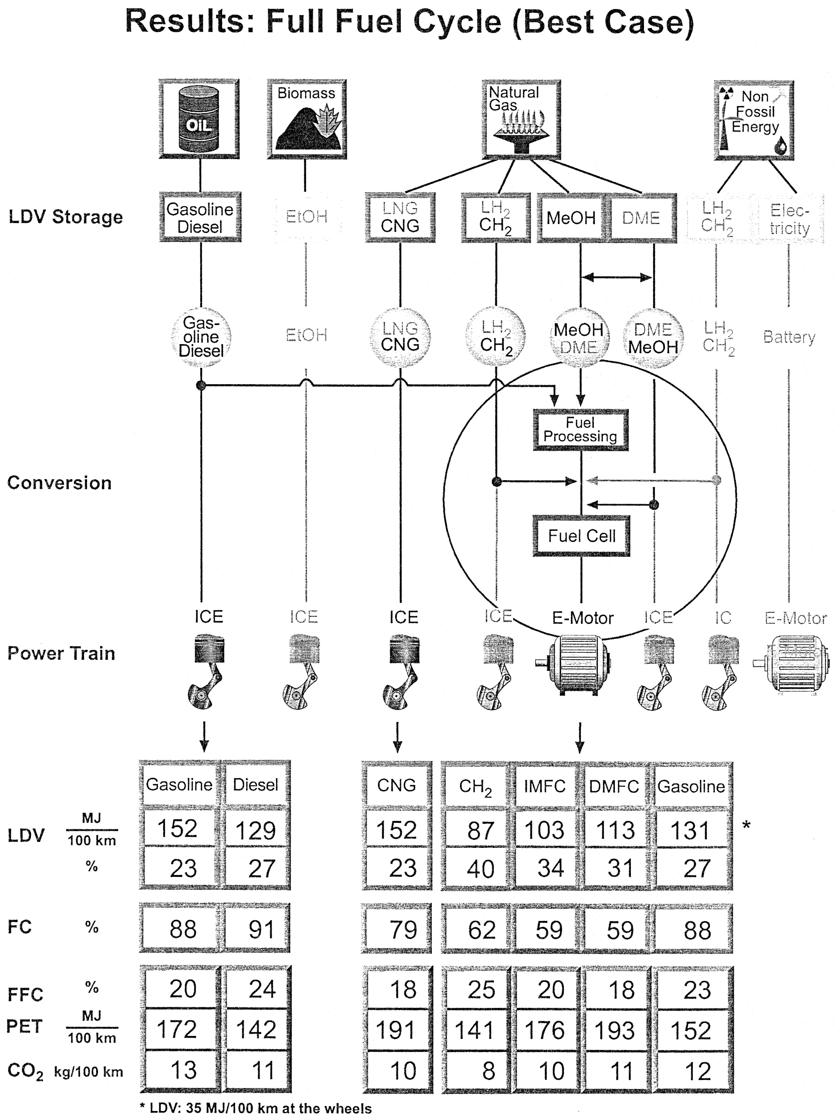
Energy Consumption FFC:
176 MJ/100 km (Natural Gas)
≙10 kg$_{CO_2}$/100 km)

Natural Gas
(Emissions in g/km)

Fuel Cycle
CO_2: 28
CO: < 1
NO_X: < 1
NMHC: <1

LDV
CO_2: 73
CO: << 1
NO_X: <<1
NMHC: << 1

Full Fuel Cycle			
CO_2	CO	NO_X	NMHC
100	0.02	0.05	0.05


Results: Full Fuel Cycle (Best Case)

		Gasoline	Diesel	CNG	CH_2	IMFC	DMFC	Gasoline
LDV	MJ/100 km	152	129	152	87	103	113	131 *
	%	23	27	23	40	34	31	27
FC	%	88	91	79	62	59	59	88
FFC	%	20	24	18	25	20	18	23
PET	MJ/100 km	172	142	191	141	176	193	152
CO_2	kg/100 km	13	11	10	8	10	11	12

* LDV: 35 MJ/100 km at the wheels

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