Breakthrough of advanced drives for cars? Perspectives and consequences

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Introduction

This paper treats the prospects for shifting to advanced drive trains in motor vehicles, particularly automobiles, and the possible environmental impacts of such shifts.

The paper is partly based on a project carried out for the National Environmental Protection Agency of Denmark by Technological Institute of Denmark and Risoe National Laboratory, the report of which is yet to be published.

Background - at the start of a new era?

During most of the 20th century, the internal combustion engine (ICE) - mostly fuelled by either gasoline or diesel oil - has been totally dominating as drive train in motor vehicles in general and automobiles in particular. Early in the century the outlook was much more open but during the inter-war period the ICE gained its dominating position.

Despite the advantages of the internal combustion engine - not least its low costs - it is by no means an unproblematic choice for vehicle traction, especially for vehicles in urban traffic. Thus, there have been good reasons for exploring other options but even so the ICE has maintained its dominating position. The technological development of automobiles has focused on refinement of existing designs, including the ICE based drive trains. Other options have been proposed and to some extent tested but the uncertainty in conjunction with radical technology shifts so far has retained the automobile development within the well-known solutions.

At moment, however, there is for the first time since the 1920s a serious chance for a break with the conventional drive systems for vehicles, replacing them with a form of advanced drive trains. It is still highly uncertain whether this break will actually materialise but the outlook is better now than it has been for decades.

A central driving factor behind this development is probably the development in emission standards and other environmental requirements - both the development that has taken place, the projected development and the possible future development of these standard. So far, the ICE has shown an impressive capability of meeting the new requirements but perhaps it is approaching its limits. And if it becomes necessary to shift to other drive trains in the future, it may be an advantage to be an early adopter of the new technology - rather than following the usual path of incremental developments from the present design.

Advanced drive systems

All advanced vehicle drive systems of any significance are based, partially on completely, on electric propulsion, i.e. propulsion by means of electrical motors. Electric propulsion is well known from rail transport and trolley buses - usually based on continuous energy supply through cables or third rails - and also from conventional electric vehicles, in which electricity is stored onboard in batteries. In addition, electrically driven vehicles may be based on electricity generated onboard the vehicle by different means.

The options - as of today - can be divided into three subcategories - battery electric vehicles, hybrid electric vehicles, and fuel cell electric vehicles.

Battery technology, the crucial issue in conjunction with the development of *battery electric vehicles (BEV)*, has made a certain progress over the last couple of decades - mostly in the form of a shift to batteries with higher energy density and longer lifetimes, but also much higher costs. There have been no major breakthroughs, however, and it is still unclear whether the demands for "advanced batteries" that could substantially improve the performance of BEVs will be met. An independent battery technology assessment carried out a couple of years ago for the Californian Air Resources Board concludes that while the advanced battery is still possible, many obstacles must be overcome to reach it. In particular, lithium batteries, considered by many to be the prime candidate for the advanced battery, are considered to have an more uncertain future than generally assumed.

In other respects, considerably improvements have been achieved, notably the development of control and power electronics which has enabled new concepts and components (e.g. new electrical motor types).

Regardless of the battery development, BEV is likely to remain a niche vehicle due to its limited range - at least based on the present perception of the requirements to an automobile. BEVs are unlikely to gain a significant share of conventional passenger cars unless promoted by regulatory instruments. In connection with the ZEV-mandate in California, the American automobile manufacturers particularly resist any requirements of BEVs in this segment, preferring rather hybrid electric or fuel cell vehicles. Also, the automobile industry se a potential market for so-called “City Electric Vehicles” and “Neighbourhood Electric Vehicles”, that is small and very small four-wheel motor vehicles with limited performance aimed at neighbourhood transport. To a great extent, such vehicles would not replace conventional passenger cars, but rather as a supplement.

(marketed BEVs)

The drive trains of *hybrid electric vehicles (HEV)* are equipped with both ICE and electric motors. This may be in the form of parallel hybrid drive trains, in which both ICEs and electric motors are connected directly to the driving wheels, or series hybrid systems, in which only the electric motors are driving the wheels while the ICE forms part of an onboard power generation plant. The latter option is equivalent to the BEV, except that the electricity is generated onboard. Also, combinations of parallel and series hybrid designs are being pursued and indeed are not unlikely to be dominating in the future given the rapid development of control technologies.

Across the different hybrid concepts, there are different design strategies. At one end, the hybrid vehicle may be perceived as virtually a BEV except that it is fitted with an ICE based "range extender". In this case, the principal design criterion is the vehicle range in the zero-emission mode (i.e. without the ICE in operation). At the opposite end, the hybrid vehicle may be virtually a conventional ICE driven vehicle except that it has a load levelling option (in the form of short-term electrical storage capacities) and consequently provide the ICE with better operation conditions. In the latter option, the principal design criterion is (typically) the specific energy consumption. Compromises between these two extremes are also possible.

The role of HEVs, therefore, is a means for improving either the capability of BEVs or of the ICE based drive train. Its future position depends to a large extent on the development of the following option.

This option is the *fuel cell electric vehicle (FCEV)* is equivalent to a series hybrid electric vehicle with onboard electricity generation carried out by a fuel cell rather than an engine/generator plant. The ideal fuel for the fuel cell is hydrogen, which can be fed directly to the fuel cell with very good energy efficiency and no harmful emissions at all from the vehicle. There are different limitations and obstacles linked to this fuel, notably the need for a large-scale transformation of the refuelling infrastructure and limitations on vehicle range due to relatively low capacity of the hydrogen storages. The typical range of an FCEV is considerably longer than that of a BEV but significantly shorter than gasoline and diesel vehicles. The main exception - among the currently available storage options - is storage as liquid hydrogen requiring which may offer ranges comparable to those of conventional automobiles. Liquid hydrogen, however, has a very poor energy-efficiency because it must be operated at very low temperatures (-253°C).

To reduce some of these problems, a different approach than direct hydrogen FCEVs - that is vehicles using hydrogen directly as fuel - has been investigated. This is based on liquid fuels, such as gasoline or methanol, being converted to hydrogen onboard the vehicle. The liquid form of these fuels allows much higher energy densities and thus longer ranges and at the same time the infrastructure transformation requirements are more limited, especially for gasoline. On the other hand, the onboard conversion results in substantial energy losses compared to the concept based on direct hydrogen fuel. Moreover, the conversion process and its fitting into the vehicle are technically and physically demanding.

The development of fuel cell technology that has happened over the last 10-15 years is the most rapid development of any automotive technologies. In this process, the automobile industry has got engaged in the development with nearly all of the major companies involved. Daimler-Benz (DaimlerChrysler) was the first major company to get involved and still has a leading role together with Toyota - as part of two different alliances (Maruo 1998).

Several manufacturers have notified of plans of producing several hundred thousands FCEVs around 2003/2004 (still a small proportion of total vehicle sale). Despite the dramatic progress made already, fuel cell technology still has a long way to go to be ready for the marketplace, especially as far as costs are concerned. The costs of the fuel cells are estimated to have to be reduced by another factor 10-20 if they are to be directly competitive with the ICE drive trains (Sørensen et al 2001). Generally this is considered to be within reach but a substantial part of the reduction is to come from the effect of volume production. Thus, there is a chicken-and-egg situation that may lead to both good and vicious spirals in the development. In any case, there will in all probability be a period during which FCEVs will be more expensive than their conventional counterparts.

As we are approaching the time of the FCEV introduction plans, it appears that the promises are roughly being kept as far as the timing is concern - but in much smaller numbers than originally envisaged. Typically, the figures are now less than a hundred vehicles, mostly leased to vehicle fleets where they can be monitored closely. The large-scale introduction is envisaged to happen beyond the year 2010.

This probably reflects that attempts at developing onboard conversion technologies have more or less failed, leaving direct hydrogen fuel as the only option. Therefore, the automotive companies most likely have considered a larger-scale introduction too risky.

Programmes and regulatory instruments

A crucial issue in connection with the development of automotive technologies concerns the extent and shaping of the public authority intervention in the form of programmes, policies, regulatory instruments etc. Indeed, most environmental improvements of the transport sector are the result of incentives created through emission standards, taxation, subsidies etc.

Three major issues are important in this context (Sperling 2002):

- advanced vehicle research and education, including materials research, key subsystems (e.g. control technologies) and, not least, training and education of engineers and scientists;
- a hydrogen infrastructure (distribution and refuelling), including standardisation, safety regulations etc.;
- incentives to direct the automotive industry and consumers towards the advanced technologies.

Three American programmes have been particularly significant for the global development of advanced automobile technologies, namely:

- the Californian Zero-Emission-Vehicle requirements introduced from 1990 onwards;
- the Partnership for a New Generation of Vehicles (PNGV) of the 1990s, a joint effort between the automobile industry and the American government to develop prototypes of a passenger car with a fuel economy 3 times better than the present American average;
- FreedomCAR, introduced in January this year as replacement of PNGV and shifting the focus from fuel efficiency to introduction of fuel cells and hydrogen

In a global context, one of the most important driving forces behind the progress of the advanced drive systems, have been the policies of the air quality authorities in California, the *California Air Resources Board (CARB).* First, they have generally been leading in the enforcement of tighter emission standards and secondly they introduced in 1990 a *ZEV-mandate*, requiring a significant share of the passenger cars sold in California to be Zero-Emission-Vehicles, i.e. cars without harmful emissions from the vehicle. The mandate is still retained today, albeit in a modified form.

According to the initial requirements of 1990, 10% of automobiles sold by the large manufactures on the Californian market were to be ZEVs in the year 2003. At that time, BEVs were perceived to be the only viable options for ZEVs. In its present form, only 2% have to be pure ZEVs (either BEVs or hydrogen driven FCEVs) whereas the remainder 8% of the sale may be covered by different types of so-called "Partial Zero Emission Vehicles", including HEVs and FCEVs with onboard conversion of liquid fuels. Furthermore, the modifications make concessions to the pressure from the automobile industry to allow sale of sub-automobile electric vehicles (City and Neighbourhood Electric Vehicles) to be including in the meeting of the requirements. The objective of the modifications of the mandate is to address the constraints on the ZEV technologies, especially in the short-term, while maintaining the core of the mandate, namely the push for long-term technological solutions. While the ZEV mandate has been of little significance for the present air quality (compared to the impact of the general development of the emissions standards), it has been - and is - a vital push for long-term automobile technologies, not only in California.

In addition to the compromises, the most recent modifications of the ZEV mandate have resulted in tougher requirements as well. Notably, the mandate is being extended to cover not just passenger cars as such but also light duty trucks, sports utility vehicles (SUVs) and vans - a vital change given the growth of these vehicles in the American market. In addition, a gradual increase of the requirements has been introduced: from 10% to 16% of the sale between the 2009 to 2018. Together, these two modifications increase the number of vehicles covered by the mandate by a factor 2.8 based on the present sales patterns. At the same, the fraction of these vehicles to be pure ZEVs has been reduced by a factor 5 (from 10% to 2%), which means that overall the required number of pure ZEVs has been roughly halved.

The *Partnership for a New Generation of Vehicles (PNGV)* was initiated in 1993 with the principal objective of tripling the fuel economy of an average passenger car for the American market without sacrifices in the performance, size, safety or costs. In practical terms, the goal was for each of the Big Three American car manufacturers to develop before the year 2003 a prototype meeting these requirements whereas there were no requirements beyond this.

This is a very ambitious goal - compared by the parties behind the PNGV to the goal of putting a man on the moon - but from the outset the initiative was criticised for being insufficiently funded (Sperling 1997; National Research Council 2001; Sperling 2001). Large sums were involved but according to the critics most of these were existing funds being reshuffled.

There were other critical points directed against the initiative. First, for addressing the ambitious and relatively long-term goal of tripling the fuel economy with near-term technologies with unacceptable emission standards - namely HEVs with diesel engines. In addition to the inconsistency between objective and means, this technological focus was deemed not to be well suited for government-industry R&D partnerships due to its incremental nature (Sperling 2002). Moreover, specific products were defined as goals, excluding the option of redirecting the focus in the course of the work. In particular, this resulted in a low priority being given to fuel cells in the research. Thirdly, the emphasis on development of prototypes rather than the commercialisation of those prototypes was being criticised.

As it happened, the work in PNGV did result in significant progress with regard to fuel cells, but not as a result of the core activities of the programme - and mostly achieved in small, independent companies.

The *FreedomCAR* lanced by the American Government earlier this year redirected the focus compared to the PNGV - to a great extent meeting much of the criticism. Now the focus is on hydrogen and fuel cells. It is still marked by insufficient funding, though, and the programme appears to be perceived by the American government to replace the near-term efforts to improve fuel economy and reduce emissions. Given that hydrogen and fuel cell inevitably are long-term measures, this naturally is very unfortunate.

Environmental impacts - fuel cycle and life cycle analysis

There are different approaches to the environmental assessments, defined not least by different system boundaries. A common measure is the vehicle efficiency, focusing on the fuel or electricity supplied to the vehicle. This approach only makes sense for fuels with comparably fuel cycles.

A "well-to-wheel" analysis provides a better basis for comparisons of different fuels, covering not only the vehicle's turnover of the energy but also the stationary part of the fuel cycle:

production and distribution of the fuel etc. As the name indicates well-to-wheel analyses usually simply follow the fuel from extraction of the primary energy to the vehicle but various side effects on other systems - for instance, for the power supply system or for the agricultural structures - may be included in the analysis.

The number of well-to-wheel analysis of alternative fuels is considerable, among others: Argonne National Laboratory (2000); Unnasch & Browning (2000); Ahlvik & Brandberg (2001); GM Corporation et al (2001); Wurster (2001). Table 1 summarises the calculated well-to-wheel fossil fuel consumption of gasoline and diesel drive trains as well as different advanced drive systems for average Danish conditions. The results apply to an average passenger car on the Danish market.

	Well-to-wheel fossil fuel consumption, MJ/km
Conventional gasoline ICE drive train	3.3
Conventional diesel ICE drive train	2.3
BEV, technology level as of 2001	2.0
BEV, advanced technology of the year 2010	1.1
HEV (BEV with range extender)	2.0
HEV (ICE with load levelling)	1.7
FCEV based on hydrogen, produced from natural gas	1.5
FCEV based on hydrogen, produced from biomass	0.45
FCEV, onboard conversion of gasoline	1.7
FCEV, onboard conversion of methanol based on natural gas	2.0
FCEV, onboard conversion of methanol based on biomass	0.6

Table 1

Well-to-wheel fossil fuel consumption of based on average Danish passenger car.

The hydrogen FCEVs in Table 1 are based on onboard storage in the form of compressed hydrogen. Storage as liquid hydrogen - a means for increasing the range of the vehicle - reduce the energy-efficiency considerably, making the hydrogen FCEV based on natural gas comparable to FCEVs based on onboard conversion of liquid fuels. The results for BEVs are based on the present average fuel mix of the power system. If the point of departure is power from renewable energy, e.g. wind power or photo voltaics, BEVs represent a very efficient utilisation of this.

Finally, life cycle analysis (LCA) is (more or less) complete accounts of environmental impacts, including environmental impacts in connection with the manufacture and disposal of technologies etc. Generally, such analyses do not substantially alter the prioritising of solutions since the operations of the vehicle typically accounts for some 80-90% of the total energy consumption and emissions. Examples of LCA of alternative fuels are: Ecotraffic (2001); Spath & Mann (2001); Weiss et al (2001); Ecotraffic (2002); Row et al (2002).

Conclusions

In the long-term, the most interesting options are FCEVs and/or HEV, with the latter being probably mostly of interest to the extent the development of the former fails or lead to costly solutions. BEVs can be an interesting supplement to these but they are unlikely to get any significant role unless there is a special effort directed towards their development and the development of battery technology.

Apart from BEVs, FCEVs with hydrogen as fuel represent the most energy-efficient solution, unless liquid hydrogen is applied as onboard storage. FCEVs based on onboard conversion of liquid fuel have roughly the same energy-efficiency as the best HEVs.

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