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Comparison of different vehicle power trains

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Abstract

Four different alternatives of mobile power train developments (hybrid diesel, fuel cell operating with hydrogen produced on a petrochemical basis, methanol reformer-fuel cell system, gasoline reformer-fuel cell system), are compared with the gasoline internal combustion engine (ICE), for well-to-wheel efficiencies, CO_2 emissions, and investment costs. Although the ICE requires the lowest investment cost, it is not competitive in well-to-wheel efficiencies and less favourable than the above alternatives for CO_2 emissions. The hybrid diesel power train has the highest well-to-wheel efficiency (30%), but its well-to-wheel carbon dioxide emission is similar to that of the fuel cell power train operated with compressed hydrogen produced on a centralised petrochemical basis. This latter case, however, has the advantage over the hybrid diesel power train that the carbon dioxide emission is concentrated and easier to control than the several point-like sources of emissions. Among the five cases studied only the on-board reforming of methanol offers the possibility of using a renewable energy source (biomass). © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Power train; Fuel reformer; Fuel cell; Hybrid diesel; Systems analysis

1. Introduction

The traffic based on automobiles is a significant source of environmental pollution and over the last decades there have been several developments to reduce their emissions. The most critical source of air pollution is the internal combustion engine (ICE), still typical for today's car. The leading alternative for this power train is the fuel cell, which can work at so-called "zero emissions". Although Southern California and several states have mandated zero emission vehicles [1], the production of clean hydrogen for fuel cells is usually associated with some emissions, so the whole "chain" is not a zero emission one. It could provide clarity about the different power train alternatives if they were compared, similar to the efficiencies, on a well-to-wheel basis, also in the case of emissions.

A comprehensive study [2] has investigated three types of fuel cell cars: compressed gas hydrogen storage, on-board steam reforming of methanol, and on-board partial oxidation (POX) of gasoline. Defining infrastructure to mean all the equipment (both off- and on-board reforming) required to bring hydrogen to the fuel cell, they found that the cost is comparable for hydrogen, methanol, and gasoline POX fuel cell vehicles. So the selection of the optimum power train highly depends on the efficiency and emissions of the power train itself.

The comprehensive study, however, has not investigated the improvements of the ICE and the recent successful attempts for the efficient use of autothermal partial oxidation (WET POX) of methanol and gasoline for on-board reforming.

In our study and comparison, the following five cases of power trains are considered:

1. internal combustion engine with gasoline, today's power train, base case;
2. hybrid diesel power train;
3. fuel cell operating with compressed hydrogen produced on a centralised petrochemical basis from natural gas (FC with compressed H_2);
4. fuel reformer-fuel cell with methanol obtained from natural gas (FR + FC methanol);
5. fuel reformer-fuel cell with gasoline (FR + FC gasoline).

In the comparison, the following system properties are estimated:

1. well-to-wheel efficiencies;
2. overall carbon dioxide emissions (well-to-wheel emissions) which is the sum of the carbon dioxide emission associated with the fuel production for the power train

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and the emission of the power train itself, related to 100 km;

3. power train cost, estimated for year 2010 [12].

The price of the fuel is excluded from this study because of different, usually country specific, tax policies.

2. Hydrogen production alternatives for fuel cells

The fuel cells need clean hydrogen with optimally no carbon monoxide, for stable operation. There are several methods to produce the necessary hydrogen. The methods can be classified into two groups.

1. Off-board production, when the hydrogen is produced on a centralised basis, in a petrochemical plant or in an onsite reformer from natural gas. Alternative solutions can be mentioned, e.g. hydrogen from biomass or municipal waste gasification, solar or wind electrolysis.
2. On-board production, when the hydrogen is produced in an on-board reformer from gasoline or methanol.

2.1. *Off-board hydrogen production on a petrochemical basis*

Steam reforming of natural gas (primarily methane) is the industry standard.

$$CH_4 + 2\,H_2O \rightarrow 4\,H_2 + CO_2$$

Due to the endothermic nature of this reaction, some part of the natural gas must be burnt to supply the heat of reaction, so the overall efficiency of the hydrogen production is about 70% (that is from one mole methane about 2.8 mol hydrogen can be obtained.

Efficiency is the ratio of the energy in the fuel (hydrogen, methanol, or gasoline) to the energy in the primary source, both calculated on a lower heating value basis. This efficiency involves the yield of the chemical reactions used for the fuel production, energy consumption of the production, and/or distillation losses.

A similar efficiency for hydrogen production can be achieved with the partial oxidation of natural gas.

$$CH_4 + \tfrac{1}{2}\,O_2 \rightarrow 2\,H_2 + CO_2$$

The yield of this reaction is about 80%, which results in the same amount of hydrogen produced [16].

Off-board hydrogen production has the advantage, regardless if it taking place in a large petrochemical plant or in an onsite advanced reformer, that the emission is concentrated and it is easier to treat than in the case of several point-like emissions typical for on-board reforming.

Other hydrogen production alternatives (hydrogen from biomass or municipal waste gasification, electrolysis from solar or wind power) are not considered in this study.

2.2. *On-board hydrogen production*

There are two potential liquid fuels for the on-board reformer, methanol and gasoline.

Several studies have cited the methanol steam reforming reaction to produce hydrogen (e.g. [2,3]) but other studies have preferred WET POX due its thermally neutral stoichiometry and faster start-up [4].

The advantage of the gasoline route is that it can be produced from crude oil with an efficiency of about 90% and using WET POX in the fuel reformer again, the hydrogen yields from the reformer need not be so high as with methanol reforming. This feature is better illustrated with systems analysis of the fuel reformer-fuel cell combination.

3. Analysis of methanol and gasoline fuel reformer-fuel cell systems

On-board hydrogen production is based on the fuel reformer which is a fixed bed heterogeneous catalytic reactor. The reformer produces, from methanol or gasoline, a hydrogen rich gas mixture by WET POX which is a combination of several other reactions, e.g. POX, methanol decomposition, and steam reforming. The overall stoichiometry for methanol is

$$4\,CH_3OH + 3\,H_2O + \tfrac{1}{2}\,O_2 \rightarrow 11\,H_2 + 4\,CO_2$$

Detailed kinetics considering six reactions for the WET POX of methanol on a commercial copper/alumina catalyst have been determined [5]. The product gas, containing significant amounts of hydrogen, should be purified from the carbon monoxide (CO) formed by the parallel decomposition of methanol.

There are two routes for this purification: preferential oxidation (PROX), where the CO content is oxidised to CO_2 or membrane separation, where the hydrogen is permeated through a palladium–silver membrane. Figs. 1 and 2 show the results of calculations for these two alternatives, the numbers indicate the flows in mole per second, other features are shown. For the calculations, the lower heating

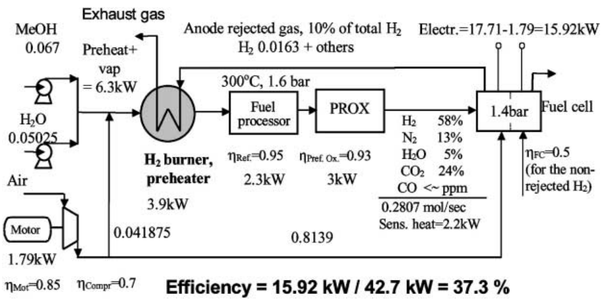

Fig. 1. Fuel processor-fuel cell, system integration, CO cleaning with PROX, units mol/s.

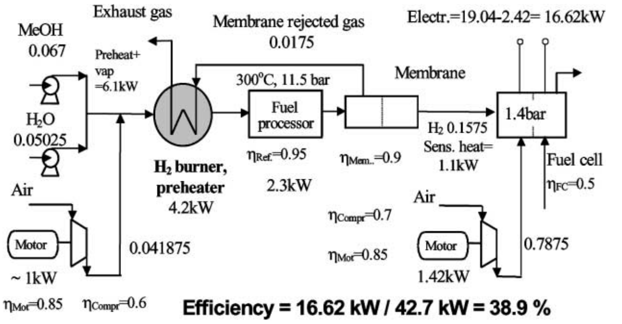

Fig. 2. Fuel processor-fuel cell, system integration, CO cleaning with membrane, units mol/s.

values of methanol and hydrogen are used ($CH_3OH = 638.4$ kJ/mol, $H_2 = 241.8$ kJ/mol). From the systems analysis it is shown that the heat content of a part of the fuel, about 10%, has to be used to supply the necessary heat of vaporisation of the water and methanol. That means that the yield of the fuel processor cannot exceed a limit of 90%. The highest known efficiency of the fuel processor is 95% and that of the PROX is 93% (these numbers are used for further systems analysis). The overall efficiency of the fuel processor is the product of these two efficiencies, 88% [6], which means that this efficiency is practically at the limit and the overall efficiency of the fuel processor-fuel cell system can only be further increased with the improvement of the fuel cell efficiency (50%).

If a membrane is used, about 90% of the hydrogen can be permeated [7] provided the CO adsorption, which inhibits permeation, can be reduced. Clean hydrogen can be produced which can be fully utilised with recycling. If PROX is used for the CO cleaning, the reformat contains 5–10 ppm CO and the anode rejected gas contains about 10–20% hydrogen. From the systems analysis, the expected best overall efficiencies of the fuel processor-fuel cell system are similar for both cases and are about 40%.

In the case of gasoline fuel, the WET POX reaction can be described as the combination of several components undergoing several reactions. Considering *i*-octane as a typical component, the overall reaction is

$$i\text{-}C_8H_{18} + 3\,O_2 + 10\,H_2O \rightarrow 8\,CO_2 + 19\,H_2$$

With gasoline as the fuel, the expected overall efficiency of the fuel reformer-fuel cell system is somewhat less than that of the methanol system and is about 35%. This is due to the hydrogen yields from gasoline WET POX being smaller than those from methanol.

For the estimation of well-to-wheel efficiencies and well-to-wheel emissions, it is necessary to consider the efficiency of the fuel production and the energy losses to transfer electricity into kinetic energy.

4. Basic assumptions for the comparison of the power trains

For the calculation of the parameters of the different power trains a car of 1300 kg weight is selected, however, the size of the car will not significantly change relative comparisons. For the case of the New European Driving Cycle, the energy requirement at the wheel is 12.3 kWh per 100 km [8]. For the calculation of the necessary energy of the power train to move the car, two energy losses are considered: the energy loss at the motor, inverter, etc. 8%, and the energy loss of the auxiliaries 16.4% [9].

Case 1: The well-to-wheel efficiency of the ICE with gasoline, today's power train is 18% [10,11] which is selected as the base case for the comparison. The efficiency of the fuel production is 90%.

Case 2: There are different data for the well-to-wheel efficiency of the hybrid diesel power train [10,11] and an average value of 30% is selected. The efficiency of the fuel production is 90%.

Case 3: The fuel cell power train operating with compressed hydrogen produced on a petrochemical basis from natural gas. The fuel cell efficiency is 50%, the efficiency of the hydrogen production from natural gas is 70%. The hydrogen gas is pressurised to a value of 300 bar [1]. The compression energy is considered.

Table 1
Basic features of different power trains[a]

Cases	Case 1: Internal combustion engine, gasoline base case	Case 2: Hybrid diesel	Case 3: FC, compressed H_2 from natural gas	Case 4: FC + FR, methanol from natural gas	Case 5: FC + FR, gasoline
Fuel (l/100 km)	6.8	4.3	10.3[b]	8.31	5.14
Water (l/100 km) without FC	–	–	4.99	2.8	6.7
Well-to-wheel CO_2 emission (kg/100 km)[c]	17	10.2	10.0	13.3	12.6
Well-to-wheel efficiency (%)	18.0	30.0	25.3	22.3	25.1
Power train investment cost (US$$_{1997}$ per 70 kWmech)[d]	2730	6230	4970	6300	6800

[a] Kinetic energy requirement (at wheel), 12.3 kWh per 100 km; for FC power trains (energy losses): motor, inverter, etc. 8%; Auxiliaries,16.4%.

[b] nm^3 H_2/100km (equivalent to 3.2 l gasoline, on lower heating value basis).

[c] 0.4 kg CO_2/100 km emission for the Pt production for FC power trains included [13].

[d] Estimated cost by [12] for year 2010.

Case 4: The efficiency of the on-board fuel reformer-fuel cell power train with methanol, according to our estimates (Figs. 1 and 2) is 40%, the efficiency of the methanol production from natural gas is 70%.

Case 5: The on-board fuel-reformer fuel cell power train with gasoline. The efficiency of the power train, according to our estimates is 35%, the efficiency of the fuel production is 90%.

The investment costs of the different power trains cannot be compared on the basis of today's prices. The newer power train developments on a fuel cell basis are significantly more expensive than the ICE gasoline power train. According to Daimler–Benz data the investment cost of a fuel cell power train is currently about US$ 4500 per kW but the target of the development should be about US$ 50 per kW [9]. Possible on-board reforming would further increase this price.

Another study estimates the prices of the different power trains of 70 kWmech for 2010 [12]. These prices are accepted and shown in Table 1.

5. Discussion

According to the efficiencies and the assumptions, a calculation is made for the well-to-wheel efficiency, the overall carbon dioxide emission (well-to-wheel emission), including the emission associated with the fuel production as well as the emission of the power train. Power train costs are also considered and accepted from [12] for the year 2010. The results of this estimation are summarised in Table 1. Figs. 3–5 show the comparisons of the five cases related to the base case. The numbers show the deviation from the selected base case (ICE gasoline) in percent.

The fuel consumption values in Table 1 are qualitatively consistent with recent literature [1,14] but the differences are most pronounced in [14]. CO_2 emissions are highest for ICE with gasoline fuel (selected as base case), however, the lowest values are obtained with the hybrid diesel and the fuel cell with compressed hydrogen. Power train costs are obviously lowest for the ICE. The other candidates show higher investment costs and among them the fuel cell with gasoline on-board reformer is the highest [12]. Again, these costs are qualitatively consistent with recent literature [1,14].

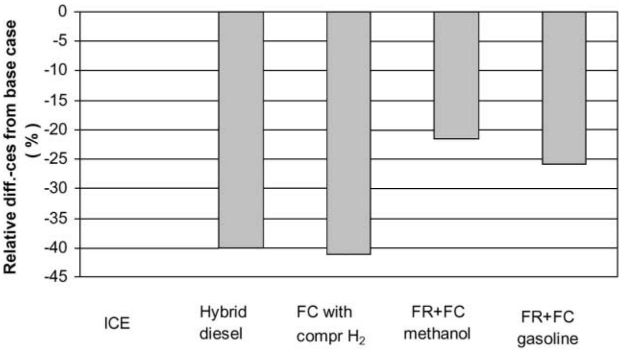

Fig. 3. Relative changes of CO_2 emissions. Base case: ICE gasoline, 0%.

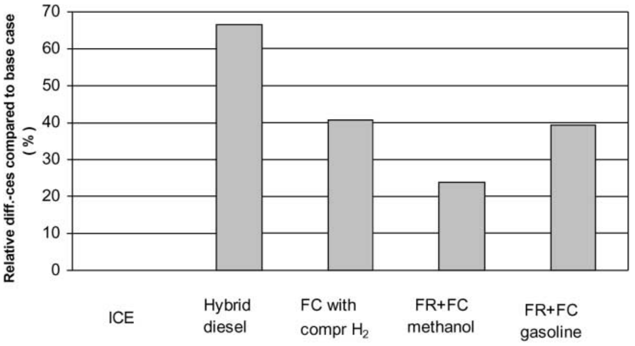

Fig. 4. Relative changes of well-to-wheel efficiencies. Base case: ICE gasoline, 0%.

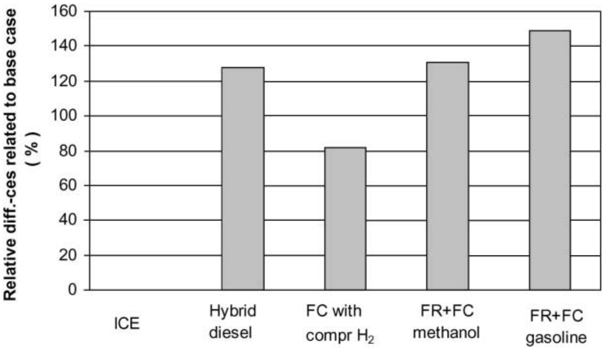

Fig. 5. Relative changes of power train investment costs. Base case: ICE gasoline, 0%.

6. Conclusions

According to the calculations and the comparison it can be concluded that

- the base case ICE gasoline power train, Case 1, is not competitive if environmental features are considered, but it has the lowest investment cost;
- the well-to-wheel efficiency is the highest in the case of the hybrid diesel power train, Case 2;
- the fuel cell power train operating with compressed hydrogen produced on centralised petrochemical basis, Case 3, and the hybrid diesel power train, Case 2, show the lowest well-to-wheel carbon dioxide emission values;
- the recent choice of the diesel hybrid by the Partnership for a New Generation of Vehicles (PNGV) emphasises the attributes of the data in Table 1 and in Figs. 3–5 [15];

To discussion in the final evaluation it should be, however, still considered that

- only the on-board reforming of methanol offers the possibility to use a renewable energy source;

- if the well-to-wheel carbon dioxide emission is considered the hydrogen production on a centralised petrochemical basis offers the possibility that the carbon dioxide emission is concentrated and it is easier to control than the case of several point-like sources of emissions.

Acknowledgements

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