Long-term Energy Efficiency Improvement for Transport, Technology Assessments

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In part one of this report, general transport and transport-flow measures are described. By using other modes of transport than road-vehicles, it is possible to save energy. An advanced park-and-ride system can lead to a 27% reduction in energy use per passenger-kilometre; in 2040 at most 10% of the total number of passenger-kilometres can be replaced by public transport. For freight transport intermodal goods transport can lead to energy-gains of about 50%, and here also a maximum of 10% of the total amount of ton-kilometres can be replaced. Within the (public) collective transportation systems, gains in energy-efficiency of about 50% (per passenger-kilometre) can be achieved by introducing light-rail systems. By using traffic information and control systems, the number of car-kilometres can, theoretically, be reduced by some 20%.

In part two, electric vehicles are discussed. By using more advanced batteries or, in future fuel-cells, the energy-efficiency of electric vehicles can be improved by 43% (advanced batteries) or 25% (fuel-cells). Probably battery-powered vehicles will not offer the same performance as vehicles with an internal combustion engine, but fuel-cell powered electric vehicles possibly will. Part of the gains can be obtained by better batteries (higher loading/unloading efficiency), but another part of the gains can be achieved by improvements on electric motors, transmission systems and motor and battery management systems. Disadvantages of electric vehicles are the low chain energy-efficiency (power plants) and the battery or fuel-cell costs: only in the more distant future prices of electric vehicles will be comparable with prices of internal combustion engine vehicles.

In part three, hybrid electric/internal combustion vehicles are discussed. These vehicles offer a performance comparable with internal combustion engine vehicles. However, the energy-benefits are not as big as with full electric vehicles. In this third part regenerative braking systems are discussed too. By using these systems, in passenger cars some 5% of the brake-energy losses can be "recuperated"; in busses these gains mount to about 30%. Energy can temporarily be stored as hydraulic pressure, as kinetic energy (in flywheels) or as electric energy maybe in so called super-capacitors. With advanced automatic transmission systems vehicles can be made even more energy-efficient. The transmission systems themselves are somewhat less efficient than manual gearing systems, but with the advanced transmission systems, engines can be used in the most efficient way. The net efficiency gains are about 5%.

In part four, improvements on internal combustion engines are discussed. By using multi-valve technology, ceramic elements, multipoint injection and turbo (intercooling) systems, energy-efficiency gains of 23% (otto-engines) to 30% (diesel-engines) seem to be possible at relatively low costs. As an alternative to steady-state internal combustion engines in, for example, hybrid vehicles, free piston engines can be used: these engines are expected to be cheaper, lighter in weight and more energy-efficient (33% gain). Furthermore, these engines can be used in so called 'mobile equipment'. In this fourth part, improvements in vehicle construction are discussed too. By reducing weight, rolling resistance (partly by reducing the weight, partly by other tires) and airdrag, efficiency gains of about 26% (compared to 1994 vehicles) seem to be possible and this at relatively low extra costs.
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Introduction

An important goal for the Dutch government for research and development (R&D) on energy technologies is the development of a sustainable transportation system for the long term (2030-2040). Priority setting in this long term R&D policy is important as a large number of technologies is available. For that reason a research programma called SYRENE is initiated and commissioned by the Netherlands Agency for Energy and the Environment (NOVEM). SYRENE is an acronym for SYstem integration of Renewable energy and End use technology in the Netherlands. The goal of this programma is to contribute to the improvement of planning of long-term R&D activities on energy technology by system studies. SYRENE consists of four sub-studies:

- infrastructure
- modal development
- sector studies
- material, energy and environmental aspects.

This study is one of the SYRENE sector studies and focuses on descriptions of long-term energy efficiency improving technologies for transport. The objective of these technology descriptions is twofold:

- Deliver preliminary information about selected technologies that can be applied in the transport sector and reduce the end-use energy demand on the long term (2030-2040).
- Deliver parameters for the technology database of MARKAL, a linear-programming model of the Netherlands energy system that is used for scenario studies within the SYRENE programme.

The preliminary character of this study must be emphasized. It is directed at making a first inventory of promising technologies, mainly based on literature sources, with emphasis on energy-efficiency improvements. As we are dealing with technologies that are often still in an early stage of development, little information is available that is relevant for practical application. For this reason, a number of parameters in this study are estimations. The descriptions can only give a first indication of the possible energetic and economic performance of new technologies in 2030/2040. In the transport sector much technologies have a mutual impact. To estimate possible effects of technologies, several technologies are combined in so called "packages".

Description of technologies

In this study only selected technologies are described. Criteria for the selection of the technologies were:

- With the technology, a significant energy efficiency improvement is to be expected up to 2030 compared to the current situation (1994).
- The technology should contribute more than 1 PJ \( (10^{15} \text{ J}) \) to primary energy savings.

The selection was made on basis of the 'Sectorstudy Transport SYRENE Program' (in Dutch: Sectorstudie SYRENE Programma').

Structure of the report

This report consists of four parts. In the first part transport and traffic flow measures are described. Transport flow measures include multi-modal passenger and goods transport and the improvement of collective transport systems. Traffic flow measures include traffic information and control systems. In part two battery and fuel-cell powered electric vehicles are described. Various types of batteries, fuel-cells and developments on electric components of vehicles are discussed. In part three hybrid electric vehicles, regenerative braking systems and new trans-
mission systems are described. These technologies are partly related to electric vehicles, but also to vehicles equipped with internal combustion engines. In part four improvements on combustion engines are discussed. Also the new developed free piston engines are described. Furthermore, improvements on vehicle construction (weight, air drag, rolling resistance) are discussed.

All chapters start with a description of the new or improved technologies. In this description, definitions and a short explanation of the technologies are given. Also general indications for energy-savings, degree of penetration, state of development, current research and development and bottlenecks are given. The description is followed by parameter-sections, where energy and economy parameters for passenger and goods transport vehicles are given. In most parameter-sections some calculations have been made. The assumptions for these calculations are printed in smaller typefonts.

**Units**

For the economic parameters the Dutch currency is used (1 Dfl = 0.5 US$, 1 ct = 0.005 US$).

For energy parameters the unit Joule (J) is used with the decimal prefixes:
- P (peta) = $1 \times 10^{18}$
- G (giga) = $1 \times 10^9$
- M (mega) = $1 \times 10^6$

In general all energy and economic parameters are given in units per vehicle kilometre. Mostly, information per person or per standard amount of goods is required. To obtain this information assumptions of the average occupancy rate or average loading have to be made.

For passenger transport this results in the units passenger-kilometre in public transport or (available) seat-kilometre for passenger cars.

For goods transport this results in the unit ton-kilometre: one ton (1000 kg) of goods transported over a distance of one kilometre.

**Abbreviations**

If abbreviations are used, first the full term will be explained, but to help the reader, below some often used abbreviations are mentioned:

- C_d air drag coefficient
- CNG compressed natural gas
- CVT continuous variable transmission system
- ICE(V) internal combustion engine (vehicle)
- (I)DI (in)direct injection diesel engine
- (F)EV (full) electric vehicle
- FPE free piston engine
- LNG liquefied natural gas
- PEM(C) proton exchange membrane fuel cell
- USDOE United States Department of Energy
- US-ABC United States Advanced Battery Consortium

**Chemicals**

- CO_{2} carbon (di) oxide
- H_{2} hydrogen
- NO\_x nitro-oxides
- O_{2} oxygen
PART I:
TRANSPORT AND TRAFFIC FLOW MEASURES

- ADVANCED PARK AND RIDE SYSTEMS
- INTERMODAL GOODS TRANSPORTATION
- AUTOMATED PUBLIC TRANSPORT SYSTEMS
- TRAFFIC INFORMATION AND CONTROL SYSTEMS
PART C
TRANSPORT AND TRAFFIC FLOW MEASURES

ADVANCED PARK AND RIDE SYSTEMS
INTERMODAL PUBLIC TRANSPORTATION
AUTOMATED PUBLIC TRANSPORT SYSTEMS
TRAFFIC INFORMATION AND CONTROL SYSTEMS
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1 ADVANCED PARK AND RIDE SYSTEMS

The aim of the advanced Park and Ride concept, called "Transferia", is to cause a modal shift towards more environmentally friendly transport modes: part of a car-trip will be replaced by a trip by public transport. Vehicles do not become more energy-efficient by the Park and Ride concept, but due to the energy-benefits of scale of collective public transport it is possible to achieve less energy-use per passenger kilometre.

1.1 Description of Transferia

Definition
Transferia are advanced derivatives of Park-and-Ride facilities in which it is possible to park a car and to continue the trip by using collective (public) transport services.

Explanation
Transferia exist of two parts: a parking-lot area and a station. The goal of Transferia is to provide a high-quality transfer, due to which many travellers will replace their own vehicle by the collective transport for a part of their trips. To create a high-quality transfer, the design of Transferia and facilities (information desks, call-boxes etc.) has to be of high quality. In large Transferia special facilities (like small shops or supermarkets, petrol stations and carwash installations) are offered as well.

Energy functions
Transferia cause a change in travelling behaviour. Instead of making the whole trip by car, one will make only part of the trip by car and the rest by collective (public) transport. Because the energy use per passenger kilometre of collective transport is lower than the energy use per passenger kilometre of individual cars, Transferia contribute to a cleaner environment and to less energy use. Contrary to some forms of intermodal goods-transport, the energy-use of the 'transhipment' of passengers in Transferia is negligible. The total effect of Transferia is reduced by the following elements:

• the combined use of individual car transport and collective transport often leads to a longer travelling distance,
• in case of more energy efficient cars, the difference between the energy use of collective transport and individual cars will be smaller (per passenger kilometre).

Penetration
The Transferia (or Park and Ride) system is especially useful for travellers having an origin outside urban areas and a destination in urban areas. For other types of relations the individual car or the collective (public) transportation system is more efficient. In Germany P+R facilities attract 5% (Cologne) to 40% (Munich) of the car-travellers. In The Netherlands Park and Ride Facilities attract 20% (Rotterdam) of the passing vehicles. Estimated is that due to the Transferia and Park and Ride facilities about 5% of the total car-kilometres (almost 8% of the passenger-kilometres by car) can be replaced by collective-transport passenger kilometres [Binsbergen, 1992]. By an extensive Transferia-promoting policy (which includes push-measures such as parking restrictions in destination areas) up to maximum 10% of the car-kilometres can be replaced. Shifts like this are generally judged as 'land slides' in modal split.)
Competing technologies
Competing technologies of advanced Park and Ride systems are automated people mover systems, other collective (public) transportation systems and energy efficient passenger or low-emission passenger cars.

State of development
There are no Transferia as such, but in several countries there are Park and Ride facilities (USA, Germany and The Netherlands). Especially in Germany the Park and Ride system is well developed: good examples can be found near Hamburg/Harburg and Aachen. There are plans to build Park and Ride facilities around the city of Berlin in the next decade. In The Netherlands there are some (very) well-used Park and Ride facilities. Examples are Voorburg (near The Hague) and a Rotterdam Metro-station (Slinge).
**Current R&D**

At the moment R&D is aimed to find the right locations for Transferia. When the aim is to attract as many *passengers* to the Transferia as possible, locations near cities are best. When the aim is to reduce as many *car-kilometres* as possible, locations near origin-areas are more effective. The behaviour of (potential) passengers plays an important role: the effect of the Transferia concept is dependent on the number of passengers who choose for this form of "combined transport". Furthermore it is important which of the available Transferia is chosen: a Transferium near the origin-zone gives a bigger positive effect on the energy use than a transferium near the destination. Research will be done about the number and places of Transferia necessary and to the possibilities of influencing travellers choice behaviour.

**Bottlenecks**

An important bottleneck are the investment costs: because there are several actors (railway companies, Ministry of Public Works, cities and private companies), it is hard to decide who has to pay the (investment) costs, although the net-costs will almost be zero (see also 'Parameters 2.2'). Another bottleneck is policy: there has to be an incentive to transfer from individual to collective transport during the trip. This incentive (shorter travelling time, lower travelling costs) has to be given by the government. As long as Transferia lack this incentive, only few people will use them.

**Availability**

All planned "Transferia" could be built in 2015: there are no technological barriers. On the other hand there are some important political and financial barriers and at last, the use of Transferia is also dependent on the willingness of travellers to use Transferia (this is related to costs and travel-time).

### 1.2 Parameters for Transferia

#### 1.2.1 Energy parameters

The energy parameters shown give an impression of possible effects of Transferia use. The figures are based on the pilot SYRENE study [Hamel, 1993]. Below, primary energy-use is shown for all transport modes.

- **1994:**
  - car: 1.74 MJ/passengerkilometre
  - train (regional and local): 1.04 MJ/pass.km (primary energy use)
  - max. benefits: 0.70 MJ/pass.km (replaced)
  - due to the longer total travel distance, the net result will be approximately 66% of the above mentioned benefit, so 0.47 MJ/pass.km [Van Binsbergen, 1992]

- **2015:** dependant on external developments (car, rail and power-plants)
- **2030:** dependant on external developments (car, rail and power-plants)

Estimations of effectiveness: reduction of approximately 5% of the amount of car-kilometres (= 7.64% of passengerkms) in 2010/2020 and 10% (15.3% of passenger kilometres) in 2030/2040.

- **1990:** 7.64% of 125,100 mln = 9,555 mln pass.km = > 4.49 PJ (although in 1990 there were no real Transferia)
- **2015:** 7.64% of 151,300 mln = 11,556 mln pass.km = > 5.43 PJ
- **2030:** 15.28% of 167,000 mln = 25,158 mln pass.km = > 11.82 PJ
1.2.2 Economic parameters

**Investment costs**

*Transferia:*

- **1994:** no investments made
- **2010/2015:** Dfl 18,000 per parking space (only parking accommodation)
- **2030/2040:** Dfl 38,000 - 50,000 per parking space (total transferium + infrastructure, parking space included)
- **Replacement investments:** (approximately the same amounts as mentioned for 2010/2015)

The investments in Transferia are investments in infrastructure; when parking places are realised in Transferia, there will be no need for parking-places in (inner) cities. Transferia need, next to parking space, railway stations. On the other hand, building parking facilities in cities is more expensive (higher ground costs, expensive infrastructure). The *net* investments will be almost zero.

Rolling stock (extra trains etc.):*

- **1994:** nil
- **2010/2015:** Dfl 0.36 - Dfl 0.50 per passenger kilometre
- **2030/2040:** Dfl 0.36 per passenger kilometre

(investment costs are calculated by multiplying the gain in passenger kilometres by the investment costs per passenger kilometre)

**Operation and maintenance costs (per year, rolling stock)**

In 1991 operation and maintenance costs for rolling stock were Dfl 0.24/passenger-kilometre (CBS, 1993).

- **1994:** nil (no Transferia in operation)
- **2010/2015:** Dfl 0.22/pass.km (estimated 10% reduction due to efficiency measures)
- **2030/2040:** Dfl 0.18/pass.km (due to efficiency measures, estimated 20% reduction in comparison with 1991)

**Operation and maintenance costs (per year, Transferia)**

- **2010/2015:** estimated Dfl 400 / parking-place
- **2030/2040:** Dfl 400 / parking-place

**Other costs**

In order to reach the above mentioned degree of penetration, several "push" measures have to be taken. These measures also cost money. On the other hand by removing parking places from the (expensive) inner cities to the (less expensive) outskirts of the city, money can be saved. The net result is uncertain.
1.2.3 Environmental parameters

Emissions
In comparison with combustion-engined passenger cars in the 90’ies, electric powered trains cause more SO₂-emissions per passenger kilometre. This is due to the "fuel-mix" in electric power plants. With new developed fuels (like sulphur-lean gasoline) and new power-plant technology (treatment of exhaust gases) part of this problem is solved. In comparison with electric vehicles, the emissions are the same (the same power-plants are used). The only difference might be the advantage of scale of collective transport versus individual transport: collective transport will cause fewer emissions per passenger-kilometre.

Materials
There is no need for special materials.

Space
Transferia need, a lot of, space because many vehicles have to be parked in these facilities. Therefore high-rise (or deep-‘sunk’) buildings or space-intensive buildings are necessary. However, this is no ‘extra’ space, because cars parked in Transferia need not to be parked elsewhere (for example: in cities). The net space use will therefore not change very much.

1.3 Calculation of energy-parameters

Passenger car
In 1990 in The Netherlands 125,100 mln passenger kilometres and 81,898 mln vehicle kilometres were made by car. The distribution of fuel use was as follows:

- 52,974 mln veh.km gasoline
- 14,801 mln veh.km diesel
- 14,123 mln veh.km LPG

The total energy-use for cars in 1990 was:

- Gasoline 141.8 PJ (so 2.68 PJ/10⁹ vehiclenkm. or 1.75 MJ/passengerkm.)
- Diesel 37.1 PJ (so 2.51 PJ/10⁹ vehiclenkm. or 1.64 MJ/passengerkm.)
- LPG 38.3 PJ (so 2.71 PJ/10⁹ vehiclenkm. or 1.78 MJ/passengerkm.)

The total energy-use for passenger trains was (final) 11.1 PJ.

Therefore, the energy use per passenger kilometre by rail is 1.00 MJ/passengerkm. (final use).

Energy-saving
The following energy savings are calculated:

- for each replaced car-passenger kilometre: -0.74 MJ/passengerkm.
- additional transport by city (light) rail, detours etc.: (total + 5% length): 0.04 MJ/passengerkm.

Net result: -0.70 MJ/passengerkm.
**Investment cost (rolling stock)**

The investments costs for rolling stock are:
- **Investment cost per train:** approx. Dfl 5 - 7.2 mln
- **Amount of seats:** approx. 200
- **Investment/seat** approx. Dfl 26,000 - 36,000
- **Investment/passengerkm.** approx. Dfl 0.36 - 0.50
- **Passengerkms/seat:** approx. 70,000 (a year)

**References**
- Egeter, B.; Th.J.H. Schoemaker et.al. (1990), *Transferia* (in Dutch), Vakgroep Verkeer, TU-Delft
- KIVI/CROW (1992), *From Park and Ride to Transferia: are we gonna make it?* (in Dutch: *Van P+R naar Transferia: gaan we het maken?*), proceedings
- NVI (1981), *Corridorstudy Park and Ride* (in Dutch: *Corridorstudie Parkeer en Reis*), Rijswijk
2 INTERMODAL GOODS TRANSPORTATION

The aim of intermodal goods transport is to shift road-transport to more energy-efficient railway or inland waterway transport. Because most industries and consumers are not connected to railways or waterways, supplementary road-transport and consequently transhipments will in most cases be a part of the transport chain. In this chapter the system of intermodal goods transport is described.

2.1 Description of intermodal goods transportation

Definition
Intermodal goods transportation consists of up to five parts: transport from origin to the point of transfer by truck, transfer from truck to train or ship, transport between points of transfer by train or ship, transfer from train or ship to truck and transport from point of transfer to the destination by truck. Sometimes the point of transfer is integrated in the origin or destination, so one transfer and one transport by truck can be skipped.

Explanation
Some transport modes use less energy per ton-kilometre than other. From the point of view of energy use, the ideal situation is to transport all goods from origin to destination by the most energy efficient mode. However, relatively few shippers (factories, distribution centres, households) are located next to railway tracks or inland waterways, so often it is not possible to use only a train or ship. In these circumstances the use of intermodal transport decreases the energy-use. Goods are transported to the nearest point of transfer by truck and then transferred to and transported by a more energy-efficient mode (train, ship). The transfer itself requires some energy, so intermodal transport only leads to energy savings for distances longer than about 30-40 km [Van Binsbergen, 1993; Walstra, 1994].

Several kinds of intermodal goods transport can be distinguished.

Combined Rail-Road transport:
- rolling road: complete trucks are transferred to railway carriages. The energy-benefit of this type of intermodal transport is marginal: only local emissions are reduced (for this reason this type of intermodal transport is used passing the Alps).
- trailer on (flat) car: trailers are transferred to more or less ordinary railway carriages. Examples are Piggy Back, Kangourou, Trailer on Flat Car (TOFC), Huckepack, Walda I and II. Some systems require a kind of transfer-facility, but these use a negligible amount of energy. The advantages of these systems are the simple construction of trailers and railway-carriages. The disadvantage is the relatively high deadweight and thus a higher rolling resistance.
- trailer train: trains are made by coupling (specially designed) semi-trailers. Examples are the CODA-E, Kombi trailer, Road-Railer and TransTrailer systems. These systems do not need special equipment for the transfers, but the forming of a complete train (including breaking-tests) is time-consuming and special-designed (robust) trailers are required. An advantage is the low deadweight.
- container transport: the several types of containers (ISO standard, DB-containers and Swop Bodies) are widely used in intermodal transport. Advantages are the relatively low deadweight and the fact that containers are widely used. The disadvantage is the need for special equipment (and energy) to transfer the containers.
Figure 2.1: examples of road-rail combined transportation systems
Combined water-road transport

- trucks-on-ship: on ferry-ships, full trucks (and truck-combinations) can be transported. This form of transport is somewhat less energy-effective, because it requires the transport of a considerable amount of deadweight. Furthermore, this form of transport is from the operations’ point of view less effective, because the (expensive) truck is useless during the sail.

- (semi)trailers-on-ship: it is also possible to transport only the semi-trailers. These are loaded and unloaded by special tractors, which are not transported themselves. In this kind of roll-on roll-off (RoRo) transport, the deadweight is relatively low.

- containers on ships: for this type of transport special equipment is needed to load and unload containers (lift-on lift off or LoLo). The carried deadweight is low, so the energy-effectiveness during the trip is optimal.

Energy functions

The benefit of intermodal transport is the difference between energy use per load-kilometre in road-transportation and transportation by train or inland ship. Most forms of intermodal transport need some energy for transferring the goods, for example the lifting and lowering of containers. On shorter hauls, the total transport distance can increase slightly if combined transport is used instead of road transport.

Penetration

Calculations show that for distances above 30 to 40 kilometres combined road-rail or combined road-inland waterway transport can lead to energy-benefits. Theoretically, if (almost) 79% of tonkilometres is transported by train or inland waterway transport and only 21% of the tonkilometres is transported by truck, maximum energy-use reduction can be achieved [Schoemaker, 1993; NEA, 1993; Peeters, 1993]. This is a very large difference with the autonomous developments, which show a modal split of 53% road-transport and only 47% rail and inland waterway transport in 2015. To achieve a shift in modal split from 53% to 21% for road-transport, three changes are necessary: a change in the costs of the modes (cheap rail and water-transport, expensive road-transport), a change in the governmental policy (national and international) and a change in the attitude of transport companies and shippers. A shift of 5% (of the ton-kilometres) from road to combined road-rail transport can already be regarded as a significant shift; even this shift will require many measures.

Competing technologies

An important competing technology is a more energy-efficient truck. If it is possible to reduce the energy-use per ton-kilometre by using fuel efficient engines or by using larger trucks (road-trains), the advantages of combined transport will decrease. From the technological point of view, pipeline transport is another competing technology (although this mode is for most goods a rather energy-inefficient mode).

State of development

Container systems will be widely used, especially when a better ‘continental’ standard size of containers and swapbodies will be realized (governmental measure). Container transport is most energy-efficient on long trips. Trailer On Flat Car (TOFC) will be an alternative for container-transport on the mid and long term. The advantage of TOFC is the practical use and fast transfer operation. The Combi-Road system will be another alternative on the mid and long term. Combi-road systems do not need special loading/unloading equipment, but this will not be an important advantage due to an increase in rail-operations. For large-scale transfer operations, ‘fast transfers’ are more
important than 'easy transfers'. The main advantage of Combi-Road systems is the energy-efficiency at shorter hauls.

Current R&D
R&D for container transport is aimed at reducing the tare weight of containers (now approximately 2.5 tons for a 20ft. ISO-container) by using aluminium or other light materials. Furthermore, research is aimed at the possibilities to enlarge the number of containers that can be transported by one vessel. A lot of research is done in the field of the loading/unloading equipment (higher capacity, lower energy-use). In the field of rail-road transport, research is done to obtain fast-securing bogie systems (for road-railer systems) and cheap handling equipment (for TOFC-systems). ‘Security’ and ‘speed’ are the keywords. In the field of combined inland shipping research is done to develop special inland container and RoRo vessels (maybe even linked by flexible couplings).

Bottlenecks
Because of the many different intermodal systems and the strongly divided market (many specialisms), it is very hard to achieve standards. As standards are the base of an effective and widespread use of systems, it is rather difficult to reach an energy-efficient total system. For governments it is difficult to choose a specific system, because all systems have their own advantages and disadvantages: there simply is a lack of fundamental research (especially on the new developments like the Walda systems) to make the right decision. The most important bottleneck from the transporters’ point of view are the operating costs: it is still more expensive to use combined transport than road-transport. From the logistic point of view, for a long time it was difficult and expensive to organise reliable (overland) intermodal goods transport. This is partly due to the organisation structure of railway companies, but also the attitude of transport companies was very important. In the last years, some important and promising projects have started to develop intermodal goods transport (combined inland waterway transport for new passenger cars, transport of containers by combined rail transport).

Availability
All road-waterway systems are in use. TOFC and, in the United States, combi-road systems are also in use. The new developed systems CODA-E and Walda have only been ‘full-scale tested’, but there is no experience in practice. Nevertheless, serious technical problems are not to be expected.

2.2 Parameters of intermodal goods transport

2.2.1 Energy-parameters
The energy-profits that can be obtained, can, for a first impression, be calculated by comparing energy-use per ton-kilometre for transport by road, rail and inland waterway. For more precise calculations information about goods flows, average loadings, vehicle sizes and fuel-use are necessary (see also [NEA, 1993; Schoemaker, 1993; Vd.Vlist, 1993]).
Table 2.2.1: Calculation of energy per tonkm for different transport modes

<table>
<thead>
<tr>
<th></th>
<th>total energy [PJ]</th>
<th>total transport [G tonkm]</th>
<th>energy/tonkm(^1) [MJ/tonkm]</th>
<th>energy per vehiclekm(^2) [MJ/veh.km]</th>
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<tr>
<td>(1990)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>road</td>
<td>71.53</td>
<td>34.90</td>
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<td>truck</td>
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<td>64.91</td>
<td>1.63</td>
<td>7.85</td>
</tr>
<tr>
<td>ship (inland)</td>
<td>20.84</td>
<td>50.65</td>
<td>0.41</td>
<td>226.49</td>
</tr>
<tr>
<td>train</td>
<td>1.71</td>
<td>7.20</td>
<td>0.24</td>
<td>3.97</td>
</tr>
<tr>
<td>(2030)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>truck</td>
<td>82.53</td>
<td>64.91</td>
<td>1.27</td>
<td>6.13</td>
</tr>
<tr>
<td>ship (inland)</td>
<td>16.15</td>
<td>50.65</td>
<td>0.32</td>
<td>175.52</td>
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<tr>
<td>train</td>
<td>1.45</td>
<td>7.20</td>
<td>0.20</td>
<td>3.37</td>
</tr>
</tbody>
</table>

(decimal points used)

\[ P = 10^{15} \quad G = 10^9 \quad M = 10^6 \]

\( ^1\): total energy use (loaded and unloaded trips) divided by tonkilometres.

\( ^2\): total energy use (loaded and unloaded trips) divided by total amount of kilometres (loaded and unloaded)

average loadings:
road: 6.1 ton (lorries and vans)
ship: 844 ton
train: 33.9 ton (per carriage; 20 carriages: 678 ton/train)

2015 figures based on ‘reduced’ European Renaissance Scenario
2030 energy-use figures based on ‘Green Technology Scenario’

[NEA, 1993; Schoemaker, 1993; Vd.Vlist, 1993]

A transhipment uses about 7.2 MJ/ton of energy. In a multimodal transport chain, mostly at least two transhipments are needed, so a total amount of 14.4 MJ/ton.

On a trip of 50 km, this will result in 0.29 MJ/tonkm, on trips of 100 km in 0.14 MJ/tonkm.

For combined transport often a container is used. This container has a tare weight of approximately 10% of the average transported weight. Because by using a container no lorry or railway carriage body is needed, not 10% but only approximately 5% of the potential energy-savings are lost.

The above mentioned (see also table 2.2.1) will result in the following energy-savings (distances are examples):

Shift road → inland waterway:
(1994) 1.224 MJ/tonkm (50 km) - 1.366 MJ/tonkm (100 km)
(2015) 0.881 MJ/tonkm (50 km) - 1.023 MJ/tonkm (100 km)
(2030) 0.629 MJ/tonkm (50 km) - 0.771 MJ/tonkm (100 km)
Shift road → rail:
(1994) 1.344 MJ/tonkm (50 km) - 1.487 MJ/tonkm (100 km)
(2015) 1.050 MJ/tonkm (50 km) - 1.191 MJ/tonkm (100 km)
(2030) 0.740 MJ/tonkm (50 km) - 0.883 MJ/tonkm (100 km)

Examples of impact:
1994: 1% road → rail: energy saving of 0.43 PJ
(= 0.6% of energy use in road transport)
2015: 5% road → rail: energy saving of 3.41 PJ
(= 3.2% of energy use in road transport)
2030: 10% road → rail: energy saving of >4.80 PJ
(dependent of amount of transported goods)

2.2.2 Economic parameters

The costs of road, waterway and rail transport reflect the costs of investments in infrastructure (road, rail), materials (vehicles) and drivers.

These costs are approximately:
- road transport: Dfl 0.132 per tonkm
- inland waterway: Dfl 0.0204 per tonkm
- railway transport: Dfl 0.0884 per tonkm
[MER, 1991; NS, 1993]

Costs of transhipments for containers are approximately Dfl 60 per container [Windt, 1988]. At an average loading (loaded containers only) of 15 ton [CBS, 1993], this means Dfl 4/ton per transhipment or Dfl 8/ton per combined trip. For combined trips of average 50 kilometres this means approximately 16 ct/tonkm, for trips of 100 km approximately 8 ct/km.

For intermodal goods transport the following extra costs can be calculated (distances are examples):

Shift road → inland waterway:
- for trips of 50 km of length: 18.04 - 13.2 = 4.84 ct/tonkm
- for trips of 100 km of length: 10.04 - 13.2 = -3.16 ct/tonkm
So for trips over 100 km, combined road-inland waterway transportation can in theory be cheaper than road transport.

Shift road → rail:
- for trips of 50 km of length: 24.84 - 13.2 = 11.64 ct/tonkm
- for trips of 100 km of length: 16.84 - 13.2 = 3.64 ct/tonkm
- for trips of 200 km of length: 12.84 - 13.2 = -0.36 ct/tonkm
So, for trips over 200 km, combined road-rail transportation can in theory be cheaper than road transport.

Due to low costs per ton kilometre, combined transport can be cheaper than road-transport. However, ‘shadow-costs’ are also important. Shadow-costs are mainly made up of interest costs. These costs will be higher if the transportation of goods takes more time, as is the case for inland waterway transport. Furthermore, costs for the transportation to and from the ships or trains should be included.
Investments (transhipment centres):
Examples of gradual investments in 25 Rail Service Centres (RSC)/Inland Waterway service Centres (IWC) for the Netherlands, actual investments are dependent on predicted use.

- 1994: 5 Rail Service Centres (RSC) and Inland Waterway Centres (IWC): Dfl 71 million
- 2010/2015: 10 RSC/IWC: Dfl 142.2 million
- 2030/2040: 10 RSC/IWC: Dfl 142.2 million

Investment per terminal approximately Dfl 14.2 million.

2.2.3 Environmental parameters

Emissions
In general a decrease of energy use leads to a decrease of emissions; when rail is used intensively there might be more SO₂ emission, due to the current fuel-mix of Dutch power plants. In the future the SO₂ emission probably will be reduced by using other types of fuel or by special devices to absorb, reform or filter SO₂.

Materials
There is no need for special materials.

Space
Transfer centres need extra space. A large increase in the number of trains used will lead to the need for new rail-infrastructure.

References
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- Peeters, P.M. (1993), A new course in freight transport (in Dutch: Goed op weg),Werkgroep '2duizend
- Rutten, B.J.C.M. (1993), Specific energy-consumption in intermodal goods transport (in Dutch: Specifiek energieverbruik in het intermodaal goederen vervoer), in proceedings 'Vervoerlogistieke werkdagen'
- Stada, J., S. Hauwert (1992), Information systems for European goods flows (in Dutch: Informatiesysteem goederenstromen Europa (ISG)), Vakgroep Verkeer, TU-Delft
- Walstra, J., A.J. van Binsbergen (1994) Transportation of polluted soil by inland shipping and rail (in Dutch, Vervoer van verontreinigde grond), publication due september 1994
- Windt, J. (1988), Combined truck/rail transport using a through-going containertrain (in Dutch: Gecombineerd weg/railvervoer dat uitgaat van de doorgaande containertrein), TU-Delft
2.2.9 Environmental Preferences

To indoor or outdoor preference, the most to approve of environmentally friendly feature was indoor. Indoor preference in the future for the CO2 emission property will be increased. The number of CO2 emissions is the number of CO2 emissions, which will be decreased for the future preference.

2.2.9.1 Indoor or Outdoor Preference

In the future, indoor or outdoor preference will be increased for the CO2 emission property of preference. The number of CO2 emissions is the number of CO2 emissions, which will be decreased for the future preference.
3 AUTOMATED PUBLIC TRANSPORT SYSTEMS

The quality of public transport services can be increased if higher frequencies can be offered. More, but smaller vehicles are necessary and, for conventional systems, more drivers would be necessary. To reduce the costs, automated public transport systems have been developed. These systems turned out to be even more energy-efficient than their conventional counterparts. In this chapter some of these automated public transport systems are described.

3.1 Description of automated public transport systems

Definition
Automated Public Transport Systems (APTS) are new systems with a high penetration and frequency in urban area, designed for the short trips. Usually these new systems are supposed to be small, light rail vehicles, also called 'people movers'.

Explanation
Compared to the passenger car, public transport is an environment-friendly mode of transport. In many ways a shift in modal-split from passenger car to public transport can be achieved. Most ways do not fit in the framework of this study (lower prices, higher frequencies of existing systems), other ways do not contribute very much to energy savings (Maglev trains). These ways/systems will not be considered.
Especially on short trips in urban areas, passenger cars are very polluting and energy-inefficient. When a fast, low price door-to-door system can be offered, these car trips will become replaced by trips by the new, energy-efficient system. APTS do not offer a door-to-door service, but due to the automatic operation they are fast and cheap.
Two types of APTS can be distinguished: Group Rapid Transit systems (GRT) and Personal Rapid Transit (PRT). The first group of systems offers cabins for more than ten people, the second group only for about four people.

Figure 3.1: different types of guideways by vehicle position [Van Witsen, 1993, adapted]
Within each type several techniques can be distinguished with regard to the position of the guideway (supported, straddling, suspended), the type of propulsion (internal electric motor, cable, induction motor) and the way of support (rubber tyres, steel wheels, magnetic levitation).

In a study on this subject [Van den Berg, 1993], two systems are classified as 'promising': the SK-system, a system with light, cable driven cabins and the VAL system, a small automated light rail vehicle on pneumatic tyres. The VAL is in operation in Lille, the SK-system has one demonstration section in Paris. The most suitable travelling distance for the SK is shorter than most suitable travelling distance for the VAL system. The SK6000 has an estimated capacity of about 4000 passengers/hour, the VAL-system more than 5000 passengers/hour.

Energy functions
APTS are only useful in areas with dense passengerflows in and around the centre of large towns. In these areas APTS will replace much trips by passenger car, so the benefit of APTS is the difference in energy-use between passenger cars in urban areas and APTS. APTS will replace several trips by foot or bicycle as well, thus replacing no-energy trips by low-energy trips.

Penetration
Application of the systems mentioned above is possible at distances between 400 and 3,000 metres. At shorter distances walking will be faster, at longer distances the traditional public transportation systems will be better. Another condition is a high intensity of pedestrians. Because of these conditions, APTS are promising in historical urban areas, at large high-quality work areas, large bus and train stations, large airports and extensive exhibition areas. With regard to The Netherlands, this means there are twenty locations where APTS are useful. These are for example Amsterdam Sloterdijk, Rotterdam Kop van Zuid and Den Haag Central Station - Hollands Spoor. The total length of these systems will be about 60 kilometres [Van den Berg, 1993; Van Witsen, 1994]. Most of these systems will be located in new developed or redeveloped urban areas. When replacements of existing public transport services are excluded and there will be no massive shift in modal split (both largely dependent on policy!), the mentioned 60 kms of track will be the maximum in 2030/2040; from the point of view of technology, all systems can be realised in the 2015/2020 period, but due to planning restrictions only part of it actually will be realised (about 15-20 kms of track: 3-4 applications).

Competing technologies
Competing, existing technologies are:
- Light-rail systems or LRT's (in Dutch cities: 'sneltram')
- Short-distance train systems (between Dutch cities and suburbs: 'Sprinter')
- Metro systems

State of development
New technologies for short distances:
SK 6000 Soulé/Kermandec, France, using a cable-system, rubber tyres (1986 Villepinte France, Vancouver Canada, Yokohama Japan)
H-Bahn Siemens/Düwag, Germany, using a suspended rail and rubber tyres (1984 Dortmund, Germany)
POMA 2000 Pomagalski, France (manufacturer of ski-lifts), using a cable-system and rubber tyres (1989 Laon, France)
MAGLEV  R&D division of British Rail, Great Britain, using magnetic levitation and linear induction motor (1975 Birmingham)

TEW  Transit Expressway (Skybus), Westinghouse, USA using rubber tyres (1971 various cities USA and Canada, 1986 Miami, Las Colinas)


New technologies for long, intra city, distances:
VAL  Véhicule Automatique Léger, MATRA, France using rubber tyres (1983 Lille France, USA, Taiwan)

UTDC  Urban Transportation Development Corp., Canada, using a linear motor and steel wheels (1985 Vancouver Canada)

M-Bahn  Magnet-Bahn AEG/Westinghouse, Germany/USA, using magnetic levitation and a linear induction motor (temporarily Berlin Germany 1989-1991)

DLR  Docklands Light Railway, Great Britain (1987 London Great Britain)

KNT  Kobe New Transit, Kawasaki, Japan using rubber tyres.

Current R&D
For all technologies mentioned above research is done to achieve a higher operational speed (higher speed, acceleration and deceleration), a higher safety (protection of passengers waiting on the platform), higher reliability (improved technology) and a higher flexibility (small cars which can be coupled).

Bottlenecks
Some of the above mentioned systems are not fully developed; especially the magnetic-levitation technology has to overcome some problems. A lot of automatic guided systems use switches which are far more complicated than switches for conventional steel-wheel trains. A problem for PRT (personal rapid transit) systems can be the low capacity. Although some manufacturers claim higher capacities there is no real proof up to now. Another problem is that all these systems are incompatible with ordinary systems, so a complete new network has to be built. Especially in European cities with extensive existing public transportation systems, this is a problem. However, this is a political (and financial) problem. For the VAL system, there are no important problems to be solved; the problem of the SK system is the fitting in in an urban area.

Availability
As is shown in the above summary, most of the systems are already in use. If enough money becomes available, APTS can be introduced at all of the twenty proposed locations by 2015.
3.2 Parameters for automated public transport systems

3.2.1 Energy parameters

Systems for short distances

The least energy is needed for the SK6000 system (208.3 Wh/placekilometre) and the TEW system (189.6 Wh/placekm). Existing systems like a tram (400 Wh/placekm) and a bus (approximately 549 Wh/placekm) use more energy. The taxi system uses about 3.06 kWh per placekm, but this system is not track or line bound. The maximum energy-profit of these light-rail systems is about 192-360 Wh/placekm (48% - 65% less energy compared to more traditional collective transport systems).

Systems for long(er) distances

For longer distances between cities less energy is needed than for short distances by using the DLR-system, which consumes about 344 Wh/placekm. The 'traditional' metro system uses even less energy: only 322.7 Wh/placekm. Other systems, like a train (650 Wh/placekm) and light rail (403 Wh/placekm) need more energy.

Indication of energy-profits:

In 2015 there may be 60 kms of track.

For the SK6000 system, the capacity is about 5,000 pass/hour. Assuming that 30% of this capacity is used, about 1500 pass/hour will travel (27,000 a day). When this occupancy can be achieved over the full length of the line and during all day, this means 1.62 million passenger kilometres (60*27,000). If all these passengers previously were travelling by car, 3,360 kWh (12 GJ) energy would be saved. In reality, the occupancy mentioned is hard to achieve. Furthermore, part of the travellers are not former car users but were of public transportation or bike. Nevertheless, the replacement of existing public transport services by these new systems can lead to a significant energy reduction. This is mainly due to the lightweight construction of the vehicles.

3.2.2 Economic parameters

Investments:

1994:
no APTS systems in use (in The Netherlands)

2010/2015:
SK6000: Dfl 42.0 million/km
TEW: Dfl 42.7 million/km
DLR: Dfl 71.2 million/km
bus: Dfl 10.4 million/km (free lane)
tram: Dfl 18.2 million/km
metro: Dfl 54.1 million/km

Total investments Dfl 2,520 - 4,272 million
(60 km of track).

2030/2040:
all 20 systems are available; maybe existing public transport systems will be replaced.
Table 3.2.2: Comparison of costs per year per km in thousands of guilders (365 days a year, 18 hours a day) at full capacity

<table>
<thead>
<tr>
<th>system</th>
<th>maintenance</th>
<th>energy</th>
<th>personnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK6000</td>
<td>330.4</td>
<td>200.3</td>
<td>1,060.1</td>
</tr>
<tr>
<td>VAL</td>
<td>520.0</td>
<td>773.1</td>
<td>1,029.1</td>
</tr>
<tr>
<td>TEW</td>
<td>371.2</td>
<td>137.8</td>
<td>773.1</td>
</tr>
<tr>
<td>DLR</td>
<td>561.6</td>
<td>547.2</td>
<td>1,494.9</td>
</tr>
<tr>
<td>bus</td>
<td>83.2</td>
<td>157.0</td>
<td>2,011.2</td>
</tr>
<tr>
<td>tram</td>
<td>146.2</td>
<td>307.4</td>
<td>1,801.8</td>
</tr>
<tr>
<td>metro</td>
<td>433.8</td>
<td>409.2</td>
<td>1,214.8</td>
</tr>
</tbody>
</table>

Note: the SK6000 and TEW systems do not need drivers, some systems (like DLR) have non driving staff aboard for reasons of security.

Technical lifetime

The technical lifetime of collective (public) transport vehicles averages about 25 years. Most light-rail systems are not very long in operation yet; only the TEW-systems operate for a longer period (23 years). The vehicles probably need to be replaced soon (or have been replaced already). The conventional public-transport vehicles can have a technical lifetime of about 30 years; the economic lifetime is often shorter (contrary to passenger cars, trams and busses are often renewed with modern interiors, more advanced technical equipment and engines).

3.2.3 Environmental parameters

Emissions

What emissions are produced depends on the fuel-mix used in the power plants. Nowadays, the emission of \( \text{SO}_2 \) is relatively high.

Materials

No specific scarce materials are needed.
### Table 3.3.1a

<table>
<thead>
<tr>
<th>SK 6000</th>
<th>H-Bahn</th>
<th>POMA 2000</th>
<th>MAGLEV</th>
<th>TEW</th>
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<td>rubber</td>
<td>rubber</td>
<td>rubber</td>
<td>magn.</td>
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<td>guidance</td>
<td>rubber</td>
<td>rubber</td>
<td>rubber</td>
<td>magn.</td>
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<td>propulsion</td>
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<td>ac</td>
<td>cable</td>
<td>linear</td>
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<td>mass loaded [ton]</td>
<td>5.50</td>
<td>10.47</td>
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<td>operat. speed [km/h]</td>
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<td>29.9</td>
<td>25.6</td>
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<td>12</td>
<td>12</td>
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<td>percentage of seats</td>
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<td>48%</td>
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<td>total</td>
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<td>330.4</td>
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**Notice:**
- ac: ac-electric (rotation) motor; linear: linear electric motor

### Table 3.3.1b

<table>
<thead>
<tr>
<th>TAXI</th>
<th>CITY-BUS</th>
<th>FREE-BUS</th>
<th>TRAM</th>
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<td>$E_{vehkm}$ kWh</td>
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<td>$E_{plkm} 10^{-3}$ kWh</td>
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<td>$P_{syskm}$ kW/km</td>
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**Notice:**
- diesel: internal combustion (diesel) engine; ac: electric rotation motor

[Van den Berg, 1993]
### Table 3.3.2a

<table>
<thead>
<tr>
<th></th>
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### Energy

<table>
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<tr>
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<th>kWh</th>
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<tr>
<td>E(vehkm)</td>
<td>6.81</td>
<td>3.87</td>
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<td>42.56</td>
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<tr>
<td>power</td>
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</tr>
<tr>
<td>P(veh) kW</td>
<td>256.74</td>
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<tr>
<td>P(syskm) kW/km</td>
<td>817.20</td>
<td>464.40</td>
<td>239.75</td>
<td>578.40</td>
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</table>

### Vehicle capacity

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<th></th>
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</thead>
<tbody>
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<td>number of seats</td>
<td>44</td>
<td>28</td>
<td>28</td>
<td>84</td>
</tr>
<tr>
<td>percentage of seats</td>
<td>28%</td>
<td>36%</td>
<td>35%</td>
<td>40%</td>
</tr>
<tr>
<td>total</td>
<td>160</td>
<td>78</td>
<td>80</td>
<td>210</td>
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### Costs [Dfl $10^3$]

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<td>personnel</td>
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<td>946.6</td>
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**ac**: ac-electric (rotation) motor; **linear**: linear electric motor [Van den Berg, 1993]

### Table 3.3.2b

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</tr>
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<td>rail</td>
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<tr>
<td>propulsion</td>
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### Energy

<table>
<thead>
<tr>
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<th>kWh</th>
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<th>kWh</th>
<th>kWh</th>
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<td>E(plkm) $10^{-3}$</td>
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<tr>
<td>Power</td>
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</tr>
<tr>
<td>P(veh) kW</td>
<td>269.18</td>
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<tr>
<td>P(syskm) kW/km</td>
<td>723.84</td>
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### Vehicle capacity

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</thead>
<tbody>
<tr>
<td>number of seats</td>
<td>80</td>
<td>144</td>
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<tr>
<td>percentage of seats</td>
<td>43%</td>
<td>52%</td>
<td>36%</td>
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<tr>
<td>total</td>
<td>187</td>
<td>278</td>
<td>220</td>
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</table>

### Costs [Dfl $10^3$]

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<table>
<thead>
<tr>
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<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>maintenance</td>
<td>443.2</td>
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<tr>
<td>energy</td>
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<tr>
<td>personnel</td>
<td>1489.2</td>
<td>1336.4</td>
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</tbody>
</table>

**ac**: ac-electric (rotation) motor; [Van den Berg 1993]

**Notes:**

Energy (syskm): energy use per systemkilometre (total energy divided by total vehicle kilometres), calculations based on full-capacity use and on stop-distances, accelerations, braking and maximum speeds characteristic for the system. [Van den Berg, 1993]. (this is theoretical energy-use, because in reality full-capacity situation will not occur during the whole day and the whole year).

Costs: costs per year for the total system (365 days a year, 18 hours a day) and maximum capacity use. (these are theoretical costs, because in reality a full-capacity situation will not occur during the whole day and the whole year).
References

- Sproule et al., A.S.C.E. Irving (1993), *Automated people movers IV, enhancing values in major activity centres*
- Witsen, M. van (1994), Delft University of Technology/Dutch Railways, interview.

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<tr>
<td>0.1</td>
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<td>0.5</td>
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<td>0.7</td>
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<tr>
<td>0.1</td>
<td>0.2</td>
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<td>0.1</td>
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<td>0.1</td>
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<tr>
<td>0.1</td>
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4 TRAFFIC INFORMATION AND CONTROL SYSTEMS

By giving drivers adequate information about the actual traffic situation, they can optimize their trips and this can lead to travel-time, energy-use and travel-distance reductions. By controlling the (maximum) speed of vehicles the average speeds can be reduced and traffic flows can be made more homogeneous (reducing the variations in vehicle speeds). This will lead to a decrease in energy use. In this chapter several traffic information and control system technologies are discussed.

4.1 Description

Definition

Traffic Information and Control Systems (TICS) are systems establishing an active contact between vehicles and the traffic control systems outside the vehicles. By this contact both vehicles and drivers can be influenced in their behaviour, vehicles by regulating speed, lanes and mutual distances, drivers by providing real-time traffic-information.

Explanation

The system consists of three parts: equipment on board of the vehicles, equipment in and along the road and a central control unit (see figure below). The input for the control unit consists of information sent by the vehicles, information from the traffic control system and information entered by operators (e.g. weather, location of road works, incidents). The output consists of signals to the roadside equipment (traffic signs and lights), real-time information to the vehicles (optimum routes, estimated times) and real-time information to service terminals (used by potential travellers planning their trips).

All these signals and information will have the following effects:

- **reduction of energy use and vehicle kilometres in urban areas due to:**
  - pre-trip information on alternative modes and routes (shortest),
  - on-board information on incidents and available parking places,
- **reduction of energy use on main routes due to:**
  - the possibility of a fixed maximum speed level of 90 km/h,
  - the possibility of forming trains and thus reducing the air resistance, reducing the number of accelerations and decelerations and increasing the road capacity.

Energy functions

Various aspects of TICS influence energy functions:

- the pre-trip information supply influences the number of car trips and their routes,
- the on-board information supply influences car speed and routes,
- the vehicle control system influences car speed and acceleration,
- the fleet-management control system influences the number of van trips and their routes.

All aspects influence both energy use and the emissions of passenger cars, vans, buses and trucks.
Figure 4.1: examples of Traffic Information and Control Systems

Penetration
- Pre-trip information supply: 100% of all drivers.
- On-board information supply: 100% of all cars, vans, busses and trucks.
- Fixed speed level of 90 km/h: 10% of all car kilometres.
- Forming trains: 40% of all car kilometres.

Competing technologies
The development of new individual or collective transportation systems.

State of development
- Pre-trip information supply: limited version in operation, large scale implementation dependent on the development of computer connections.
- On-board information supply: probe passenger cars and pilot projects in several cities, limited version in operation for vans and busses.
- Fixed speed level: probe passenger cars, in operation for vans and trucks (compulsory).
- Forming trains: electronically connected probe cars in operation, physically connected vehicles only in plans.

Current R&D
Europe: DRIVE program and PROMETHEUS program (Siemens, Philips, Telefunken System Technik)
America: Intelligent Vehicle Highway System program (Transcom, General Motors, Ford, Chrysler)
Japan: Vehicle Information and Communication System program (Metropolitan Expressway Public Corporation, Hanshin Expressway Public Corporation, Japan Highway Public Corporation, Japan Traffic Management Technology Association, Sumimoto Electric)

Bottlenecks
- Responsibility for the driving with the driver or with the control system?
- Communication between vehicles and control centre: what frequencies to use for what areas and how to avoid signals from interfering with each other.
- Information input and management: what information is necessary, how can it be collected and where and how soon will it be available.
- Combining pilot projects into a large scale implementation.
- Security and liability problems.

Availability
Urban area:
- pre-trip information supply: 1995-2000
- on-board information supply: 1995-2000
Main routes:
- fixed speed level: 2000-2005
- forming trains: 2010-2015

4.2 Parameters

4.2.1 Energy parameters

Reference energy use: 2.7 MJ/vehkm

Energy use
1994: 2.7 MJ/vehkm 0.2% reduction of number of vehkm.\(^1\)
2010/2015: 2.3 MJ/vehkm max. 20% reduction of number of vehkm.\(^2\)
2030/2040: 2.1 MJ/vehkm max. 20% reduction of number of vehkm.\(^3\)

\(^1\) 1% Reduction of the number of vehicle kilometres means 2.1 PJ reduction of the total energy use (210 PJ).

\(^2\) 1% Reduction of the number of vehicle kilometres means 1.8 PJ reduction of the total energy use (179 PJ).

\(^3\) 1% Reduction of the number of vehicle kilometres means 1.6 PJ reduction of the total energy use (163 PJ).

4.2.2 Economical parameters

Investments
1994: 
2010/2015: Dfl 1,000 million (research and development)
about Dfl 2,000 (equipment, per vehicle)
2030/2040: about Dfl 2,000 (equipment, per vehicle)
Operation and maintenance costs:

1994: less than 0.01 ct per vehicle kilometre
2010/2015: less than 0.01 ct per vehicle kilometre
2030/2040: less than 0.01 ct per vehicle kilometre

Technical life: onboard: car lifetime (except software)

4.2.3 Environmental parameters

Emissions
No emissions caused by TICS technology.
Reduction of existing emissions by vehicles.

Materials
No use of scarce materials.

4.3 Calculation of reductions

Energy use
The energy use of passengercars on highways at 120 km/h is about 3.2 MJ/vehkm.
The energy use on other main roads at speeds of 90 km/h is about 2.4 MJ/vehkm.
In urban areas, at low (average) speed, the energy use is about 3.2 MJ/vehkm.

[Hamel, 1993]

Vehicle kilometres
Distribution of vehicle kilometres on roads in The Netherlands:
- highways: 40% (10% faster than 90 km/h)
- other main roads: 30%
- urban area: 30%
This results in an average energy use of: 2.7 MJ/vehkm

Effects
Total effect of pre-trip information:
average energy use: 2.6 MJ/vehkm
5% reduction of all vehicle kilometres

Total effect of on-board information:
average energy use: 2.5 MJ/vehkm
>5% reduction of all vehicle kilometres

Total effect of fixed speed level:
average energy use: 2.6 MJ/vehkm
no effect on vehicle kilometres

Total effect of forming trains:
average energy use: 2.4 MJ/vehkm
no effect on vehicle kilometres

Estimates of degree of penetration

<table>
<thead>
<tr>
<th>Year</th>
<th>Pre-trip Information</th>
<th>On-board Information</th>
<th>Fixed Speed Level</th>
<th>Forming Trains</th>
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</thead>
<tbody>
<tr>
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<td>1% of total effect</td>
<td>0% of total effect</td>
<td>0% of total effect</td>
<td>0% of total effect</td>
</tr>
<tr>
<td>2010/2015</td>
<td>100% of total effect</td>
<td>100% of total effect</td>
<td>100% of total effect</td>
<td>5% of total effect</td>
</tr>
</tbody>
</table>
2030/2040  pre-trip information  100% of total effect
  on-board information  100% of total effect
  fixed speed level  100% of total effect
  forming trains  50% of total effect

[Westerman, 1994]

References
- Catling, I (1994), *Advanced Technology for Road Transport: IVHS and ATT*
- Hamerslag, Westerman (1993), *Effectiveness of several policies towards traffic and transportation* (in Dutch: *Effectiviteit van enige beleidsmaatregelen ten aanzien van verkeer en vervoer* )
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- Westerman, M. (1994), *interview*, Delft University of Technology, Department of Transportation Planning and Highway Engineering
PART II:
BATTERY AND FUEL-CELL ELECTRIC VEHICLES

- BATTERIES FOR ELECTRIC VEHICLES
- FUEL-CELLS
- ELECTRIC COMPONENTS OF VEHICLES
PART III

SPECIALIZED AND HYBRID ELECTRIC VEHICLES

1. ELECTRIC ORTHOGONAL STEER VEHICLES

2. ELECTRIC COMMUTED INDUCTION VEHICLES
PART II:
BATTERY AND FUEL-CELL ELECTRIC VEHICLES

1 BATTERIES FOR ELECTRIC VEHICLES

1.1 Short-term battery technologies

1.1.1 Description of lead-acid batteries

1.1.2 Parameters of short-term batteries for passenger cars

1.1.3 Parameters of short-term batteries for vans

1.1.4 Parameters of short-term batteries for busses

1.2 Mid-term battery technologies

1.2.1 Description of sodium-sulphur and sodium-metal-chloride batteries

1.2.2 Description of nickel-zinc batteries

1.2.3 Description of aluminium-air and zinc-air batteries

1.2.4 Parameters of mid-term batteries for passenger cars

1.2.5 Parameters of mid-term batteries for vans

1.2.6 Parameters of mid-term batteries for busses

1.3 Long term battery technologies

1.3.1 Description of lithium-based batteries and US-ABC goals

1.3.2 Parameters of long-term batteries for passenger cars

1.3.3 Parameters of long-term batteries for vans

1.3.4 Parameters of long term batteries for busses

2 FUEL-CELLS

2.1 PEM fuel-cells

2.1.1 Description of PEM fuel-cells

2.1.2 Parameters of PEM fuel-cells for passenger cars

2.1.3 Parameters of PEM fuel-cells for vans

2.1.4 Parameters of PEM fuel-cells for busses

2.1.5 Parameters of PEM fuel-cells for trucks

2.2 Alkaline fuel-cells

3 ELECTRIC SYSTEMS

3.1 Electric motors

3.1.1 Rotation motors

3.1.2 Linear motors

3.1.3 Efficiency of electric motors

3.2 Auxiliary systems

3.2.1 Motor and battery management system

3.2.2 Transmission systems for electric vehicles

3.2.3 Regenerative braking

3.3 Energy supply

3.3.1 Stationary energy supply

3.3.2 Energy supply during a drive
1 BATTERIES FOR ELECTRIC VEHICLES

In the development of "electric vehicles", the battery is the most important bottleneck. It may be assumed that by the time batteries can compete with combustion engines, all other problems of electric vehicles will be solved too. In this chapter various types of batteries will be discussed. Other issues such as motor types, motor management and regenerative braking are discussed in chapter 3 of this part.

In this chapter, for each period only the most promising battery will be discussed:

- 1994 lead-acid (Pb-acid)
- 2015 sodium-sulphur (NaS), nickel-zinc (NiZn), sodium-nickel-chloride (NaNiCl₂), zinc-air (ZnO₂), aluminium-air (AlO₂)
- 2030 lithium-based

These systems can compete best with internal combustion-engine (ICE) vehicles in that period. Calculations about mass of batteries and costs are only made for passenger cars and (small) vans. Although there are some examples of battery powered buses and (light) trucks (SITA-France), for busses and lorries other systems are more likely.

Figure 1: example of battery-powered test vehicle: an adapted Peugeot 205 ("voiture électrifiée")

For the calculations it is important to make a distinction between maximum specific power and the energy-density of a battery. To start and accelerate a (passenger) vehicle a certain amount of power (W) is needed: therefore, the Maximum Specific Power of batteries is important (W/kg). To obtain a useful driving range, it must be possible to store energy in a battery (J); therefore, the Energy Density (Wh/kg or Wh/l) is important. In the United States, the US Advanced Battery Consortium has been formed. The goal of this consortium is to develop a cheap, lightweight battery which is capable for a drive range of more than 125 miles (50 miles for average daily usage, 50 miles for reserve and 25 miles for the equivalent climate control system load). As is foreseen that costumers appear to be unwillingly to pay much over Dfl 2,000 more than the equivalent internal combustion engine (ICE) vehicle costs, the extra costs of electric vehicles should be less than Dfl 2,000 in the future; the battery-costs must therefore be less than Dfl 300/kWh.
The US-ABC consortium has selected the following battery types:

**Mid-term battery technologies:**
- nickel-metal-hydride
- sodium-sulphur
- sodium-nickel-chloride

**Long-term battery technologies:**
- lithium-metal-sulfide
- lithium-polymer

In this study, zinc-air \((\text{ZnO}_2)\) and aluminium-air \((\text{AlO}_2)\) batteries have been added.

The energy efficiency of an electric vehicle is composed of the energy efficiency of the charger, the efficiency of the battery (loading/unloading), the efficiency of the motor and the transmission and the efficiency and energy use of the motor/battery controller and management system. The energy efficiency of an electric vehicle is remarkably higher than that of an internal combustion engine powered vehicle. As to chain energy efficiency, electric vehicles are however comparable with ICE-vehicles, due to the relatively low efficiency of power plants. By improving the power plant efficiency, the chain efficiency of electric vehicles can be improved.

**Note:**

*In this chapter improvements of electric motors, transmission systems for electric motors and the motor/battery management control systems are included in a "package" (see also the notes added to the energy parameters).*

Developments on electric motors, transmission systems and management control systems will be discussed shortly in the last chapter of this second part.

### 1.1 Short-term battery technologies

#### 1.1.1 Description of lead-acid batteries

**Definition**

Batteries are fed by a charger from the grid and are used to store electricity onboard vehicles: where vehicles are driving, there is no form of external power supply. Of all available battery types, the lead-acid battery is the most developed but also less promising type. The lead-acid battery is well known as the battery in vehicles for electricity supply to spark-plugs and accessories.

**Explanation**

The lead-acid battery uses \(\text{PbO}_2\) as oxidator and \(\text{Pb}\) as reductor, with sulphuric acid as electrolyte. When the battery is in use, both poles are changed into \(\text{PbSO}_4\), diluting the electrolyte. When charging the battery, the opposite reactions take place.

**Energy functions**

Because of the low specific energy, lead-acid batteries are only really suitable for light, small passenger cars and vans, which do not need a large driving-range; this means that they can only be used in urban area vehicles.

(general lead-acid characteristics)

- working temperature: 10 - 45 °C
- theoretical E-density: 161 Wh/kg
- cell-voltage (charged): 2.1 Uc/V
(improved lead-acid battery as is used in GM's Impact)

- specific E 2h rate: 35 Wh/kg
- power density: 280 W/kg
- E density 2h rate: 80 Wh/l
- power density: 650 W/l
- self-discharging rate: <0.1% a day
- cycle life: >500 cycles
- costs: <300 Dfl/kWh

(chloride lead-acid)

- specific E 2h rate: 30 Wh/kg
- power density: 80 W/kg
- E density 2h rate: 60 Wh/l
- power density: 160 W/l
- cycle life: >500 cycles
- costs: <300 Dfl/kWh (160 Dfl/kWh projected [Diaz, 1991])

Wallentowitz, 1994)

Kahlen, 1992; Dabels, 1992; IDA-1, 1993; I&T, 1993; VDI, 1992

The energy efficiency (loading/unloading) of lead-acid batteries is estimated at 70% up to 95%(!) [VDI, 1992]; for the 1994-period calculations, an efficiency of 75% is used [Brogan, 1992].

Penetration

The possible use of lead-acid batteries is limited to urban trips due to the low specific energy. About 75% of the car trips (in cities) is shorter than 10 km and 2% exceeds 50 km. Most of the cars only incidentally run longer distances (holidays and so on). A maximum penetration of lead-acid powered vehicles of about 30% can be expected (passenger cars and vans in cities) [Bossche, 1992]. Other sources state 5% (1995) to 20% (2020) of city-cars and 20% (1995) up to 80% (2020) of "modular battery package"-vehicles can be equipped with a battery electric propulsion system, seen from the technological point of view [Kram, 1989]. The 1995-estimates of [Kram, 1989] seems to be rather high now (1994): a 5 - 15% share might be more realistic. For vans no specific figures are mentioned, but the same degree of penetration as for passenger cars is possible. Electric busses will hardly be used (<2%, estimate). Of course, the actual penetration is dependent on government measures, prices of competing technologies and taxes (note that about half of the consumer price of ICE-vehicles in The Netherlands are made up of taxes).

Competing technologies

Competing technologies are other types of batteries and fuel-cell vehicles, especially in the 2015 and 2030 periods. From the point of view of energy use, lean internal combustion vehicles (ICE-vehicles) are important competitors. From the point of view of emissions, battery-powered vehicles can drive without producing any local emissions. This can not be achieved by even the most advanced ICE-vehicles.

State of development

Lead-acid batteries are fully developed and widely used in cars for additional power. Nevertheless, research still is going on to improve the battery's performance.
Current R&D

Leading institutes are the following battery manufacturers: Ceac, Oldham (USA), Sonnenschein, Varta (Germany), Sorapac (France) [Wallace, 1992; IDA-I, 1993; I&T, 1993]

Bottlenecks

The most important bottleneck is the low specific energy. Improvement can be expected in tubular batteries. Other problems are the discharge capacity (now at most 80%) and the recharging speed (in common circumstances several hours). Lower O&M costs are expected from maintenance free batteries, but due to relatively short life time (cycles) of most batteries, the replacement costs are high. The recharging time can be an important practical bottleneck (see long-term battery technologies).

Availability

The lead-acid battery is already available in several electric cars and vans that are on the market. Most of the vehicles are adapted ICE-vehicles, but there are also some specially designed electric vehicles available (France).

1.1.2 Parameters of short-term batteries for passenger cars

Energy parameters

Reference energy use: 2.56 MJ/vehkm (energy efficiency: 19%, estimated), this is 1.71 MJ/seatkilometre (calculated with 1.5 available seats per passenger car).

Energy use with lead-acid battery:

1994: 1.36 MJ/vehkm (energy efficiency of vehicle: 52%)
0.91 MJ/seatkm

2010/2015: (replaced by mid-term technologies)
2030/2040: (replaced by long-term technologies)

Total mass of vehicle: 1,445 kg
Mass of battery-pack: 625 kg
Drive range: 60 km

Calculation of required energy for driving (ICE and EV, excl. losses) based on "lower estimation" [Bossche, 1992]: Energy (Wh/vehicle tonkm) = 80 + (80 / vehicle mass); energy-efficiency for passenger cars is estimated. The calculated energy use for internal combustion engine (ICE)-vehicles and full electric vehicles (FEV) is somewhat higher than the energy use calculated in "Cars and Climate Control" [IEA, 1993]. Their estimates are 2.3 MJ/km (gasoline-ICE) and 0.69 MJ/km (full electric vehicle). The result for ICEs is comparable to, for example, 2.6 MJ/vehkm [Delsey, 1991].

The energy efficiency for electric vehicles is composed of charger efficiency (90%, for loading the battery from the grid), battery loading-unloading efficiency (75%), transmission efficiency (85%) and the combined energy use and energy efficiency of the controller and the energy-efficiency of the motor (90%) [Brogan, 1992; NOVEM, 1992]

Mass of internal combustion engine vehicle 920 kg [Rutten, 1990], base vehicle mass 820 kg (incl. electric motor(s), but excl. ICE and tanks). Travel distance/year: 16,500 km [CBS, 1993].

Required driving range 50 km; due to the power requirements a larger battery is necessary which is possible to offer a driving range of almost 60 km. Cruise speed 70 km/h [Martin, 1992].
Economic parameters

Reference vehicle costs Dfl 22,000 [Martin et al., 1992].
Reference maintenance costs Dfl 0.33/km or Dfl 0.22/seatkm, based on Dfl 130/GJ [Kram et al., 1989].

Investments (per vehicle) 1994:

- Dfl 3,500 - 6,560 (battery)
- Dfl 13,000 (engine, transmission, controller)
- Dfl 18,500 (base vehicle costs)

Total: Dfl 35,000 - 38,060

Operation and maintenance costs, including renewal of battery packs, (per kilometre): 23.7 ct/km, 15.9 ct/seatkm; based on Dfl 175/GJ [Kram et al., 1989].
Technical life: 1.7 - 5.2 year (290 cycles a year; 500 - 1,500 cycles/battery)
At an estimated average speed of 30 - 50 km/h and 500 cycles/battery, this results in 580 - 900 working hours.

Calculation of battery mass and costs based on [Dabels, 1992; IDA-1, 1993; I&T, 1993].
Calculation of vehicle costs based on [Martin, 1992].

Environmental parameters

The use of (full) electric vehicles causes no local emissions: full electric vehicles are zero emission vehicles. The generation of energy in powerplants usually causes emissions (in oil, coal or gas fired power stations) or other types of pollution (in case of nuclear power plants). Batteries can pose environmental problems in accidents and at the end of a car-life: lead and acids have to be disposed of unless they are reused. In lead-acid batteries only common materials are used.

1.1.3 Parameters of short-term batteries for vans

Energy parameters

Reference energy use: 6.48 MJ/vehkm (energy efficiency: 20%); this can be compared to an energy use of approximately 3.73 MJ per ton-kilometre (payload 1.735 ton).

Energy use with lead-acid battery:
- 1994: 2.51 MJ/vehkm (energy efficiency: 52%)
- 2010/2015: (replaced by mid-term technologies)
- 2030/2040: (replaced by long-term technologies)

Total mass of vehicle: 3,500 kg
Mass of battery-pack: 1,000 kg
Payload: 904 kg
Drive range: 50 km

As the maximum mass of vans in The Netherlands is 3500 kg, the mass of the battery pack has no influence on the total vehicle mass, but the battery mass "consumes" a
part of the loading capacity of the van. This load-capacity therefore is lower in comparison with ICE-vans. The effective energy use (the energy use per transported ton) is 2.78 MJ/ton-kilometre.

Mass of internal combustion engine van, including maximum loading, 3,500 kg. Base vehicle mass 1,600 kg (incl. electric motor(s), excl. ICE and tanks) [Delsey, 1992; Wieman, 1994]. Travel distance/year: 20,900 km [CBS, 1993]. Required driving range 50 km at "crui se" speed of 70 km/h (figures are equal to passenger cars). Calculation of "net energy" (energy for driving without losses) is based on the "lower estimation" of energy use [Bossche, 1992]: Energy (Wh/vehicle tonkm) = 80 + (80 / vehicle mass); reference energy efficiency is estimated. Compared to the reference energy use some authors calculate relative lower energy use (3.8 MJ/km at 646 kg of loading [Haspel, 1991] and 5.4 MJ/km at full load [Rijkeboer, 1994]) but based on fuel-consumption also relatively higher figures can be calculated (4.56 MJ empty [Wieman, 1994]).

### Economic parameters

Reference vehicle costs Dfl 45,000 (ICE-van) [Wieman, 1993].

Reference maintenance costs Dfl 1.43/vehkm or Dfl 0.82/tonkm (interpolated cost estimate of Dfl 220/GJ, based on [Kram et al., 1989]).

**Investments (per vehicle) 1994:**

- Dfl 5,580 - 10,460 (battery)
- Dfl 28,000 (engine, transmission, controller)
- Dfl 34,500 (base vehicle costs)

**Total:** Dfl 68,080 - 72,960

Operation and maintenance costs (per kilometre): 43.4 ct/km or 47.3 ct/tonkm (based on Dfl 210/GJ (extrapolated for mass, based on [Kram, 1989]).

Technical life: 1.2 - 3.6 year (420 cycles a year; 500 - 1,500 cycles/battery).

At an estimated average speed of 30 - 50 km/h, this results in 500 - 2,500 working hours. When a driving range of about 75 kilometres is required, the necessary battery pack would have a mass of about 1,500 kg; the available loading capacity would be approximately 400 kg. The energy use for this vehicle is approximately 2.5 MJ/km (6.2 MJ/tonkm).

Calculation of battery mass and cost based on [Dabels, 1992; IDA-1, 1993; I&T, 1993].

Calculation of maintenance costs based on [Dabels, 1992; IDA-1, 1993; I&T, 1993].

Calculation of vehicle costs based on [Wieman, 1994].

Calculation of maintenance costs based on [Kram et al., 1989]; for the ICE vehicle the maintenance costs are approximately Dfl 220/GJ (interpolated), for electric vehicles Dfl 210/GJ. Because electric vehicles are more energy-efficient, this results in lower maintenance costs for electric vehicles.

### 1.1.4 Parameters of short-term batteries for busses

**Energy parameters**

Reference energy use: 13.2 MJ/vehkm (energy efficiency: 21%); this can be compared to an energy use of approximately 0.38 MJ per seat-kilometre.

Energy use with lead-acid battery:

- **1994:** 5.74 MJ/vehkm (energy efficiency: 52%)
- 0.16 MJ/seatkm
- **2010/2015:** (replaced by mid-term technologies)
- **2030/2040:** (replaced by long-term technologies)
Total mass of vehicle: 18,900 kg
Mass of battery-pack: 2,980 kg
Drive range: 50 km

Mass of internal combustion engine bus 16,500 kg, base vehicle mass 16,240 kg (incl. electric motor(s), excl. ICE motor and tanks); reference energy efficiency is estimated. Number of seats: 35. Travel distance/year: 60,000 km [CBS, 1993]. Required driving range in 1994: 50 km. Cruise speed 70 km/h, average speed approximately 30 km/h.

**Economic parameters**

Reference vehicle costs Dfl 245,000;
Reference maintenance costs Dfl 4.88/vehkm (Dfl 0.14/seatkm), based on maintenance costs Dfl 370/GJ [Kram et al., 1989].

Investments (per vehicle) 1994:
- Dfl 12,750 - 23,900 (battery)
- Dfl 272,000 (base vehicle, electric system and adaptations)
- Dfl 284,760 - 295,910 (total vehicle)

Operation and maintenance costs (per kilometre): 270 ct/km or 7.7 ct/skm, based on Dfl 470/GJ [Kram, 1989]

Technical life: 0.4 - 1.3 year (1,200 cycles a year; 500 - 1,500 cycles/battery)
At an estimated average speed of 30 km/h (city) this results in approximately 830 - 2,500 operating hours.

**Note** If a driving range of 150 kilometres is required, the battery-pack would have a mass of about 9 ton, resulting in a total vehicle mass of 25 ton; the energy use would be 7.7 MJ/km.

Calculation of battery mass and cost based on [Dabels, 1992; IDA-1, 1993; I&T, 1993]. Calculation of required energy based on: energy (Wh/vehicle tonkm) = 53 + (76 / vehicle mass) (calibrated on ICE-net.energy use of 0.95 kWh/km for a 16.5 ton vehicle).

### 1.2 Mid-term battery technologies

#### 1.2.1 Description of sodium-sulphur and sodium-metal-chloride batteries

**Definition**
Battery fed from the grid, used to store electricity onboard vehicles. Sodium-based batteries meet the midterm goals of USABC. Their characteristics include a higher energy density (kWh/kg and kWh/l) than (improved) lead-acid batteries.

**Explanation**
The sodium-sulphur battery essentially differs from batteries with a liquid electrolyte, because it has a solid electrolyte ($\beta$-Al$_2$O$_3$), with fluid sodium and sulphur.
With discharging sodium, ions go through the ceramic to the sulphur and compose a salt Na$_2$S$_x$. The sodium-sulphur technology was already patented in 1965 by Ford Motor company. The sodium-metal-chloride battery has a cell which is similar to the sodium-sulphur battery, but which is using a nickel-electrode (nickel-chloride as positive electrode). [Kahlen, 1992; Eriksson, 1992].
Energy functions

The energy-density of sodium sulphur batteries is higher than the energy-density of lead-acid batteries. Theoretically, this will lead to lighter batteries, but because the driving range of lead-acid battery-equipped vehicles is low, we assumed that the driving range will be extended first. This will lead to a somewhat higher mass of the battery and, in comparison with lead-acid batteries, higher battery-costs.

sodium sulphur (NaS)

- working temperature: 300-350 °C
- specific E 2h rate: 100 Wh/kg
- power density: 110 W/kg
- E density 2h rate: 130 Wh/l
- power density: 140 W/l
- cell-voltage (charged): 2.08 V
- self-discharging rate: 15-17% a day (includes heating-energy)
- cycle life: <500 cycles
- costs: <300 Dfl/kWh (220 Dfl/kW projected [Diaz, 1991])

[Kahlen, 1992; Dabels, 1992; IDA-1, 1993; I&T, 1993]

NaS-Pb Cell (Chloride - RWE Energietechnik)

Figure 1.2.1a: example of sodium sulphur cell

sodium metal chloride (ex.: Na/NiCl₂)

- working temperature: 250-370 °C
- specific E 2h rate: 80 Wh/kg
- power density: 100 W/kg
- E density 2h rate: 105 Wh/l
- power density: 130 W/l
- self-discharging rate: 15-17% a day (includes heating energy)
- cycle life: <500 cycles
- costs: <300 Dfl/kWh

[Kahlen, 1992; Dabels, 1992; IDA-1, 1993; I&T, 1993]
The temperature of both types of batteries always has to be approximately 300-350°C. Even when the vehicle is not in use, the battery must constantly be heated, which costs about 90 kW of continuous power. These batteries therefore can only be used effectively in cars which are used frequently.

**Penetration**

If the higher energy-density of the batteries is used to increase the driving range, a larger scale use of full electric vehicles can be expected, especially in intra-city traffic. Some estimates for penetration of electric vehicles (passenger cars) mount to 70%-80% of total vehicles [NOVEM, 1992: only intra city; Kram, 1989: overall], but to be on the safe side a maximum overall penetration of 30% in 2010/2015 [Bossche, 1992] is expected. Estimates for vans were not found, but a same degree of penetration is likely. Around the year 2000, electric busses may be available, so at 2010/2020 15%-20% of the busses can be electric powered (estimate, based on "maximum penetration" estimate of 30% [Kram, 1989].

**Competing technologies**

Competing technologies are other types of batteries and the first fuel-cell vehicles. The other USABC midterm technology is the nickel-metal-hydride battery technology.

**State of development**

Sodium-sulphur batteries are available at the moment (production by ABB Heidelberg), but not widely in use. Some doubts exist about reliability and sodium-sulphur batteries are, at the moment, expensive.

**Current R&D**

Leading institutes are:
- ABB Germany
- Argonne National Laboratory (Ill., USA)
- Sandia National Laboratory (N.M., USA)
- Idaho National Laboratory (Idaho, USA), especially sodium-beta-sulphur technology
- Silent Power, England
- AEG-Anglo American (NaNiCl₂)

[Wallace, 1992; IDA-2, 1993; Wallentowitz, 1994]
Bottlenecks
Risks (fire of sodium) and high temperatures are important points to overcome for the sodium-sulphur batteries. Though there are fewer safety problems, sodium-metal-chloride batteries also have to be kept at high temperatures at all times. This is less desirable for, say, private users. The recharging time can be an important practical bottleneck (see long-term battery technologies).

Availability
Sodium-sulphur batteries are tested in electric vehicles of a.o. Mercedes and BMW. The main producer of sodium-sulphur batteries is ABB. Sodium-metal-chloride batteries are tested in vehicles of German Mail and the Bavarian government. In these fleets, batteries of AEG-Anglo American are used.

1.2.2 Description of nickel-zinc batteries

Definition
Battery fed from the grid, used to store electricity onboard vehicles. Nickel-zinc batteries are no part of the research programme of USABC. Their characteristics include a higher energy density (kWh/kg and kWh/l) than (improved) lead-acid batteries.

Explanation
Nickel-zinc batteries can theoretically offer a remarkable higher power-density, but they offer a lower energy rate compared with sodium-sulphur and sodium-metal-chloride batteries. In some circumstances a nickel-zinc battery will therefore be a better option.

Energy functions
The energy-density of nickel-zinc batteries is higher than the energy-density of lead-acid batteries. Theoretically, this will lead to lighter batteries, but like in the case of NaS batteries, we assumed the driving range will be extended first.

nickel-zinc (NiZn)

- specific E 2h rate: 60 Wh/kg
- power density: 500 W/kg
- E density 2h rate: 100 Wh/l
- power density: 800 W/l
- cycle life: < 500 cycles
- costs: 300-1,000 Dfl/kWh

[Dabels, 1992; IDA-1, 1993]

Penetration
See sodium-sulphur batteries.

Competing technologies
Competing technologies for electric vehicles or other types of batteries and the first fuel-cell vehicles.

State of development
In development from 1978 - 1986 [IDA-1, 1993].

Current R&D
The development of nickel-zinc batteries is stopped, because of the high prices and the relatively short lifetime of the batteries.
**Bottlenecks**
The price and relatively short life-cycle are important points to overcome. The recharging time can be an important practical bottleneck (see long-term battery technologies).

1.2.3 Description of aluminium-air and zinc-air batteries

**Definition**
Battery fed from the grid, used to store electricity onboard vehicles. Aluminium-air batteries are no part of the research programme of USABC. Their characteristics include a higher energy density (kWh/kg and kWh/l) than lead-acid batteries.

**Explanation**
Aluminium-air and zinc-air use air (oxygen) as oxidator, therefore the relative mass can theoretically be less than batteries with a reductor and an oxidator.

**Energy functions**
The energy-density of aluminium-air and zinc-air batteries is higher than the energy-density of lead-acid batteries. The figures for the power-density vary by a factor five. The low estimates lead to a high calculated battery mass, due to the power requirements. When the high estimates are used, somewhat better results were calculated than with other midterm technologies. In that case results (costs) for vans and busses are far more better than using other batteries.

**aluminium-air (Al-O₂)**
- specific E 2h rate: 250 Wh/kg
- power density: 30 - 150 W/kg
- cycle life: unknown
- costs: < 300 Dfl/kWh
[Darbel, 1992; IDA-1, 1993]

**zinc-air (Zn-O₂)**
- specific E 2h rate: 100 - 300 Wh/kg
- power density: 40 - 150 W/kg
- cycle life: 200 cycles
- costs: 100 Dfl/kWh
[Darbel, 1992; IDA-1, 1993]

**Penetration**
If the rather high expectations of zinc-air and aluminium-air batteries come true, these batteries are somewhat better than nickel-zinc batteries, though aluminium-air and zinc-air are more expensive. When the lower estimates of power-density turn out to be correct, the other battery types prevail.

Some estimates for penetration of electric vehicles (passenger cars) mount to 70%-80% of total vehicles [NOVEM, 1992: only intra city; Kram, 1989: overall], but to be on the safe side a maximum overall penetration of 30% in 2010 [Bossche, 1992] is expected.

**Competing technologies**
Competing technologies are other types of batteries and the first fuel-cell vehicles.
State of development, current R&D and bottlenecks

As the "air" technologies are rather new, reliable estimates of costs and capabilities are hard to give: in practice "promising" batteries as sodium-sulphur batteries operate less good than was expected. Note the development of sodium-sulphur batteries started already in 1965 and yet the batteries are not very reliable. The same goes more or less for nickel-zinc batteries. So, by way of conclusion, a lot of research and above all a lot of testing in practice have to be done before the real value of these types of batteries can be determined. Recharging time can be an important practical bottleneck; see also 2030/2040 "bottlenecks".

1.2.4 Parameters of mid-term batteries for passenger cars

Reference energy use 2.56 MJ/vehkm (efficiency: 19%, estimated), 1.71 MJ/seatkm.
Reference vehicle costs Dfl 22,000 [Martin et al., 1992].
Reference maintenance costs Dfl 0.33/km or Dfl 0.22/seatkm (based on Dfl 130/GJ) [Kram et al., 1989].

| Table 1.2.4: Characteristics of mid-term battery technologies for passenger cars |
|---|---|---|---|---|
|   | NaS | NaNiCl₂ | NiZn | Al₂O₃ | ZnO₂ |
| energy use [MJ/km] | 0.90 | 0.91 | 0.88 | 0.85 - 1.30 | 0.85 - 1.21 |
| effective use [MJ/seatkm] | 0.60 | 0.61 | 0.59 | 0.57 - 0.92 | 0.57 - 0.81 |
| efficiency | 73% | 73% | 73% | 73% | 73% |
| range [km] | 180 | 155 | 100 | 350 - 1,095 | 350 - 420 |
| mass [kg] | | | | |
| battery pack | 455* | 500* | 410 | 330* - 1,670* | 330* - 1,250* |
| total vehicle | 1,280 | 1,320 | 1,230 | 1,150 - 2,490 | 1,150 - 2,070 |
| costs [Dfl] | | | | |
| battery pack | 10,000 | 12,000 | 7,330 - 24,440 | 25,000 - 125,000 | 12,500 - 37,500 |
| total vehicle | 31,500 | 33,500 | 28,830 - 45,940 | 46,500 - 146,500 | 34,000 - 59,000 |
| maint. [ct/km] | 13.5 | 14.0 | 13.2 | 12.8 - 20.7 | 13.1 - 18.2 |
| maint. [ct/seatkm] | 9.0 | 9.3 | 8.8 | 8.5 - 13.8 | 8.7 - 12.1 |
| technical life [yr] | 5.5 | 4.8 | 3.0 | 10.7 - 33.0 | 4.5 - 12.8 |
| technical life [hr] | 1,800 - 1,580 | 1,000 - 1,670 | 3,530 - 18,150 | 1,480 - 7,050 |
| vehicle costs: base vehicle Dfl 18,500; electric system and adaptations: Dfl 3,000 (battery excl.) costs are based on Dfl 150/GJ [Kram et al., 1989] |

* mass determined by power requirements (50 kW, peak)
effective energy use per seatkilometre, calculated with 1.5 (average) available seats per passenger car

Notes on technical life and vehicle costs: see Table 1.2.4.
Higher energy-efficiency is obtained by better battery loading-unloading efficiency (now 90%) and the assumption that in an electric vehicle a transmission system is no longer needed. For reference values, the 1994 vehicle is used. For the electric vehicle only improvements on batteries and engines are included, while the transmission system is omitted (base vehicle mass, air resistance etc. are the same). The improvements of battery characteristics first are used to increase the driving range, which is now 100 km. Technical life for most battery-types: 3 years (165 cycles a year, 500 cycles/battery). For the calculation of maintenance costs, the 2020 estimates of Dfl 150/GJ are used [Kram et al., 1989].

For most mid-term batteries, the required power is important. Some authors think this will pose no problems because super capacitors would be used. These capacitors would have a very high efficiency (100%) and a very high capacity (10 Wh/kg) [I&IT, 1993]. If super capacitors really can be used, the battery mass and as a consequence the energy use will be remarkably less if the range is limited to 100 kilometres (as is the case with nickel zinc batteries).

For zinc-air batteries (for example), the introduction of super capacitors would mean:
- energy use 0.75 - 0.81 MJ/vehkm (0.50 - 0.54 MJ/seatkm)
- battery mass 69 - 225 kg, vehicle mass 890 - 1050 kg., mass for capacitor (10 kW/kg) included
- battery costs Dfl 2.250 - Dfl 6.750 (excl. costs for capacitor because these costs are unknown)

Environmental parameters

Full electric vehicles cause no local emissions: full electric vehicles are zero emission vehicles. The use batteries can pose environmental problems in case of accidents and at the end of a car-life: the batteries have to be disposed of or have to be reused. In sodium-sulphur batteries only common materials are used. Sodium-sulphur batteries pose some safety problems (danger of explosion).

1.2.5 Parameters of mid-term batteries for vans

Reference energy use: 6.48 MJ/vehkm (energy efficiency: 20%); this means 3.74 MJ per tonne-kilometre (payload 1.735 ton).

Reference vehicle costs Dfl 45,000 (ICE-van) [Wieman, 1993].

Reference maintenance costs Dfl 1.43/vehkm or Dfl 0.82/tonkm (interpolated cost estimate of Dfl 220/GJ, based on [Kram et al., 1989]).

For results, see table 1.2.5 (next page).
Table 1.2.5: Characteristics of mid-term battery technologies for vans

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>NaS</th>
<th>NiNaCl₂</th>
<th>NiZn</th>
<th>AιO₂</th>
<th>ZnO₂</th>
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<td>Energy</td>
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<td>Use [MJ/km]</td>
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<td>100</td>
<td>100</td>
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<td>200 - 250</td>
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<tr>
<td>Battery Pack</td>
<td>500</td>
<td>620</td>
<td>820</td>
<td>330 - 1,667</td>
<td>330 - 1,250*</td>
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<td>Maintenance [ct/km]</td>
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<td>1,000-1,670</td>
<td>1,000 - 1,670</td>
<td>1,690 - 14,060</td>
<td>1,010 - 3,380</td>
</tr>
</tbody>
</table>

*1 mass determined by power requirements (50 kW, peak)

effective energy use per loading tonne-kilometre

effective maintenance costs per loading tonne-kilometre

Notes:

- Standard range is 100 km, for vehicles where power requirements determine the mass of the battery pack, the range is calculated.
- Vehicle costs: base vehicle Dfl 34,500; electric system and adaptations Dfl 7,000 (battery excl.)
- Maintenance costs are based on Dfl 190/GJ (extrapolated for mass, base: [Kram et al., 1989])

For aluminium-air and zinc-air batteries, the power requirements are important. If the use of super capacitors would be possible, the battery mass and so the energy use (per tonne-kilometre) will be remarkably less if the range is limited to 100 kilometres (as is the case with the other mid-term batteries).

For zinc-air batteries (for example) the introduction of super capacitors would mean:

- Energy use 1.78 MJ/vehkm (1.03 - 1.27 MJ/tkm)
- Battery mass 165 - 494 kg, loading capacity 1.406 - 1.730 kg.
- Battery costs Dfl 4.938 - Dfl 14.815 (excl. costs for capacitor because these are unknown)

1.2.6 Parameters of mid-term batteries for busses

Reference energy use: 13.2 MJ/vehkm (energy efficiency: 21%); this can be compared to an energy use of approximately 0.38 MJ per seat-kilometre.

Reference vehicle costs Dfl 245,000.

Reference maintenance costs Dfl 4.88/vehkm (Dfl 0.14/seatkm);

based on maintenance costs of Dfl 370/GJ [Kram et al., 1989]
Table 1.2.6: Characteristics of mid-term battery technologies for buses

<table>
<thead>
<tr>
<th></th>
<th>NaS</th>
<th>NaNiCl₂</th>
<th>NiZn</th>
<th>Al₂O₃</th>
<th>ZnO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>use [MJ/km]</td>
<td>4.19</td>
<td>3.37</td>
<td>4.71</td>
<td>3.82</td>
<td>4.41</td>
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<tr>
<td>ef. use [MJ/vehkm]</td>
<td>0.12</td>
<td>0.12</td>
<td>0.13</td>
<td>0.11</td>
<td>0.13</td>
</tr>
<tr>
<td>efficiency</td>
<td>73%</td>
<td>73%</td>
<td>73%</td>
<td>73%</td>
<td>73%</td>
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<tr>
<td>range [km]</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250 - 820</td>
<td>250 - 280</td>
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<tr>
<td>mass [kg]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>battery pack</td>
<td>2,910</td>
<td>3,790</td>
<td>5,450</td>
<td>1,060</td>
<td>4,000 - 4,000²</td>
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<tr>
<td>total vehicle</td>
<td>18,830</td>
<td>19,710</td>
<td>21,370</td>
<td>16,980</td>
<td>18,920</td>
</tr>
<tr>
<td>costs [Dfl]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>battery pack</td>
<td>64,060</td>
<td>91,060²</td>
<td>98,060</td>
<td>79,550 - 300,000</td>
<td>30,000 - 90,000</td>
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<tr>
<td>total vehicle</td>
<td>295,560</td>
<td>322,560</td>
<td>329,560</td>
<td>311,050 - 531,500</td>
<td>261,500 - 321,500</td>
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<tr>
<td>maint. [ct/km]</td>
<td>186.6</td>
<td>194.5</td>
<td>209.5</td>
<td>169.9</td>
<td>166.3</td>
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<tr>
<td>maint. [ct/vehkm]</td>
<td>5.3</td>
<td>5.6</td>
<td>6.0</td>
<td>4.9</td>
<td>4.8</td>
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<tr>
<td>technical life [yr]</td>
<td>2.1</td>
<td>2.1</td>
<td>4.170</td>
<td>1,710 - 4,170</td>
<td>1,710 - 4,170</td>
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<tr>
<td>technical life [hr]</td>
<td>4.170</td>
<td>4.170</td>
<td>4.170</td>
<td>4.170</td>
<td>4.170</td>
</tr>
</tbody>
</table>

¹ mass determined by power requirements (120 kW, estimated)
² lowest cost estimate

Notes:
- ef.use [MJ/vehkm]: effective energy use per seat-kilometre
- maint. [MJ/vehkm]: effective maintenance costs per seat-kilometre
- range: standard range is 250 km, for vehicles where power requirements determine the mass of the battery pack, the range is calculated
- vehicle costs: base vehicle Dfl 218,000; electric system and adaptations Dfl 13,500 (battery pack excl.)
- maintenance: costs are based on Dfl 445/GJ [Kram et al., 1989]

For aluminium-air and zinc-air batteries the power requirements are important. If the use of super capacitors would be possible, the battery mass and so the energy use (per seat-kilometre) will be remarkably less if the range is limited to 250 kilometres (as is the case with the other mid-term batteries).

For zinc-air batteries (for example) the introduction of super capacitors in buses would mean:
- energy use 3.78 - 4.20 MJ/vehkm (0.108 - 0.120 MJ/seatkm)
- battery mass 875 - 2.914 kg, total vehicle mass 16.8 - 18.8 ton (includes mass of capacitor).
- battery costs Dfl 29,144 - Dfl 87,433 (excl. costs for capacitor)

1.3 Long term battery technologies

1.3.1 Description of lithium-based batteries and US-ABC goals

Definition
Battery fed from the grid, used to store electricity onboard vehicles. Li-based batteries meet the long-term goals of USABC. Their characteristics again include a higher energy density (kWh/kg and kWh/l) than mid-term battery technologies.
**Explanation**

The lithium electrode from the Li/MnO\(_2\) battery will be changed to a carbon electrode that stores the lithium ions [Kahlen, 1992].

**Energy functions**

The lithium-based batteries have a higher energy-density than the sodium-sulphur type batteries, so by the same energy-output they are lighter. In comparison with sodium-sulphur batteries the lithium-iron-disulphide battery’s specific energy rate is improved by 65% and the power-density by 81%.

<table>
<thead>
<tr>
<th>lithium-iron-(di)sulfide (LiAl-FeS(_2))</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>working temperature: 400 °C</td>
<td></td>
</tr>
<tr>
<td>specific E 2h rate: 165 Wh/kg - 100 Wh/kg [Wallentowitz, 1994]</td>
<td></td>
</tr>
<tr>
<td>power density: 200 W/kg</td>
<td></td>
</tr>
<tr>
<td>E density 2h rate: 225 Wh/l</td>
<td></td>
</tr>
<tr>
<td>power density: 255 W/l</td>
<td></td>
</tr>
<tr>
<td>cycle life: &lt;500 cycles</td>
<td></td>
</tr>
<tr>
<td>costs: 300-1000 Dfl/kWh</td>
<td></td>
</tr>
<tr>
<td>cell voltage: 3 V.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>lithium polymer</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>working temperature: 10-45°C</td>
<td></td>
</tr>
<tr>
<td>specific E 2h rate: 100 Wh/kg</td>
<td></td>
</tr>
<tr>
<td>power density: 200 W/kg</td>
<td></td>
</tr>
<tr>
<td>E density 2h rate: 75 Wh/l</td>
<td></td>
</tr>
<tr>
<td>power density: 160 W/l</td>
<td></td>
</tr>
<tr>
<td>cycle life: &lt;500 cycles</td>
<td></td>
</tr>
<tr>
<td>costs: &lt;300 Dfl/kWh</td>
<td></td>
</tr>
</tbody>
</table>

[Kahlen, 1992; Debels, 1992; IDA-1, 1993; I&T, 1993]

**US-ABC goals**

| working temperature: (not specified)     |  |
| specific E 2h rate: 200 Wh/kg            |  |
| power density: 400 W/kg                  |  |
| E density 2h rate: (not specified)       |  |
| power density: (not specified)           |  |
| cycle life: 1000 cycles                  |  |
| costs: 100 Dfl/kWh                       |  |

Lithium-iron-(di)sulfide batteries only operate under high temperatures: battery management systems are necessary. Advantage of the lithium-iron-(di)sulfide batteries is their safety: they do not explode or cause leakage of dangerous materials.

In case of lithium-polymer batteries the negative electrode is replaced by an organic electrode. An important advantage of the lithium-polymer batteries is the lower working temperature: although some temperature control system will be necessary (winter periods), the desired temperatures are easier to maintain. Another interesting advantage of lithium-polymer batteries is the fact that they can be moulded: they can be "stowed away" in specially designed electric vehicles.
Penetration
Although better results (drive range, acceleration, speed etc.) can be achieved with lithium-based batteries than lead-acid batteries and even most mid-term battery technologies, yet the typical "battery-characteristics" are important. The drive range is still smaller than of comparable internal combustion-engine (ICE) vehicles. The total mass of the batteries, motor(s) and other driving systems is still higher than of comparable ICE-vehicles. For (incidental) long distances and very intensive use of cars, full electric vehicles simply are not able to meet with the performance of ICE-vehicles. Estimates of 80% (overall, "changeable battery package") [Kram et al., 1989] are made. Estimates for vans are not given, but the same maximum share as passenger cars is realistic. For busses a maximum share of 30% is estimated [Kram et al., 1989]. Compared to the high estimations for passenger cars, 50% does not seem to be unrealistic (from the technological point of view). In the 20-year period (2015 - 2035) most busses will be replaced (since the introduction of short-term and mid-term technologies).

Competing technologies
When lithium-based batteries will be on the market, it is possible that (advanced) fuel-cell systems are available too. When this is the case, a strong competition can be expected. It is however more likely that lithium-based batteries will be available earlier than fuel-cells. Other competing technologies are mid-term battery technologies (which will be fully developed when lithium-based batteries come in sight).

State of development
(Small) lithium-based batteries are widely used, for example in computers, but these batteries are not rechargeable. The long-term lithium technologies presently exist only at small cell level and their development is focused on building fundamental electro-chemistry in laboratory experiments [Wallace, 1994; IDA-1, 1993].

Current R&D
Current R&D about lithium-iron-(di)sulphide batteries is done in Europe and the United States (USABC consortium), especially by the Argonne National Laboratory and SAFT America. Research on lithium-polymer batteries is done by WR Grace/Johnson, Delco Remy/Valence, Sandia National Laboratory and Lawrence Berkely Laboratory. Also Sony, Yuasa Battery Company (Japan) and Varta (Germany) are working on lithium-based batteries.

Bottlenecks
One of the problems is the high temperature the lithium-iron-(di)sulphide battery needs to function: to keep the battery on the right temperature a special battery-management has to be installed. A practical bottleneck can be the charging time of the battery; when this charging time can not be less than 5-15 minutes (maximum refuelling-time of gasoline car), users need special time and space for charging. At charging times of several hours, the car must be parked at special designed load stations or in garages. This can be a problem for car-owners who have to park their car on streets or in open parking facilities.

Availability
Batteries for electric vehicles will be on the market around 2000-2005 [IDA-1, 1993]. The lithium-polymer batteries will on the market at a later stage.
1.3.2 Parameters of long-term batteries for passenger cars

For 2030 three calculations have been made. The first and second calculations are based on expectations of developments of lithium-based batteries; the third calculation is based on USABC goals. These USABC goals only refer to batteries: all other parameters are unchanged.

Reference energy use: 2.56 MJ/vehkm (energy efficiency: 19%), 1.71 MJ/seatkkm (1.5 seats per vehicle available).
Reference vehicle costs Dfl 22,000 [Martin et.al., 1992].
Reference maintenance costs Dfl 0.33/km or Dfl 0.22/seatkkm, based on Dfl 130/GJ [Kram et.al., 1989].

| Table 1.3.2: Characteristics of long-term battery technologies for passenger cars |
|-----------------|-----------------|-----------------|
|                 | LiAlFeS₂         | Li-Polymer       | US-ABC (goals)  |
| energy use [MJ/km] | 0.77             | 0.77             | 0.86             |
| ef.E.use [MJ/seatkkm] | 0.52             | 0.52             | 0.58             |
| efficiency       | 77%              | 77%              | 75%              |
| range [km]       | 190              | 120              | 105              |
| mass [kg]        |                  |                  |                  |
| battery pack     | 250 *            | 250 *            | 165 *            |
| total vehicle    | 1,070            | 1,070            | 945              |
| costs [Dfl]      |                  |                  |                  |
| battery pack     | 9,075 - 41,250   | 5,500 - 7,500    | 2,500            |
| total vehicle    | 30,575 - 62,750  | 54,000 - 29,000  | 24,000           |
| maintenance [ct/km] | 9.7             | 9.7             | 10.8             |
| maintenance [ct/seatkkm] | 6.5             | 6.5             | 7.2             |
| technical life [years] | 5.8             | 3.5             | 6.3             |
| technical life [hours] | 1,920 - 3,190   | 1,160 - 1,940   | 2,080 - 3,470   |

Higher energy-efficiency is obtained by better battery loading-unloading efficiency (now 95%) and the assumption that a transmission is no longer needed. As reference value, the 1994 vehicle is used. For the electric vehicle only improvements on batteries, engines and transmission systems are included. (VDI estimates 11 - 25% higher prices for electric vehicles in comparison with ICE vehicles; this would mean Dfl 24,400 - 27,500, which is in the same range as US-ABS goals [VDI, 1992]).

If super capacitors have the efficiency and capacity as expected by some authors and these capacitors would be available, the use of these capacitors would mean an important decrease in energy use (if the range of the vehicles is limited to 100 kms). This decrease is to be expected because for all long term batteries the power requirements are important.
For LiAlFeS$_2$ batteries (for example), the introduction of super capacitors would mean:

- energy use 0.73 MJ/vehkm (0.487 MJ/seatkm)
- battery mass 123 kg, total vehicle mass 950 kg (includes mass of capacitor).
- battery costs Dfl 4,460 - 20,273 (excl. costs for capacitor because these costs are unknown)

**Environmental parameters**

The use of (full) electric vehicles causes no local emissions: full electric vehicles are zero emission vehicles. The batteries can pose environmental problems in accidents and at the end of a car-life: the batteries have to be disposed of or have to be reused.

In sodium-sulphur batteries only common materials are used. Sodium-sulphur batteries pose some safety problems (danger of explosion).

### 1.3.3 Parameters of long-term batteries for vans

Reference energy use: 6.48 MJ/vehkm (energy efficiency: 20%, estimated); this can be compared to an energy use of approx. 3.73 MJ per ton-kilometre (payload 1.735 ton).

Reference vehicle costs Dfl 45,000 (ICE-van) \cite{Wieman1993}.

Reference maintenance costs Dfl 1.43/vehkm or Dfl 0.82/tonkm (interpolated cost estimate of Dfl 220/GJ, based on \cite{Kram1989}).

| Table 1.3.3: Characteristics of long-term battery technologies for vans |
|--------------------------|--------------------------|--------------------------|
|                         | LiAlFeS$_2$             | Li-polymer               | US-ABC (goals)           |
| energy                  |                          |                          |                          |
| energy use [MJ/km]      | 1.68                    | 1.68                    | 2.00                     |
| ef.E.use [MJ/tonkm]     | 1.04                    | 1.18                    | 1.23                     |
| efficiency              | 77%                     | 77%                     | 65%                      |
| range [km]              | 100                     | 100                     | 100                      |
| mass [kg]               |                          |                          |                          |
| battery pack            | 280                     | 470                     | 280                      |
| total vehicle           | 3,500                   | 3,500                   | 3,500                    |
| loading capacity        | 1,620                   | 1,430                   | 1,620                    |
| costs [Dfl]             |                          |                          |                          |
| battery pack            | 10,300 - 46,800         | 10,300 - 14,040         | 5,560                    |
| total vehicle           | 51,790 - 88,280         | 51,790 - 55,540         | 47,060                   |
| maintenance [ct/km]     | 26.9                    | 26.9                    | 32.0                     |
| maintenance [ct/tonkm]  | 16.6                    | 18.8                    | 19.7                     |
| technical life [years]  | 2.4                     | 2.4                     | 4.8                      |
| technical life [hours]  | 1,000 - 1,670           | 1,000 - 1,670           | 2,000 - 3,300            |

**notes**

- ef.E.use [MJ/tkm]: effective energy use per loading ton-kilometre
- maintenance [ct/tkm]: effective maintenance costs per loading ton-kilometre
- range: standard range is 100 km
- vehicle costs: base vehicle and electric system Dfl 41,500 (see mid-term technologies)
- maintenance: costs based on Dfl 160/GJ (extrapolated for time and mass, base: \cite{Kram1989})
1.3.4 Parameters of long term batteries for busses

Reference energy use: 13.2 MJ/vehkm (energy efficiency: 21%); this is approximately 0.38 MJ per seat-kilometre.
Reference vehicle costs Dfl 245,000.
Reference maintenance costs Dfl 4.88/vehkm (Dfl 0.14/seatkm); based on maintenance costs Dfl 370/GJ [Kram et.al., 1989].

Table 1.3.4: Characteristics of long-term battery technologies for busses

<table>
<thead>
<tr>
<th></th>
<th>LiAlFeS₂</th>
<th>Li-polymer</th>
<th>US-ABC (goals)</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>energy use [MJ/km]</td>
<td>3.71</td>
<td>3.94</td>
<td>4.40</td>
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<tr>
<td>ef.E.use [MJ/seatkm]</td>
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<td>0.11</td>
<td>0.13</td>
</tr>
<tr>
<td>efficiency</td>
<td>77%</td>
<td>77%</td>
<td>65%</td>
</tr>
<tr>
<td>range [km]</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>mass [kg]</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>battery pack</td>
<td>1,560</td>
<td>2,730</td>
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<tr>
<td>total vehicle</td>
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<td></td>
</tr>
<tr>
<td>battery pack</td>
<td>56,730 - 257,860</td>
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<tr>
<td>total vehicle</td>
<td>288,230 - 489,360</td>
<td>291,660 - 313,530</td>
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<td>maintenance [ct/km]</td>
<td>156.0</td>
<td>165.4</td>
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<td>maintenance [ct/skm]</td>
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<td>5.3</td>
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<tr>
<td>technical life [years]</td>
<td>2.1</td>
<td>2.1</td>
<td>4.2</td>
</tr>
<tr>
<td>technical life [years]</td>
<td>4,170</td>
<td>4,170</td>
<td>8,330</td>
</tr>
</tbody>
</table>

ef.E.use [MJ/seatkm]: effective energy use per seat kilometre
maintenance [ct/skm]: effective maintenance costs per seat kilometre

Notes:
- standard range is 250 km
- vehicle costs: base vehicle and electric system Dfl 231,500 (see mid-term technologies)
- maintenance: costs based on Dfl 420/GJ (extrapolated value, base: [Kram et.al., 1989])

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2 FUEL-CELLS

In this chapter fuel-cells will be discussed. Fuel-cells convert fuel directly into electricity, without a combustion process and without moving parts. Unlike a battery, the fuel-cell generates power from fuel stored onboard the vehicle. The main features of the fuel-cell system are the fuel, the oxidant (oxygen from the air), and two electrodes with an electrolyte sandwiched between them. By removing the intermediate step of combustion, fuel-cells would virtually eliminate automotive air pollution and would be two and a half to three times as efficient as internal combustion engine vehicles.

Note Developments in the field of electric motor technology, transmission systems for electric vehicles and motor management systems are included in the figures mentioned in this chapter. The developments are briefly discussed in the third chapter of this second part.

2.1 PEM fuel-cells

2.1.1 Description of PEM fuel-cells

Definition
In a Proton Exchange Membrane fuel-cell (PEM) hydrogen fuel is converted into electricity without a combustion process. The hydrogen fuel is stored on board the vehicle or is extracted from ethanol, methanol or CNG by a "reformer". The PEM fuel-cell works at a relatively low operating temperature (up to 100 °C) [RDE, 1993; Swan, 1992].

Explanation
The construction of fuel-cells resembles the construction of batteries, but the way they work is different. The electrolyte of the PEM fuel-cell is a membrane of activated fluor polymer. The "fuels" are hydrogen (which may carry 1% of CO at most) and air (oxygen). The membrane functions as a proton conductor; platinum is used as a catalyst.

The reactions in the cell are as follows:
Anode reaction: \( \text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^- \)
Cathode reaction: \( \text{O}_2 + 4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2\text{O} \) (water production)
(Operating temperature: 50 - 100 °C)

Individual low-voltage fuel-cells are packed in so called "stacks", just like accumulator cells are packed in "batteries". Figure 2.1.1 (next page) shows in a schematic way the operation of a (single) fuel-cell.

The hydrogen fuel has to be stored in specially designed tanks (higher pressure in comparison with ordinary LNG-tanks). Another possibility is to obtain hydrogen from ethanol (or methanol or CNG). Ethanol is easier to transport and to store than hydrogen, but to obtain hydrogen, a reformer is necessary. This reformer adds complexity and (much) weight to the system. Besides the reformer a "preoxidizer" is needed to remove CO.

In the following, the use of hydrogen fuel and the storage of hydrogen on board the vehicle is assumed, so there is no need for a reformer and a preoxidizer. PEM fuel-cells have to be cooled (by water) and only work under pressure: a lot of extra machinery will be necessary to let the cell work [RDE, 1993]. A vehicle equipped with a fuel-cell and
without a reformer only produces energy and water: vehicles cause no air-pollution (although somewhere hydrogen has to be produced).

Energy functions
Application is theoretically possible in all kinds of vehicles. Initially fuel-cells will mainly be used in busses and trucks because of the weight and volume of the first generation hydrogen tanks, but also due to the enormous costs. A fuel-cell can produce 0.2 - 0.4 kW/kg. The storage capacity of (potential) energy in hydrogen tanks is about 660 Wh/kg. In later years this can be increased up to 3300 Wh/kg [Swan, 1992].

Penetration
When it will be possible to create lightweight hydrogen-tanks and when it is indeed possible to make relatively cheap PEM fuel-cells, a penetration of 100% for electric cars and vans is, theoretically, achievable in 2030/2040. This because the characteristics of PEM fuel-cell powered vehicles are almost the same as the characteristics of present combustion engine powered vehicles. Although refuelling time, the radius of action and especially costs and weight will at first performance be important disadvantages of fuel-cell vehicles. Because the optimistic forecasts of costs can be questioned, it is likely that a high degree of penetration only can be achieved by strong (local) environmental demands.

For busses relatively small (and lightweight) fuel-cells will first be available around 2000 - 2010 (estimated, others say 2000 [BPS, 1993]). The estimated degree of penetration of 30% in 2020 [Kram et al., 1989] seems to be possible. For 2030/2040 there are no estimates, but when fuel-cells with good characteristics (weight, volume) are on the market in 2010, in 2030/2040 all busses in theory can be replaced.

For trucks no estimates are given. Because for trucks the payload (weight and volume) is important, only relatively lightweight and small fuel-cells can be used. If useful fuel-cells for busses will become available in 2000, it will take some extra time to introduce

---

Figure 2.1.1: single cell schematic
(more powerful) fuel-cells for trucks. The degree of penetration in 2015/2020 will therefore be very low. In 2030/2040 some 30% of all trucks (same as 2020 estimate for busses) will possibly be equipped with fuel-cells.

**Competing technologies**
Other types of fuel-cells are Phosphoric-acid, Molten Carbonate, Solid Oxide (around 2015 on the market) and Alkaline fuel-cells. However, the PEM fuel-cell is considered to be the most promising type of fuel-cell with regard to transport, maybe with the exception of the Monolithic Solid Oxide Fuel-Cell (MSOFC). These MSOFC fuel-cells have high efficiencies and have a more simple way of construction and use [RDE, 1993]. Also competitive are advanced batteries.

**State of development**
The only fuel-cell vehicles until now are technology demonstration vehicles, not equipped with any type of motor management. Most fuel-cells are in use for military purposes (not only for vehicles). A field-test will be carried out in 1996; the use in large fleets can be expected in 2000-2005. Mass production is possible in 2010, applications in busses around the year 2000 [Van den Broeck, 1994; Ballard 1994].

**Current R&D**
Most of the research and development is carried out by industry. Examples are ELENCO (Belgium), Ballard Power Systems in (Canada), Mitsubishi Heavy Industries, Sumimato Electric (Japan), International Fuel-cells, Energy Partners, Allied Signal, Analytic Power, Delco-Remy (GM), Allison Gas Turbine Division (GM) (all USA) and Siemens (Germany) [Teagan]. Most research is directed to stationary appliances.

**Bottlenecks**
The most important bottleneck is the price, caused by the platinum catalyst in particular and by the bipolar plates (polymer) and the membrane (all "materials-costs"). At the moment, research on fuel-cells is aimed at the reduction of the platinum loading and at cheaper materials (anode/cathode, membrane). Problems are the weight of the hydrogen storage-tanks (although less then the weight of advanced batteries) and of the reformer (in case methanol, ethanol or CNG is used). Also a problem is the storage of hydrogen: in a day 0.5 to 3% of the stored hydrogen evaporates, even from the most sophisticated tanks. This leakage poses safety risks. Furthermore, 10-25% of the fuel is lost during refuelling of cryogenic hydrogen, due to "boiling off" [IEA, 1993]. Practical bottlenecks for users will be the limited availability of hydrogen refuelling stations and the rather complicated refuelling process (there is already a big difference in LPG-refuelling in comparison with gasoline refuelling). Unless "hybrid" fuel-cell cars will be developed, large scale use of these type of vehicle is only possible in combination with a rather dense fuel-supply network.

**Availability**
At the moment, only test-applications have been made, for example in busses [BPS, 1993]; possibly in the last years of this century fuel-cell powered busses will be produced. Applications in other electric vehicles are foreseen around 2010-2015 [Van den Broeck, 1994].
2.1.2 Parameters of PEM fuel-cells for passenger cars

Reference energy use: 2.56 MJ/vehkm (energy efficiency: 19%), effective energy use: 1.71 MJ/seatkilometre (average: 1.5 available seats per passenger car).
Reference vehicle costs Dfl 22,000 [Martin et al., 1992].
Reference maintenance costs Dfl 0.33/km or Dfl 0.22/seatkm, based on Dfl 130/GJ [Kram et al., 1989].

<table>
<thead>
<tr>
<th>Table 2.1.2: Characteristics of fuel-cell technologies for passenger cars</th>
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<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>energy</td>
</tr>
<tr>
<td>energy use [MJ/km]</td>
</tr>
<tr>
<td>ef.E.use [MJ/seatkm]</td>
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<tr>
<td>efficiency</td>
</tr>
<tr>
<td>range [km]</td>
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<tr>
<td>mass kg]</td>
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<tr>
<td>fuel-cell¹</td>
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<tr>
<td>hydrogen tank</td>
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<tr>
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<td>costs [Dfl]</td>
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<td>hydrogen tank</td>
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<tr>
<td>total vehicle</td>
</tr>
<tr>
<td>maintenance [ct/km]</td>
</tr>
<tr>
<td>maintenance [ct/seatkm]</td>
</tr>
<tr>
<td>technical life [hours]</td>
</tr>
</tbody>
</table>

¹ "mass of fuel-cell" includes auxiliary equipment like cooling plates, a humidification section, end plates, circulation pumps and an air compressor [based on Swan, 1992].
² "costs of fuel-cell" can be seen as costs for fuel-cell and auxiliary equipment, because these costs will be marginal in comparison with fuel-cell costs, though these costs were not included in the calculations by [Swan, 1992].
ef.E.use [MJ/seatkm]: effective energy use per seatkilometre, calculated with 1.5 (average) available seats per passenger car
maintenance [ct/seatkilometre]: effective maintenance costs per seatkilometre
technical life [years]: based on [Kram et al., 1989], values between brackets based on average mileage and on operation hours
vehicle costs: base vehicle costs, electric system included, Dfl 31,500 (1994) - 21,500 (2015/2020 and 2030/2040); costs for fuel-cell and tanks not included in base vehicle costs; estimates based on [Martin, 1982; Swan, 1992].
maintenance: costs based on Dfl 230/GJ (1994), Dfl 180/GJ (2010/2015), Dfl 130/GJ (2020/2030); costs are based on costs for buses; costs for 2020/2030 based on extrapolated bus costs [Kram et al., 1989].

Mass of internal combustion engine vehicle 920 kg, base vehicle mass 870 kg (incl. electric motor(s) and 50 kg starting-battery package, excl. ICE and tank). Travel distance/year: 16,500 km [CBS, 1993]. Required driving range 560 km [IEA, 1993], "cruise" speed 70 km/h [Martin, 1992].

**note** Although data for 1994 and 2010/2015 are given, fuel-cell powered passenger cars will probably not be used in these periods. The above figures are based on hydrogen as a fuel, so there is no need for a reformer.
Estimates of costs of fuel-cells vary enormously; there are several reasons:

- it is not at all clear what will be the smallest amount of platinum needed (platinum loading); as platinum is very expensive (about Dfl 130/g), this is an important factor;
- in a PEM fuel-cell several specific materials are used; these materials are expensive now, but it is uncertain what the costs will be in the future
- primary sources do rather not make estimates about future costs, so most estimates are done by "desk-researchers".

Rather high cost estimates are made by Swan [Swan, 1992]: Dfl 4,350/kW, while low costs estimates are given by Kram [Kram et.al., 1989]: Dfl 300/kW. For 2020/2030 the maximum costs are estimated, based on a lower platinum use [Swan, 1992] and a 66% reduction of costs for the bipolar plate.

The (average) 2010/2015 estimates for a complete fuel-cell passenger car, Dfl 70,000, are higher than the Dfl 48,000 estimates by Delucci [Williams, 1994]. The average 2020/2030 estimates for the fuel-cell costs (Dfl 11,650) are higher than the Dfl 8,000 estimates for the fuel-cell and power system by Kuhn [Williams, 1994].

In none of the examined reports and interviews estimates for the operation and maintenance costs have been made. The common opinion is that these estimates are not useful because there is too less experience in this field [Van den Broeck, 1994]. For this study, O + M costs are based on estimates of fuel-cell O + M costs for busses [Kram et.al., 1989]; cost ratios for electric battery-vehicles have been used.

Technical life of fuel-cells is at the moment hard to estimate. Estimated is 5,000 to 10,000 hours of operation, but reliable data are not available [Van den Broeck, 1994]. At an average speed of 30 - 50 km/h and an average driving distance of 16,500 kilometres/year, this results in 330 - 550 operational hours a year. Thus the replacement period of fuel-cells in passenger cars can be estimated at 9 - 30 years. From the point of view of investment costs, it is very unlikely fuel-cells will be used (and sold) that cannot be used a full car lifetime.

Environmental parameters

Emissions
If hydrogen is used as a fuel, water is the only "emission". If methanol and a reformer are used, CO$_2$ is the most important emission. Because of the higher efficiency of the fuel-cell, it produces less CO$_2$ than a combustion engine of the same capacity [Kram et.al., 1989].

Materials
The only material that is relatively limited, is the platinum used as a catalyst.

2.1.3 Parameters of PEM fuel-cells for vans

Reference energy use: 6.48 MJ/vehkm (energy efficiency: 20%); this is approximately 3.73 MJ per tonne-kilometre (payload 1.735 ton).

Reference vehicle costs Dfl 45,000 (ICE-van) [Wieman, 1993].

Reference maintenance costs Dfl 1.43/vehkm or Dfl 0.82/tonkm (interpolated cost estimate of Dfl 220/GJ, based on [Kram et.al., 1989]).
<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Energy</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Energy use [MJ/km]</td>
<td>2.61</td>
<td>2.22</td>
<td>2.22</td>
</tr>
<tr>
<td>Efficiency [MJ/tonkm]</td>
<td>6.12</td>
<td>1.75</td>
<td>1.64</td>
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<tr>
<td><strong>Range</strong></td>
<td>560</td>
<td>560</td>
<td>560</td>
</tr>
<tr>
<td><strong>Mass [kg]</strong></td>
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<td></td>
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<tr>
<td>Fuel-cell</td>
<td>760</td>
<td>430</td>
<td>340</td>
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<td>Hydrogen tank</td>
<td>610</td>
<td>105</td>
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<tr>
<td>Total vehicle</td>
<td>3,500</td>
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<tr>
<td>Loading capacity</td>
<td>430</td>
<td>1,260</td>
<td>1,350</td>
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<td><strong>Costs [Dfl]</strong></td>
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<td></td>
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<tr>
<td>Fuel-cell</td>
<td>220,450</td>
<td>12,920 - 187,380</td>
<td>12,920 - 37,500</td>
</tr>
<tr>
<td>Hydrogen tank</td>
<td>1,660 - 3,110</td>
<td>1,410 - 2,640</td>
<td>1,410 - 2,640</td>
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<td>Total vehicle</td>
<td>284,610 - 286,060</td>
<td>55,830 - 313,530</td>
<td>55,830 - 81,620</td>
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<tr>
<td><strong>Maintenance [ct/km]</strong></td>
<td>73.0</td>
<td>51.0</td>
<td>37.7</td>
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<tr>
<td><strong>Technical Life [years]</strong></td>
<td>10 (7 - 25)</td>
<td>10 - 15 (7 - 25)</td>
<td>15 (7 - 25)</td>
</tr>
<tr>
<td><strong>Technical Life [hours]</strong></td>
<td>5,000 - 10,000</td>
<td>5,000 - 10,000</td>
<td>5,000 - 10,000</td>
</tr>
</tbody>
</table>

*1 "mass of fuel-cell" includes auxiliary equipment like cooling plates, a humidification section, end plates, circulation pumps and an air compressor. [Swan, 1992]

*2 "costs of fuel-cell" can be seen as costs for fuel-cell and auxiliary equipment, because these costs will be marginal in comparison with fuel-cell costs, though these costs were not included in the calculations by [Swan, 1992].

ef.E.use [MJ/tonkm]: effective energy use per loading tonnekilometre, calculated with the available loading capacity;

maintenance [ct/km]: effective maintenance costs per loading tonnekilometre;

technical life [years]: based on [Kram et.al., 1989], values between brackets based on average mileage and on operation hours

technical life [years]: (Van den Broeck (rough estimate) 1994)

vehicle costs: base vehicle costs, electric system included, Dfl 62,500 (1994) - 41,500 (2015/2020 and 2030/2040); costs for fuel-cell and tanks not included in base vehicle costs

maintenance: costs based on Dfl 280/GJ (1994), Dfl 230/GJ (2010/2015), Dfl 170/GJ (2020/2030); (based on costs for busses; costs for 2020/2030 based on extrapolated bus costs, base for estimates: [Kram et.al., 1989])

Mass of vehicle, including maximum loading, 3,500 kg. Base vehicle mass 1,600 kg (incl. electric motor(s)) [Delsey, 1992; Wieman, 1994]. Travel distance/year: 20,900 km [CBS, 1993]. Estimated required driving range 560 km at "cruise" speed of 70 km/h (figures equal to passenger cars); average speed approximately 50 km/h. Technical life of fuel-cell up to 15 years [Kram et.al., 1989]. This means that in one van-life the fuel-cell probably should have to be replaced once. At an average speed of 30 - 50 km/h (estimated) and 20,900 km/year, a van will be used around 420 - 700 hours a year. With a lifetime of 5,000 - 10,000 hours, the replacement period would be in theory 7 - 25 years. It is not very likely that fuel-cells will be used (sold) that have to be replaced in a van's lifetime.

**Note**: Although data for 1994 and 2010/2015 are given, fuel-cell powered vans will probably not be used in these periods.
2.1.4 Parameters of PEM fuel-cells for busses

Reference energy use: 13.2 MJ/vehkm (energy efficiency: 21%). For 35 seats, this means 0.38 MJ/seatkm.
Reference vehicle costs Dfl 245,000.
Reference maintenance costs Dfl 4.88/vehkm (Dfl 0.14/seatkm);
based on maintenance costs Dfl 370/GJ [Kram et al., 1989].

| Table 2.1.4: Characteristics of fuel-cell technologies for busses |
|---------------------------------|-----------------|-----------------|-----------------|
|                                | 1994            | 2010/2015       | 2030/2040       |
| energy                         |                 |                 |                 |
| energy use [MJ/km]             | 5.69            | 4.83            | 4.79            |
| ef.E.use [MJ/skm]              | 0.28            | 0.14            | 0.14            |
| efficiency                     | 50%             | 59%             | 59%             |
| range [km]                     | 250             | 250             | 250             |
| mass [kg]                      |                 |                 |                 |
| fuel-cell"²"                   | 1.660           | 940             | 750             |
| hydrogen tank                  | 600             | 100             | 100             |
| total vehicle                  | 17,300          | 17,280          | 17,090          |
| costs [Dfl]                    |                 |                 |                 |
| fuel-cell"³"                   | 481,500         | 28,200 - 408,850| 27,920 - 80,960 |
| hydrogen tank                  | 3,030           | 1,370 - 2,580   | 1,380 - 2,550   |
| total vehicle                  | 755,100         | 261,070 - 642,930| 260,780 - 315,010|
| maintenance [ct/km]            | 355.8           | 256.2           | 208.2           |
| maintenance [ct/skm]           | 10.1            | 7.3             | 5.9             |
| technical life [hours]         | 10,000          | 10,000          | 10,000          |

*¹ based on 20 seats, while calculations for 2010/2015 and 2020/2030 are based on 35 seats [BPS, 1993; Van den Berg, 1993].  
*² "mass of fuel-cell" includes auxiliary equipment like cooling plates, a humidification section, end plates, circulation pumps and an air compressor [Swan, 1992].  
*³ "costs of fuel-cell" can be seen as costs for fuel-cell and auxiliary equipment, because these costs will be marginal in comparison with fuel-cell costs, though these costs were not included in the calculations by [Swan, 1992].

vehicle costs: base vehicle costs, electric system included, Dfl 272,000 (1994) - 231,500 (2015/2020 and 2030/2040); costs for fuel-cell and tanks not included in base vehicle costs.


Technical life of fuel-cells is estimated to be 5,000 to 10,000 hours; by an average speed of 30 km/h and a travelling distance of 60,000 km/year, the bus is used 2,000 hours a year. This means that in one bus-life the fuel-cell will have to be replaced several times (about 4 times). Other sources estimate a lifetime of approximately 15 years [Kram et al., 1989]; then the fuel-cell has to be replaced only once or maybe twice in a busses' lifetime. Mass of internal combustion engine bus 16,500 kg, base vehicle mass 16,240 kg (incl. electric motor(s) and 60 kW auxiliary battery-pack, excl. ICE and tanks [BPS, 1993]). Number of seats: 35 (reference, 2010/2015 and 2020/2030) or 20 (1994, due to the fuel-cell volume). Travel distance/year: 60,000 km [CBS, 1993]. Required driving range 250 km, "cruise" speed 70 km/h, average speed approximately 30 km/h.

note Prototype busses are developed by Ballard Power Systems in 1991-1992 (20 passengers), 1993-1994 (40 pass.). In 1998 75-passenger fuel-cell powered busses should be commercially available [BPS, 1993]. These 75-passenger busses will have approximately 35 seats [Van den Berg, 1993].
2.1.5 Parameters of PEM fuel-cells for trucks

Reference energy use: 16.2 MJ/vehkm (energy efficiency: 23%), 0.58 MJ/tonkilometre, (payload 28 ton).

Reference vehicle costs Dfl 220,000 [Wieman, 1994].

Reference maintenance costs Dfl 1.70/vehkm (Dfl 0.06/tonkm); based on [Kram et.al., 1989].

Table 2.1.5: Characteristics of fuel-cell technologies for trucks

<table>
<thead>
<tr>
<th></th>
<th>1994</th>
<th>2010/2015</th>
<th>2030/2040</th>
</tr>
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<tr>
<td>energy</td>
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<tr>
<td>energy use [MJ/km]</td>
<td>7.49</td>
<td>6.37</td>
<td>6.37</td>
</tr>
<tr>
<td>ef.E.use [MJ/tonkm]</td>
<td>0.32</td>
<td>0.24</td>
<td>0.23</td>
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<tr>
<td>efficiency</td>
<td>50%</td>
<td>59%</td>
<td>59%</td>
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<tr>
<td>range [km]</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>mass [kg]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fuel-cell</td>
<td>2,190</td>
<td>1,240</td>
<td>990</td>
</tr>
<tr>
<td>hydrogen tank</td>
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<td>loading capacity</td>
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<tr>
<td>fuel-cell</td>
<td>633,800</td>
<td>37,150-538,730</td>
<td>37,150-107,750</td>
</tr>
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<td>hydrogen tank</td>
<td>8,520 - 15,970</td>
<td>7,240 - 13,570</td>
<td>7,240 - 13,570</td>
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<td>total vehicle</td>
<td>908,320-915,770</td>
<td>241,390-749,310</td>
<td>241,390-318,320</td>
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<td>maintenance [ct/km]</td>
<td>839.2</td>
<td>611.4</td>
<td>515.9</td>
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<td>maintenance [ct/tkm]</td>
<td>35.9</td>
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<tr>
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<td>15 (3 - 8)</td>
<td>15 (3 - 8)</td>
<td>15 (3 - 8)</td>
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<tr>
<td>technical life [hours]</td>
<td>10,000</td>
<td>10,000</td>
<td>10,000</td>
</tr>
</tbody>
</table>

*1 "mass of fuel-cell" includes auxiliary equipment like cooling plates, a humidification section, end plates, circulation pumps and an air compressor [Swan, 1992].

*2 "costs of fuel-cell" can be seen as costs for fuel-cell and auxiliary equipment, because these costs will be marginal in comparison with fuel-cell costs, though these costs were not included in the calculations by [Swan, 1992].

vehicle costs: base vehicle costs Dfl 174,000; electric system Dfl 92,000 (1994) down to Dfl 23,000 (other periods), so vehicle costs Dfl 266,000 (1994) and Dfl 197,000 (2010/2015 - 2020/2030); costs do not include costs for fuel-cell and tanks.

maintenance: costs based on Dfl 1,120/GJ (1994), Dfl 960/GJ (2010/2015), Dfl 170/GJ (2020/2030); (based on costs for busses; costs for 2020/2030 based on extrapolated bus costs, base for estimates: [Kram et.al., 1989]).

Technical life of fuel-cells is estimated to be 5,000 to 10,000 hours; at an estimated average speed of 30 - 50 km/h and a travelling distance of 60,000 km/year, the bus is used 1,200 - 3,000 hours a year. This means a replacement period of 3 - 8 years, (based on 10,000 life time). In one truck-life the fuel-cell will have to be replaced several times (± 3 times). Other sources estimate a life-time of approximately 15 years [Kram, 1989]; then the fuel-cell has to be replaced only once. Reference energy use of trucks based on average fuel consumption (a.o. [Wieman, 1994]), energy efficiency estimated. Mass of truck, including maximum loading, 35,000 kg. Base vehicle mass 6,270 kg (incl. electric motor(s) and starting-battery package) [Wieman, 1994]; maximum payload (combustion engine) 28,000 kg. Travel distance/year: 60,000 km (50,000 truck, 90,000 tractor) [CBS, 1993]. Estimated required driving range 1000 km at "cruise" speed of 70 km/h; average speed approximately 50 km/h.

**note** Although data for 1994 and 2010/2015 are given, fuel-cell powered trucks will probably not be used in these periods. In literature no examples of (developments of) fuel-cell powered trucks are found.
2.2 Alkaline fuel-cells

No specific information could be obtained about Alkaline-based Fuel-Cells (AFC) for non-stationary applications. Alkaline-based fuel-cells will be easier to construct and use. The alkaline fuel-cell costs can therefore, in the first years, be lower compared with PEM fuel-cell costs.

Technical features
Alkaline-based fuel-cells operate under slightly higher temperatures than PEMs; this can be a disadvantage. Operating temperatures are 80 - 120 °C.

Anode reaction: \( \text{H}_2 + 2\text{OH}^- > 2\text{H}_2\text{O} + 2\text{e}^- \) (water production)
Cathode reaction: \( \text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- > 4\text{OH}^- \)

As no platinum catalyst is used, the construction costs are expected to be lower. The omission of platinum is also important in relation to the amount of CO allowed: when a reformer is used, a special CO-converter (preoxidizer) will probably not be necessary.

Competing technologies
The PEM fuel-cell is a favoured technology due to its use of solid electrolyte, cold start capability, relatively high power density and efficient characteristics [Swan, 1992].

State of development
AFCs were used by NASA in the Apollo (1.5 kW AFCs) and the Space Shuttle programmes (7 kW).
AFCs are expected to be commercially available round the year 2000 [ECN, 1990]. At first, the AFCs will probably be used for stationary applications only.
References
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- Delsey, J. (1992), *Environmental comparison of electric, hybrid and advanced heat engine vehicles*, in proceedings "the urban electric vehicle", OECD, Paris
3 ELECTRIC SYSTEMS

In this chapter, developments in motor technology, motor management systems and future possibilities for battery charging will be discussed shortly. The (efficiency and cost) developments have already been incorporated in the battery and fuel-cell energy-efficiency and costs calculations (see also notes in chapters 1 and 2).

3.1 Electric motors

3.1.1 Rotation motors

DC motor drives
Characteristic for a DC (direct current) motor is its collector. It switches the armature winding in order to fit the right current direction to the flux direction. Collector and brush-system are relatively voluminous and expensive. Wear and maintenance costs are not that important anymore, because the collector and brushes can be built for a motor and car lifetime. The traditional variable speed system consists of a DC motor fed from an electronic motor controller. At present, this system is regarded as cost-efficient compared with other alternatives. Disadvantages of this type of motors are the size, the mass (80 - 160 kg, chopper mass 15 kg), the efficiency and the difficulties with adaptation to transmission systems.

- peak efficiency: 85-89% (Brush)
- efficiency at 10% load: 80-87%
- cost/peak shaft: 40-60 Dfl/kW

[Dabels, 1992]

The DC-motor is widely used in electric vehicles as Renault Master/Express, Peugeot J5, Citroën C15/C25 and AX, Fiat Panda and Sita SE2040/Lama 6000 (both light trucks).

AC motor drives
AC (alternative current) asynchronous motors are relatively cheap, small and lightweight but they need a motor controller which is more advanced (so at the moment more expensive). The generally used three phase AC-voltage will be built up by a converter (part of the motor management system).

- peak efficiency: 94-95%
- efficiency at 10% load: 93-94%
- cost/peak shaft: 5.5 - 10.0 Dfl/kW

[Dabels, 1992]

AC-motors are used in the Renault Clio and concept cars like Renault Zoom, Nissan Future Electric Vehicle 2 and GM-IMPACT.

Permanent magnet motor drives (PMM)
New, powerful permanent magnets make it possible to develop high performance motors, specially suited for electrical vehicles (motors with a high power to mass ratio). Disadvantages are the high costs and difficulties to obtain the required torque characteristic.

- peak efficiency: 95-97%
- efficiency at 10% load: 73-82%
- cost/peak shaft: 10-40 Dfl/kW
- max. revolutions: 4,000 - 10,000
Switched reluctance motor drives

Switched reluctance motor drives are newly developed electric motors. They lightweight and relatively small, so they can be built-in in wheels. As these types of motors are under development, there is not much specific information available.

- peak efficiency: 90%
- efficiency at 10% load: ?
- cost/peak shaft: ?

3.1.2 Linear motors

Linear motors are constructed in a completely different way compared with the above mentioned motors. In linear motors only part of the motor is placed in the vehicle, the other part is located in the infrastructure.

Four types of linear motors can be distinguished:
- long stator linear synchronous motor (LLSM),
- short stator linear synchronous motor (SLSM),
- long stator linear induction motor (LLIM),
- short stator linear induction motor (SLIM).

LLSM: the active part of the motor is spread along the track, with as disadvantage its relatively high energy use. The constantly powered direct current polar system can easily be built-in in the vehicle.

SLSM: the active and relatively heavy part of the motor is located in the vehicle; along the track a constantly powered polar system is placed.

LLIM: as in LLSM, the active part of the motor is spread along the track; the onboard part of the engine is as (less) complicated as in LLSM.

SLIM: as in LLSM, the active and relatively heavy part of the motor is located in the vehicle; the infrastructure can easily be constructed; the "motor" part of the infrastructure consists of a throughgoing conducting strip along the track.

In the SLIM and LLIM systems a small air split (< 10 mm) between vehicle and infrastructure is required. This asks for a complicated adjustment (levelling) system. For LSM systems the air-gap may be bigger. The (L)LSM system is the most frequently used system; (L)LIM systems can only be found in Vancouver (Skytrain) and Toronto. [Zeevenhoven, 1993].

3.1.3 Efficiency of electric motors

Energy efficiency from sub powerstation to "wheels" (for guided vehicles) for LIM and rotation motors are different:
- electric motor: 89%
- LIM: 70% + 1 à 2 kW/ton
  (per km and at 30 km/h: 0.03 kWh/ton)
- LSM: 82%
Calculation of electric power-efficiency in case of rotation motors and overhead line:

- efficiency overhead line: 97% (1000 kW, 1500 V)
  99.7% (100 kW, 1500 V), losses of 310 W/km
- efficiency motor: 92%
- efficiency of transmission: 97%

Total: (max.) 0.997 x 0.92 x 0.97 = 0.89 (89% efficiency to sub powerstation)
  (min.) 0.97 x 0.92 x 0.97 = 0.86 (86%)

MagLev (LSM)
- efficiency distribution: 97.5% (100 kW, 375 V), losses of 2550 W/km
- efficiency of LSM: 85%

Total: 0.975 x 0.85 - 0.82 (82% from sub powerstation)

[Zeevenhooven, 1993]

For the H-Bahn (in Dortmund, Germany), research has been done to choose between a rotation motor or a LIM. The result was:
- rotation motor, DC: 1.079 kWh/km, 25 Wh/pass.km
- LIM: 1.884 kWh/km, 45 Wh/passkm. (320 passengers)

In this last example, LIM technology uses about 75% more energy compared with rotation motors. This is mainly due to the linear motor itself: the energy needed for levitation is marginal.

3.2 Auxiliary systems

3.2.1 Motor and battery management system

In electric road vehicles a motor management system is applied to use the available energy most efficiently. The motor management system makes it also possible to control speed, to control the charging of the batteries and to use regenerative braking systems.

Some advanced batteries, like sodium-sulphur, can only operate at high temperatures. To create an environment with a constant, high temperature a battery management system and an initial heating device are necessary. Furthermore, these types of batteries must be insulated very well. The advantage of the battery management system is that the battery can keep its performance from -20°C up to +60°C (temperature under the bonnet in summertime).

When two motors are used, a far more complex management system is needed, because in curves the left and right wheels rotate at different speeds (up to 25% difference).

3.2.2 Transmission systems for electric vehicles

Ordinary DC-motors can principally be used without using a transmission system, as is showed in Renault’s Express-Electrique and Master. For the high-revolution AC motors, special gears are needed. Only in combination with such a gearing system, the advantages of these motors (small, lightweight) can be used.
### 3.2.3 Regenerative braking

Regenerative braking on (normal) battery powered electric vehicles is not very useful because the loading rate capacity is too low: the energy generated can not be stored soon enough in the batteries [Schol, 1993]. Still, regeneration of 5-10% of energy should be possible in urban driving [Brogan, 1992]. By the development and use of "super-capacitors", the generated braking energy can be stored for a relatively short time. The energy-efficiency of these capacitors is almost 100% [Wallentowitz, 1994], the power-density should be 10 kW/kg [I&T, 1993]. If this high estimate of power-density is realistic, there will be no weight problems: for passenger cars and even for vans and buses, these super capacitors would only weigh several kilograms. In literature so far no test results or even applications of super capacitors in electric vehicles were found.

With modern motor management systems in trains, trams and light rail systems, it is possible to save 20 to 30% of the energy use by regenerative braking. Most energy can be saved in case a vehicle has to brake often, as is the case in urban areas. Mostly, the energy generated by braking can be fed back to the mains. In part III (chapter 2) of this report regenerative braking systems based on flywheel and hydraulic technologies will be discussed.

### 3.3 Energy supply

#### 3.3.1 Stationary energy supply

Up till now, the recharging of battery powered vehicles takes some hours (for the IMPACT test vehicle this is 3 - 4 hours). To recharge the batteries, the battery electric vehicle has to be connected to a power supply device (a charger). In most test fleets, users are able to recharge the battery at night in their own garage. In case of full-scale application of electric vehicles, this is no longer possible: for most of the car drivers simply have no own garage. Their car is parked on public roads or in parking lots. If fast recharging (less than several minutes a day) is not possible, this means that extensive infrastructure for recharging electric vehicles has to be built. "Refuelling stations" can hardly be used, because the recharging of the batteries of an individual vehicle consumes much time (and space), so the "turn over" of these stations becomes very low. Solutions have to be found to make private, vandalism and "electricity-theft" secure grid-connected sockets in residential and commercial/office areas. Up till now, this seems to be an underestimated problem. Only if the recharging speed is comparable to the refuelling speed of gasoline cars, electric cars can be recharged at recharging stations.

#### 3.3.2 Energy supply during a drive

In almost all tram, metro and light rail systems, energy is supplied from outside the vehicle. This leads to a remarkable weight reduction in comparison with (electric) vehicles which have to carry the energy themselves. For road-vehicles there are some ideas to build a power-supply system in the road. Power is transferred without physical contact, but by "inductors", deployed at lane centerline. Full-scale tests are expected to take place in 1995 [Ross, 1992].
When this type of energy-transfer is a success (from the point of view of costs, but also energy-efficiency), this system can also be used to recharge batteries during a ride. Thus the problems mentioned above (3.3.1), can, at least partly, be solved.

![Diagram of a roadway powered electric vehicle concept](image)

**Figure 3.3.2: roadway powered electric vehicle concept** [Ross, 1992]

### References
- I&T (1993), *The battery, the motor and the electronics reviewed and improved* (in French: *La batterie, le moteur et l'électronique revus et corrigés*), in Industries et Techniques, nov. 1993
PART III:
HYBRID ELECTRIC VEHICLES,
REGENERATIVE BRAKING SYSTEMS AND
NEW TRANSMISSION SYSTEMS
PART III

HYBRID ELECTRIC VEHICLES

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1 HYBRID ELECTRIC VEHICLES

Hybrid vehicles are vehicles that are equipped with two different propulsion systems. In this chapter the various combinations of internal combustion engines with electric motors will be discussed. The main advantage of this type of hybrid vehicles is that they combine the advantages of combustion engines (range, high energy-density of fuel) with the advantages of an electric drive (no emissions, low noise).

1.1 Description of hybrid electric vehicles

Definition
These propulsion systems in hybrid vehicles can be used simultaneously (series-hybrid) or in an alternate way (parallel-hybrid). The series hybrid system is used to fill power shortages for the main powering system or to generate energy for this main propulsion system. In the parallel-hybrid system, the most appropriate of the available systems in a certain situation is used. Hybrid electric-internal combustion engine vehicles are especially suitable to combine demands for low, local emissions (for example in urban areas) and acceptable driving ranges (outside urban areas).

Explanation
The concept of a series-hybrid drive consists of a medium-sized steady state and therefore very efficient internal combustion engine (ICE), producing electricity that is either stored in batteries or directly used for the electric drive. The batteries buffer the surplus of energy and deliver it when more power is needed than supplied by the ICE. Due to the multiple conversion of energy, the total efficiency is limited. Furthermore, the IC engine is, in comparison with full electric vehicles, noisy and the weight and costs of the generator and its controller are high. In order to increase the energy-efficiency, it is better to charge the batteries from the grid than from the internal combustion engine. The only efficient way to load batteries while driving, is the use of regenerative braking.

The parallel systems allow the ICE and an electric drive to deliver power to the wheels directly. An ordinary but small, transient operating and therefore relatively low efficient, internal combustion engine and a small add-on electric drive is used. The advantage of this system is the direct use of the ICE. The electric drive is used in cities where zero or low emissions are allowed. The efficiency of a parallel hybrid drive can be lower than of a series hybrid drive due to the low efficiency of a transient ICE in comparison.
son with a steady-state ICE. Better efficiency can be achieved by adding a continuous variable transmission for the ICE, thus forcing a more or less steady-state operation by the ICE. The parallel hybrid system requires a Power Train Management System which controls the blend of power from the electric motor and the auxiliary power unit to the wheels. The system makes decisions based on the state of charge of the battery, the driving conditions (city or freeway), the driver demands for acceleration or regenerative braking etc. In some test vehicles, the drive is programmed so that the ICE automatically starts up and engages, under certain preset conditions of battery charge and driver demand, at speeds above 25 to 30 mph. In this way, the electric motor load is relieved resulting in an extension of the driving range to 150 miles or more. The driver can program the control system in the all electric mode for journeys less than 50 miles, so that the auxiliary power unit (ICE) is inhibited from operation until the battery drops to 20% state of charge (SOC) or lower [Samuel, 1992].

A third system is the so called Universal Hybrid System that combines the steady state ICE with the advantages of its direct use for propulsion. The combination of the ICE and the electric drive is done by a planetary gear box. In principle, the one drive is working on the sunwheel and the other on the outer ring. The propulsion is fixed to the satellite carrier. Momentum and speed for the propulsion can be varied by the electric drive. With these systems high efficiencies can be achieved [Streicher, 1992].

A fourth rather exotic type of hybrid vehicle is a vehicle with a modular electric motor and a modular ICE. The user can choose to couple one of the two modules to the vehicle: the most appropriate for the trip. A look-a-like system provides an ICE in a trailer, which can be coupled to a (normally) electrically operated bus. The universal hybrid system and the modular system are not described in this report.

Energy functions
Efficiency chains occurring in hybrid vehicles:
steady state ICE → generator → control → electric drive: 18%
steady state ICE → generator → control → batt. → cont. → el.drive: 12%
steady state ICE:
transient ICE → generator → control → battery → control → el.drive 6%
transient ICE: 15%
gird → battery charger → battery → control → electric drive 53%
[Streicher, 1992]

The overall efficiency of hybrid vehicles is dependent on the use. Average speed, acceleration and method of "refuelling" determine the efficiency.
In comparison with internal combustion engines, hybrid vehicles use less energy. On the other hand, hybrid vehicles use more energy than full electric vehicles:

Average driving demand:
- electric vehicles: 26 kWh/100 km (0.94 MJ/km)
- hybrid (VW Golf): 2.5 - 3.3 l diesel + 16.3 - 16.5 kWh/100 km electric energy (1.5 - 1.8 MJ/km)
- small ICE-cars: (Daihatsu Cuore - Mazda 121) 50.4 - 57.6 kWh/100 km 5.6 - 6.4 l/100 km (gasoline) (1.8 - 2.1 MJ/km)
- standard ICE: (91.7 kWh/100 km) 9.9 l/100 km (gasoline) (3.3 MJ/km)

[Streicher, 1992; Delsey, 1992]
energy use figures between brackets (kWh/km or MJ/km) added

Hybrid vehicles tend to be heavier than their ICE-counterparts:
- Hybrid Golf: 1175 kg (payload 325 kg)
- Golf model 82: 805 kg (payload 435 kg)

Due to this difference in weight the energy use of hybrid vehicles is at higher speeds in general higher than of comparable ICEs:
- Hybrid (VW Golf): 6.8 l (90 km/h) - 9.0 l (120 km/h)
- Standard ICE: 6.5 l (90 km/h) - 8.5 l (120 km/h)
  (note: at these speeds the internal combustion engine of the hybrid vehicle is used, figures are based on distances of 100 km)

[Delsey, 1992]

In a balanced hybrid system, power requirements of the ICE and Electric motor can be complementary so the weight and size of both the internal combustion engine as the electric motor can be reduced. This can lead to a lower overall energy use [Streicher, 1992; Wallentowitz, 1994]. Exact data for this types of combinations are not yet available.

It is attractive to decrease the weight of (hybrid) electric vehicles, because in this way the weight of batteries can be reduced as well: the required power for acceleration contributes to the heavy weight of some types of batteries.
Comparison between a gasoline vehicle, a battery powered vehicle and a hybrid vehicle

<table>
<thead>
<tr>
<th></th>
<th>Small Gasoline Vehicle</th>
<th>Sodium Sulphur Battery Powered Vehicle</th>
<th>Hybrid Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine/Motor</td>
<td>50 kW</td>
<td>20 kW cont.</td>
<td>10 kW cont.</td>
</tr>
<tr>
<td>Power Rating</td>
<td>continuous</td>
<td>50 kW peak</td>
<td>30 kW ICE, cont.</td>
</tr>
<tr>
<td>Driving Range</td>
<td>600 km</td>
<td>30-100 km</td>
<td>600 km</td>
</tr>
<tr>
<td>Energy Use</td>
<td>0.08 l/km</td>
<td>0.25 kWh/km (main)</td>
<td>0.2 kWh/km</td>
</tr>
<tr>
<td></td>
<td>(2.6 MJ/km)</td>
<td>(0.9 MJ/km)</td>
<td>0.07 l/km</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.7 - 2.3 MJ/km)</td>
</tr>
<tr>
<td>Retail Price Elements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base Vehicle</td>
<td>Dfl 18,800</td>
<td>fl 18,800</td>
<td>Dfl 18,800</td>
</tr>
<tr>
<td>Engine/Transmission</td>
<td>Dfl 3,600</td>
<td></td>
<td>Dfl 2,600</td>
</tr>
<tr>
<td>Motor/Controller</td>
<td>-</td>
<td>Dfl 13,400-22,400</td>
<td>Dfl 7,400-15,000</td>
</tr>
<tr>
<td>Battery</td>
<td>-</td>
<td>Dfl 4,400-9,000</td>
<td>Dfl 3,000</td>
</tr>
<tr>
<td>Total</td>
<td>Dfl 22,400</td>
<td>Dfl 36,800-50,000</td>
<td>Dfl 32,000-39,400</td>
</tr>
<tr>
<td>Maintenance Costs</td>
<td>3.6 ct/km</td>
<td>2.4 ct/km</td>
<td>3.6 ct/km</td>
</tr>
</tbody>
</table>

[Note: in the (low) maintenance costs for electric batteries, replacement costs apparently are not included.]

Penetration
By some authors, the hybrid car is considered as a transition technology: while electric vehicles are not fully developed (especially the battery or fuel-cell part of the vehicles), the hybrid car can match to low emission requirements and can be used as a normal car. Especially for city-based vehicle owners, this technology can be of importance. Vehicles which are used mostly outside the cities, are not likely to be substituted by hybrid vehicles (energy use is even higher!).

Competing Technologies
On the short term, improved ICE vehicles are important competitive technologies: the energy use will decrease as will the emissions. On the long term, flywheel systems and super capacitors will make full electric vehicles more useful and in the "far" future, fuel-cell powered vehicles will be an important competitive technology.

State of Development, Current R&D
Some test vehicles have been built (well known is the Volkswagen Hybrid Golf). Current research and development is aimed at the decrease of the vehicle weight, the improvement of the motor-control system, the improvement of the transmission system (Continuous Variable Transmission for example), the improvement of the auxiliary (steady state) internal combustion engine and the coupling to regenerative breaking systems. Research is done by:

- Volkswagen, Chico and Golf parallel hybrid (Germany)
- Ford Motor Corp. and Institut für Kraftfahrwesen (Germany)
- Clean Air Transport AB, parallel hybrid (Sweden)
- Audi Duo convertible, exchangeable duo-motor (Germany)
- Renault Espace parallel hybrid (France)
- Peugeot 405 convertible, exchangeable motor (France)
- AVL List, Universal hybrid system (Austria)
Bottlenecks
Like all "hybrid" technologies, the availability of a dual technology system adds extra weight and extra costs in comparison with mono-technology systems. The user has both the advantages and the disadvantages of both systems. Manufacturers will try to decrease weight and costs to obtain a serious alternative for full-ICE vehicles. There are no important technological barriers for the further development of hybrid vehicles.

Availability
Test vehicles are already running, but most vehicles are not commercially available. In 2010 hybrid vehicles will be on the market if research is continued.

1.2 Parameters for hybrid passenger cars

Reference energy use 2.56 MJ/km; 1.71 MJ/seatkilometre.
Reference vehicle costs Dfl 22,000 [Martin et al., 1992]. Reference maintenance costs Dfl 0.33/km or Dfl 0.22/seatkilometre, based on Dfl 130/GJ [Kram et al., 1989].

Table 1.2: Characteristics of hybrid passenger cars

<table>
<thead>
<tr>
<th></th>
<th>1994</th>
<th>2010/2015</th>
<th>2020/2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electric drive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>use [MJ/km]</td>
<td>1.27</td>
<td>0.80</td>
<td>0.74</td>
</tr>
<tr>
<td>eff. use [MJ/seatkilometre]</td>
<td>0.84</td>
<td>0.53</td>
<td>0.50</td>
</tr>
<tr>
<td>efficiency</td>
<td>52%</td>
<td>73%</td>
<td>77%</td>
</tr>
<tr>
<td>ICE-drive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>use [l/km] (diesel)</td>
<td>0.087</td>
<td>0.061</td>
<td>0.060</td>
</tr>
<tr>
<td>use [MJ/km]</td>
<td>3.08</td>
<td>2.16</td>
<td>2.12</td>
</tr>
<tr>
<td>use [MJ/seatkilometre]</td>
<td>2.05</td>
<td>1.44</td>
<td>1.41</td>
</tr>
<tr>
<td>efficiency</td>
<td>21%</td>
<td>27%</td>
<td>27%</td>
</tr>
<tr>
<td>mass [kg]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>battery pack</td>
<td>300</td>
<td>70[1]</td>
<td>30</td>
</tr>
<tr>
<td>fuel tank</td>
<td>50</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>total vehicle</td>
<td>1,270</td>
<td>1,020</td>
<td>990</td>
</tr>
<tr>
<td>costs [Dfl]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>battery</td>
<td>1,690</td>
<td>5,000</td>
<td>620</td>
</tr>
<tr>
<td>total vehicle</td>
<td>27,340</td>
<td>27,650</td>
<td>23,270</td>
</tr>
<tr>
<td>maintenance [ct/km][2]</td>
<td>22.2 - 39.5</td>
<td>12.0 - 27.7</td>
<td>9.3 - 27.2</td>
</tr>
<tr>
<td>maintenance [ct/seatkilometre]</td>
<td>14.8 - 26.3</td>
<td>8.0 - 18.5</td>
<td>6.2 - 18.1</td>
</tr>
</tbody>
</table>

[1] weight determined by power requirements
[2] first (lower) values for electric drive, second (higher) values for diesel drive

Assumptions for calculations:
- all periods: Required power: 10 kW (electric), 30 kW (ICE); range: 30 km (electric), 500 km (ICE).
  Maintenance costs Dfl 128.3/GJ for diesel drive.
  Mass base vehicle, internal combustion engine and electric motor included, 920 kg.
- 1994: Pb-acid battery, 75% loading/unloading efficiency, 85% transmission efficiency, 25% ICE efficiency.
  Maintenance costs Dfl 175/GJ (electric drive), incl. replacements of battery.
  Base vehicle costs, small ICE and electric system included, battery excluded, Dfl 25,650
2010/2015: AlO₂ battery, 90% loading/unloading efficiency, 90% (ICE) transmission efficiency, 30% ICE efficiency; Maintenance costs Dfl 150/GJ, incl. replacements of battery. Base vehicle costs, small ICE and electric system included, battery excluded Dfl 22,650.

2030/2040: US-ABC goal type battery, 95% efficiency; 90% (ICE) transmission efficiency, 30% ICE efficiency. Maintenance costs Dfl 125/GJ, incl. replacements of battery. Base vehicle costs, small ICE and electric system included, battery excluded Dfl 22,650.

Calculation of required energy for driving (ICE and EV, excl. losses) based on "lower estimation" [Bossche, 1992]: Energy (Wh/vehicle tonkm) = 80 + (80 / vehicle mass); energy-efficiency for passencars is estimated. The calculated energy use for internal combustion engine (ICE)-vehicles and full electric vehicles (FEV) is higher than the energy use calculated in "Cars and Climate Control" [IEA, 1993]. Their estimates are 2.3 MJ/km (gasoline-ICE) and 0.69 MJ/km (full electric vehicle). Result for ICEs is comparable to, for example, 2.6 MJ/vehkm [Delsey, 1991]. Maintenance costs based on costs for battery powered cars [Kram, 1989]; costs extrapolated for 2020/2030 and costs for diesel-ICE powered cars [Kram, 1989].

Environmental parameters

If electric drive is used and there is no need for a transient ICE, noise is low and local emissions are zero. In electric drive the vehicle uses less energy (i.e., electrical energy!) than standard ICE vehicles. As with full electric vehicles, for the "electric mode" of hybrid vehicles, the total energy use is dependent of the energy-efficiency of power plants. In 1994, ICE drive with the electric vehicle uses more energy than the standard ICE counterpart; in other periods energy use is less (note: reference for every period is 1994; in due time also standard ICEs will be developed further). Also when the electric drive is used for additional "power-requirements", a smaller engine can be used which is more fuel efficient. In principle, this combination can lead to a lower overall energy use [Wallentowitz, 1994]. Hybrid cars produce more emissions and use more energy at high speeds than comparable ICE-vehicles due to the higher vehicle weight.

1.3 Parameters for hybrid vans

Reference energy use: 6.48 MJ/vehkm (energy efficiency: 20%); this can be compared to an energy use of approximately 3.73 MJ per ton-kilometre (payload 1.735 ton). Reference vehicle costs Dfl 45,000 (ICE-van) [Wieman, 1993]. Reference maintenance costs Dfl 45,000 (ICE-van) [Wieman, 1993]. Reference maintenance costs Dfl 1.43/vehkm or Dfl 0.82/tonkm (interpolated cost estimate of Dfl 220/GJ, based on [Kram et al., 1989]).

(for results see table 1.3, next page)
### Table 1.3: Characteristics of hybrid vans

<table>
<thead>
<tr>
<th></th>
<th>1994</th>
<th>2010/2015</th>
<th>2020/2030</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>energy electric drive</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>use [MJ/km]</td>
<td>2.51</td>
<td>1.78</td>
<td>1.68</td>
</tr>
<tr>
<td>ef. use [MJ/tkm]</td>
<td>2.03</td>
<td>1.13</td>
<td>1.00</td>
</tr>
<tr>
<td>efficiency</td>
<td>52%</td>
<td>73%</td>
<td>77%</td>
</tr>
<tr>
<td><strong>ICE-drive</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>use [l/km] (diesel)</td>
<td>0.172</td>
<td>0.136</td>
<td>0.136</td>
</tr>
<tr>
<td>use [MJ/km]</td>
<td>6.10</td>
<td>4.80</td>
<td>4.80</td>
</tr>
<tr>
<td>use [MJ/tkm]</td>
<td>4.93</td>
<td>3.06</td>
<td>2.86</td>
</tr>
<tr>
<td>efficiency</td>
<td>21%</td>
<td>27%</td>
<td>27%</td>
</tr>
<tr>
<td><strong>mass [kg]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>battery pack</td>
<td>500</td>
<td>170(^{1})</td>
<td>60</td>
</tr>
<tr>
<td>fuel tank</td>
<td>100</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>total vehicle</td>
<td>3,500</td>
<td>3,500</td>
<td>3,500</td>
</tr>
<tr>
<td>payload</td>
<td>1,240</td>
<td>1,570</td>
<td>1,680</td>
</tr>
<tr>
<td><strong>costs [Dfl]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>battery</td>
<td>2,790</td>
<td>12,500</td>
<td>1,170</td>
</tr>
<tr>
<td>total vehicle</td>
<td>56,740</td>
<td>58,950</td>
<td>47,700</td>
</tr>
<tr>
<td>maintenance [ct/km](^{2})</td>
<td>52.7 - 132.6</td>
<td>33.8 - 104.3</td>
<td>26.9 - 104.3</td>
</tr>
<tr>
<td>maintenance [ct/tkm](^{2})</td>
<td>42.6 - 106.9</td>
<td>21.5 - 66.4</td>
<td>16.1 - 62.1</td>
</tr>
</tbody>
</table>

\(^{1}\) weight determined by power requirements \\
\(^{2}\) first (lower) values for electric drive, second (higher) values for diesel drive

**Assumptions for calculations:**

- **all periods:** Required power: 25 kW (electric), 70 kW (ICE).
- **1994:** Pb-acid battery, 75% loading/unloading efficiency, 85% transmission efficiency, 25% ICE efficiency; range: 25 km (electric), 500 km (ICE); maintenance costs Dfl 210/GJ, incl. replacements of battery. Base vehicle costs, small ICE and electric system included, battery excluded, Dfl 53,950.
- **2010/2015:** Al\(_2\)O\(_3\) battery, 90% loading/unloading efficiency, 90% (ICE) transmission efficiency, 30% ICE efficiency; range: 50 km (electric), 500 km (ICE); maintenance costs Dfl 190/GJ, incl. replacements of battery. Base vehicle costs, small ICE and electric system included, battery excluded, Dfl 46,450.
- **2030/2040:** US-ABC goal type battery, 95% efficiency; 90% (ICE) transmission efficiency, 30% ICE efficiency; range: 50 km (electric), 500 km (ICE); maintenance costs Dfl 160/GJ, incl. replacements of battery. Base vehicle costs, small ICE and electric system included, battery excluded, Dfl 46,450.

Mass of internal combustion engine van, including maximum loading, 3,500 kg. Travel distance/year: 20,900 km [CBS, 1993]. Calculation of "net energy" (energy for driving without losses) is based on "lower estimation" [Bosche, 1992]: Energy (Wh/vehicle tonkm) = 80 + (80 / vehicle mass); energy efficiency is estimated. Compared to the reference energy use some authors calculate relative lower energy use (3.8 MJ/km at 646 kg of loading [Haspel, 1991] and 5.4 MJ/km at full load [Rijkeboer, 1994]) but based on fuel-consumption also relatively higher figures can be calculated (4.56 MJ empty [Wieman, 1994]). Maintenance costs for electric drive based on interpolation (car, bus) of maintenance costs for battery powered vehicles; extrapolated for 2020/2030. Maintenance costs for diesel drive based on interpolation (car, bus) of maintenance costs for diesel-ICE powered vehicles.
1.4 Parameters for hybrid busses

Reference energy use: 13.2 MJ/vehkm (energy efficiency: 21%); this can be compared to an energy use of approximately 0.38 MJ per seat-kilometre.

Reference vehicle costs Dfl 245,000.
Reference maintenance costs Dfl 4.88/vehkm (Dfl 0.14/seatkm); based on maintenance costs Dfl 370/GJ [Kram et al., 1989].

<table>
<thead>
<tr>
<th>Table 1.4: Characteristics of hybrid busses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
</tr>
<tr>
<td>energy electric drive</td>
</tr>
<tr>
<td>use [MJ/km]</td>
</tr>
<tr>
<td>ef. use [MJ/skm]</td>
</tr>
<tr>
<td>efficiency</td>
</tr>
<tr>
<td>ICE-drive</td>
</tr>
<tr>
<td>use [l/km] (diesel)</td>
</tr>
<tr>
<td>use [MJ/km]</td>
</tr>
<tr>
<td>use [MJ/skm]</td>
</tr>
<tr>
<td>efficiency</td>
</tr>
<tr>
<td>mass [kg]</td>
</tr>
<tr>
<td>battery pack</td>
</tr>
<tr>
<td>fuel tank</td>
</tr>
<tr>
<td>total vehicle</td>
</tr>
<tr>
<td>costs [Dfl]</td>
</tr>
<tr>
<td>battery</td>
</tr>
<tr>
<td>total vehicle</td>
</tr>
<tr>
<td>maintenance [ct/km]*</td>
</tr>
<tr>
<td>maintenance [ct/skm]*</td>
</tr>
</tbody>
</table>

* first (lower) values for electric drive, second (higher) values for diesel drive

Assumptions for calculations:
all periods: Required power: 45 kW (electric), 135 kW (ICE).
Base vehicle costs (ex. battery) Dfl 240,400.
Maintenance costs Dfl 370/GJ (diesel drive).
1994: Pb-acid battery, 75% loading/unloading efficiency,
85% transmission efficiency, 25% ICE efficiency;
range: 60 km (electric), 250 km (ICE);
maintenance costs Dfl 470/GJ, incl. replacements of battery.
Base vehicle costs, (small) ICE and electric system included, battery excluded, Dfl 260,300.
2010/2015: AlO2 battery, 90% loading/unloading efficiency,
90% (ICE) transmission efficiency, 30% ICE efficiency;
range: 100 km (electric), 250 km (ICE);
maintenance costs Dfl 445/GJ, incl. replacements of battery.
Base vehicle costs, (small) ICE and electric system included, battery excluded, Dfl 246,800.
2030/2040: US-ABC goal type battery, 95% efficiency;
90% (ICE) transmission efficiency, 30% ICE efficiency
range: 100 km (electric), 250 km (ICE);
maintenance costs Dfl 420/GJ, incl. replacements of battery.
Base vehicle costs, (small) ICE and electric system included, battery excluded, Dfl 246,800.

Mass of internal combustion engine bus 16,500 kg, base vehicle mass 16,240 kg (incl. electric motor(s), excl. ICE motor and tanks); energy efficiency is estimated. Number of seats: 35. Travel distance/year: 60,000 km [CBS, 1993]. Maintenance costs for electric drive based on maintenance costs for battery powered buses [Kram, 1989]; figures for 2020/2030 extrapolated.
1.5 Parameters for hybrid trucks

Reference energy use: 16.2 MJ/vehkm (energy efficiency: 23%); 0.58 MJ/tonkm (payload 28 ton).

Reference vehicle costs Dfl 220,000 [Wieman, 1994];
Reference maintenance costs Dfl 1.70/vehkm (Dfl 0.06/tonkm);
based on [Kram et.al., 1989].

Table 1.5: Characteristics of hybrid trucks

<table>
<thead>
<tr>
<th></th>
<th>1994</th>
<th>2010/2015</th>
<th>2020/2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electric drive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>use [MJ/km]</td>
<td>7.22</td>
<td>5.11</td>
<td>4.84</td>
</tr>
<tr>
<td>ef. use [MJ/tonkm]</td>
<td>0.29</td>
<td>0.19</td>
<td>0.18</td>
</tr>
<tr>
<td>efficiency</td>
<td>52%</td>
<td>73%</td>
<td>77%</td>
</tr>
<tr>
<td>ICE-drive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>use [l/km] (diesel)</td>
<td>0.496</td>
<td>0.390</td>
<td>0.390</td>
</tr>
<tr>
<td>use [MJ/km]</td>
<td>17.5</td>
<td>13.8</td>
<td>13.8</td>
</tr>
<tr>
<td>use [MJ/tonkm]</td>
<td>0.71</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>efficiency</td>
<td>21%</td>
<td>27%</td>
<td>27%</td>
</tr>
<tr>
<td>mass [kg]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>battery pack</td>
<td>3,440</td>
<td>530</td>
<td>400</td>
</tr>
<tr>
<td>fuel tank</td>
<td>580</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>total vehicle</td>
<td>35,000</td>
<td>35,000</td>
<td>35,000</td>
</tr>
<tr>
<td>loading capacity</td>
<td>24,560</td>
<td>27,470</td>
<td>27,600</td>
</tr>
<tr>
<td>costs [Dfl]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>battery</td>
<td>19,240</td>
<td>40,000</td>
<td>8,070</td>
</tr>
<tr>
<td>total vehicle</td>
<td>266,640</td>
<td>263,400</td>
<td>231,470</td>
</tr>
<tr>
<td>maintenance [ct/km]</td>
<td>627.8 - 183.8</td>
<td>398.7 - 144.9</td>
<td>309.9 - 144.9</td>
</tr>
<tr>
<td>maintenance [ct/tonkm]</td>
<td>25.6 - 7.48</td>
<td>14.5 - 5.27</td>
<td>11.2 - 5.25</td>
</tr>
</tbody>
</table>

*first (higher) values for electric drive, second (lower) values for diesel drive

Assumptions for calculations:

all periods: required power: 80 kW (electric), 230 kW (ICE);
1994: Pb-acid battery, 75% loading/unloading efficiency, 85% transmission efficiency, 25% ICE efficiency; range: 60 km (electric), 250 km (ICE); maintenance costs Dfl 870/GJ, incl. replacements of battery.
2010/2015: AlO2 battery, 90% loading/unloading efficiency, 90% (ICE) transmission efficiency, 30% ICE efficiency; range: 100 km (electric), 250 km (ICE); maintenance costs Dfl 780/GJ, incl. replacements of battery.
2030/2040: US-ABC goal type battery, 95% efficiency; 90% (ICE) transmission efficiency, 30% ICE efficiency; range: 100 km (electric), 250 km (ICE); maintenance costs Dfl 640/GJ, incl. replacements of battery.

Maintenance costs based on maintenance costs for (battery powered) buses, extrapolated for energy use (on the road) and in time (for 2020/2030).
Reference energy use of trucks based on average fuel consumption (a.o. [Wieman, 1994]), energy efficiency estimated. Mass of truck, including maximum loading, 35,000 kg.
References
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- Kram, T. en P.A. Okken (1989), *Chances for alternative fuels in road-transport in the Netherlands until 2000 influenced by the price of oil and the NO\(_x\) and CO\(_2\) limits* (in Dutch: *Kansen voor alternatieve brandstoffen in het wegverkeer in Nederland onder invloed van de olieprijs, NO\(_x\)- en CO\(_2\)-plafonds*), Energy Study Center of the Netherlands Energy Research Foundation, Petten
- Martin, D. and L. Michaelis (ETSU) (1992), *The environmental impact of electric vehicles*, in proceedings "the urban electric vehicle", OECD, Paris
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- Streicher, W. (1992), *Energy demand, emissions and waste management of EVS, Hybrids and small Conventional cars*, in proceedings "the urban electric vehicle", OECD, Paris
- Wallentowitz (1994), *Review*
2 REGENERATIVE BRAKING

In normal driving conditions, especially in urban areas, much kinetic energy is dissipated (transferred to heat) while braking. With regenerative braking systems, a part of this "lost" energy is recuperated. In this chapter two types of regenerative braking systems will be discussed in detail: the flywheel system and the hydraulic-pressure system.

2.1 Description of regenerative braking systems

**Definition**

Regenerative braking can be described as the recuperation of kinetic energy while braking. This type of recuperated energy is stored for propulsion purposes, especially for acceleration. In a flywheel system, recuperated energy is stored as kinetic energy in a rotating flywheel. In a hydraulic system, recuperated energy is stored as hydraulic pressure in pressure tanks.

**Explanation**

Normally, while braking, in the braking mechanism much kinetic energy is dissipated into useless heat-energy. The aim of regenerative braking is to reuse part of this kinetic energy by storing this energy in a system that is capable of fast charging. This fast-charge request makes the use of electrochemical storage of recuperated energy, as in batteries, almost impossible, although short-period storage of electric energy in "super capacitors" seems to be rather promising. The transfer of energy can take place very fast and relatively efficient by using flywheels (kinetic energy → kinetic energy) or hydraulic or pneumatic pressure systems (kinetic energy → high pressure). In case of flywheels, the kinetic energy is transferred to the axles by an (automatic) transmission system or by a generator - electromotor system. In case of hydraulic accumulators, the pressure is transferred to the axles by a hydraulic motor.

![Diagram of CUMULO system](image)

*Figure 2.1a: CUMULO system as applied in some busses [Volvo, in: Haspel, 1991]*

Examples of hydraulic pressure systems are the CUMULO system (VOLVO), the SHL system (Voith and MAN) and the new developed MBECS system (Mitsubishi).
Extra weight of cumulo system: 75 kg/1000 kg vehicle weight (loaded)
Efficiency loading/unloading: 45%
Life time: 13 years
Maintenance costs: 5% of investments, yearly
Investment costs: Dfl 3,200/1000 kg
(Dfl 31,500 - 63,000 for trucks, Dfl 46,000 for busses)

Flywheel systems can be found in buses (Gyro bus, Oerlikon system), where a flywheel forms the accumulator which powers an electric motor.

Examples of new developed flywheel systems ("mechanical battery"):  
- 30 cm diameter, 30-40 kg aluminium MPMG (melt powder melt growth) neodymium-iron-boron (Fe-Nd-B) superconducting disk, storing cap. 100 Wh of energy, (stationary laboratory model, Japan)
- 2 foot cubic area, carbon fibre matrix, 25 kW, 20,000 RPM, 95% efficiency (Livermore)
- AFS: 20 flywheel systems would be necessary to power GM’s electric prototype vehicle IMPACT and it would cost about Dfl 11,000, nearly 4 times the costs of IMPACT’s 32 lead-acid batteries. Flywheels store up to four times more energy and last for at least 250,000 miles (Clarke, 1992).

Most flywheels are combined with electric driving systems (accumulator and electric motors), but some systems are used in a mechanical mode, for example in combination with a Continuous Variable Transmission. Also the Birmingham-exposition prototype tram uses a mechanical coupling between the flywheel and the driving system (Zweeden, 1993).

Extra weight of flywheel system: 66 kg/1000 kg vehicle weight (loaded)
Efficiency loading/unloading: 55%
Life time: 10 years
Maintenance costs: 5% of investments, yearly
Investment costs: Dfl 2,200/1000 kg

Figure 2.1: example of "electromechanical battery" (AFS) [Clarke, 1992]
In most cases, a special gearing system has to be used that allows the use of flywheels or hydraulic/pneumatic pumps-motors next to or in addition to the normal propulsion system. The traditional gearing system can be omitted. Automatic transmissions and especially transmission systems like the CVT can be used in combination with so called "one mode" or "dual mode" flywheel systems. In one-mode systems, the axles are driven by the engine (normal drive) or the flywheel (start acceleration). In dual-mode systems the flywheel is used to improve the engine-efficiency, also while driving. In an electric vehicle, the motor management system must also be capable of handling the stored energy in flywheels or in pressure tanks. Superconducting flywheel systems, which have no "mechanical" bearings, need a high-tech control unit and need to be cooled. Flywheels with mechanical bearings will operate at relatively low speeds, so the efficiency will be low. Only when superconducting flywheels will be available, really energy-efficient use of flywheel systems is possible.

Energy functions
The energy-efficiency of the systems is relatively low, about 50% (note: these are all benefits, because the energy-efficiency of "traditional" braking systems is 0%). With super capacitors a high efficiency will probably be possible (about 100%); the weight will be about 10 kW/kg [I&T, 1993]. No further information is available on weight and efficiency in practice, neither on size or costs.

Penetration
There are no principal technological objections to limit the penetration of regenerative breaking systems. It is however more attractive to use these systems in vehicles with automatic transmission systems, so the penetration of these systems will follow the penetration of automatic transmissions (also CVT). The flywheel system can be used in busses (<1% in 1994, <15% in 2010 and <25% in 2040 [V.d. Graaf, 1994]) and later on maybe in passenger cars, vans and trucks (no estimates of penetration given).
Hydraulic/pneumatic system can most efficiently be used in vehicles with pneumatic/hydraulic engines. This means these systems can be used in mobile equipment (high penetration, especially in combination with free-piston engines). Due to the relatively high weight, applications in busses, trucks and maybe city vans are possible (all relatively low penetration: busses <1% in 1994 up to 5% in 2030; distribution vehicles 0% in 1994, <2% in 2010 and <5% in 2040 [V.d. Graaf, 1994]).
As the largest part of the energy-losses is due to city-traffic, vehicles which are used mostly in cities form the main target-group.

Competing technologies
The systems described above are mutually competing. These systems can be combined with all electric or hydraulic propulsion systems. In case of electric vehicles the "super capacitor" can be an important competitive technology. In a super capacitor, electric energy is stored at a high speed. This energy can be used to recharge the battery or to power the vehicle at acceleration. Estimates of efficiency are about 100% [Wallentowitz, 1994], and weight estimates are 10 kW/kg (!) [I&T, 1993]. It is far from clear how reliable these expectations are. Especially when these capacitors are in practice, it is not clear if the high expectations can be met. There is no information available on costs.

State of development
Regenerative braking systems are widely used in electric-powered rail systems, for which it is possible to feed the recuperated energy directly to the overhead wires. Furthermore, tests are executed with flywheel systems as well with hydraulic-
Pneumatic systems in busses. At the moment there are no commercial systems for vans, passenger cars or trucks available.

**Current R&D**

Hydraulic systems:
- CUMULO: VOLVO Flygmotor (Sweden)
- SHL: Voith and MAN (Germany)
- MBECS: Mitsubishi (Japan)

Flywheel:
- aluminium MPMG flywheel: Superconductivity Research Laboratory, Tokyo (Japan)
- superconducting/magnetic bearing: Argonne National Laboratory, Lawrence Livermore Laboratory
- rotating wheels, embedded in magnets and spinning in vacuum: American Flywheel Systems, Seattle (USA) and CCM, Nuenen (The Netherlands)
- Magnet Motor, Starnberg (Germany)

**Bottlenecks**

For hydraulic systems bottlenecks are weight (oil-tank and pressure tank) and noise (hydraulic motor). Thanks to better insulation, the noise problem can be reduced, but in that case the weight of the system will increase.

For flywheel systems bottlenecks are costs, reliability, durability (vacuum), complexity (superconducting bearings, small tolerances, vibration of flywheel, construction of bearing and noise).

**Availability**

Hydraulic systems: available prototypes for busses; commercially available after the year 1995 (busses) and after 2000 (trucks)


### 2.2 Parameters of regenerative braking for passenger cars

**Energy parameters**

Reference energy use: 2.56 MJ/vehkm (energy efficiency: 19%), this is 1.71 MJ/seat-kilometre (calculated with 1.5 available seats per passenger car).

Energy use:
- 1994: (no applications)
- 2010/2015: 2.48 MJ/vehkm (3% less energy use) 1.66 MJ/seatkil
- 2030/2040: 2.43 MJ/vehkm (5% less energy use) 1.62 MJ/seatkil

Loading/unloading efficiency: 55% [Haspel, 1991]
In passenger cars, only flywheel systems will be used. Figures based on energy savings with regenerative braking in mixed trips. Energy savings can be (much) higher in cities, but lower outside cities.

**Economic parameters**

Reference vehicle costs Dfl 22,000; reference maintenance costs Dfl 0.33/km or Dfl 0.22/seatkm.

Extra investments of regenerative braking system:
- 1994: Dfl 2,200/1,000 kg, so: Dfl 2,100 - 3,100 per vehicle
- 2010/2015: Dfl 1,500/1,000 kg, so: Dfl 1,500 - 2,100 per vehicle
- 2030/2040: Dfl 1,180/1,000 kg, so: Dfl 1,140 - 1,650 per vehicle

Vehicle weight: 970 (base + 50) to 1,400 kg.


[investment cost estimates based on Graaf, 1994]

Maintenance costs: about 5% of investments costs (yearly) [Haspel, 1991]

**Environmental parameters**

Flywheel systems do not cause emissions; the mechanical-bearing systems do not use scarce materials. Some advanced magnetic bearing systems need special materials as neodymium and boron. Flywheels pose noise problems.

### 2.3 Parameters of regenerative braking for vans

**Energy parameters**

Reference energy use: 6.48 MJ/vehkm (energy efficiency: 20%); this is approximately 3.73 MJ per ton-kilometre (payload 1.735 ton).

Energy use:
- 1994: (no applications)
- 2010/2015: 5.83 MJ/vehkm (10% less energy use)
  - 3.89 MJ/tonkm (payload 1.5 ton)
- 2030/2040: 5.64 MJ/vehkm (13% less energy use)
  - 3.76 MJ/tonkm (payload 1.5 ton)

Loading/unloading efficiency of regenerative braking system: 55% [Haspel, 1991]

In vans, for reasons of weight-reduction, only flywheel systems will be used. Figures based on energy savings with regenerative braking in mixed trips. Energy savings are (much) higher in cities but lower outside cities. Estimates of energy use based on 235 kg extra system weight due to regenerative braking system.
Economic parameters

Reference vehicle costs Dfl 45,000 (ICE-van) (Wieman, 1993); reference maintenance costs Dfl 1.43/vehkm or Dfl 0.82/tonkm (interpolated cost estimate of Dfl 220/GJ, based on (Kram et al., 1989)).

Extra investments:
1994: Dfl 2,200/1,000 kg, so about: Dfl 7,700 per vehicle
2010/2015: Dfl 1,500/1,000 kg, so about: Dfl 5,250 per vehicle
2030/2040: Dfl 1,200/1,000 kg, so about: Dfl 4,200 per vehicle

[cost estimates based on V.d. Graaf, 1994]
Maintenance costs: about 5% of investments costs (yearly) (Haspel, 1991)

Environmental parameters

Flywheel systems do not cause emissions; the mechanical-bearing systems do not use scarce materials. Some advanced magnetic bearing systems need special materials as neodymium and boron. Flywheels pose noise problems.

2.4 Parameters of regenerative braking for buses

Energy parameters

Reference energy use: 13.2 MJ/vehkm (energy efficiency: 21%); this can be compared with an energy use of approximately 0.38 MJ per seat-kilometre.

Energy use:
flywheel (EMAFER)
1994: 10.6 MJ/vehkm (20% less energy use, only test applications)
  0.30 MJ/seatkm
2010/2015: 9.24 MJ/vehkm (30% less energy use)
  0.26 MJ/seatkm
2030/2040: 9.24 MJ/vehkm (30% less energy use)
  0.26 MJ/seatkm
[V.d. Graaf, 1994]
Loading/unloading efficiency: 55% (Haspel, 1991)

hydraulic systems (CUMULO)
1994: 11.5 MJ/vehkm (15% less energy use, only test applications)
  0.33 MJ/seatkm
2010/2015: 10.6 MJ/vehkm (20% less energy use)
  0.30 MJ/seatkm
2030/2040: 9.9 MJ/vehkm (25% less energy use)
  0.28 MJ/seatkm
Loading/unloading efficiency: 45%
[V.d. Graaf, 1994; Haspel, 1991]
In busses flywheel systems as well as hydraulic systems can be used. Figures based on energy savings with regenerative braking in mixed trips. Energy savings can be (much) higher in cities (CUMULO: up to 33%), lower outside cities (20%).

**Economic parameters**

Reference vehicle costs Dfl 245,000.
Reference maintenance costs Dfl 4.88/vehkm (Dfl 0.14/seatkm).

Extra investments:
flywheel systems:
- 1994: Dfl 150,000 per vehicle
- 2010/2015: Dfl 100,000 per vehicle
- 2030/2040: Dfl 80,000 per vehicle
[V.d. Graaf, 1994]
Maintenance costs about 5% of investments costs (yearly).
Lifetime about 10 years (1994), 15 years (2010) and 20 years (2030)
[V.d. Graaf, 1994; Haspel, 1991]

hydraulic systems:
- 1994: Dfl 3,200/1000 kg, so about: Dfl 46,000 per vehicle
(estimated)

No estimates are known for future situations.
Maintenance costs: about 5% of investments costs (yearly) [Haspel, 1991]
Lifetime about 15 years (1994/2010) up to 20 years (2030)

**Environmental parameters**

Flywheel systems do not cause emissions; the mechanical-bearing systems do not use scarce materials. Some advanced magnetic bearing systems need special materials as neodymium and boron. Hydraulic systems do not cause emissions and do not need scarce materials. In general hydraulic systems and flywheel systems are noisy.

2.5 **Parameters of regenerative braking for trucks**

**Energy parameters**

Reference energy use: 16.2 MJ/vehkm (energy efficiency: 23%),
0.58 MJ/tonne-kilometre, (payload 28 ton).

At average speeds, the heavy hydraulic regenerative braking system actually increases the energy use:
- 1994: (no applications)
- 2010/2015: 15.7 MJ/vehkm (3% less energy use)
  0.61 MJ/tonkm (payload 25.7 ton)
- 2030/2040: 15.4 MJ/vehkm (5% less energy use)
  0.60 MJ/tonkm (payload 25.7 ton)
Loading/unloading efficiency: 45% [Haspel, 1991]
In trucks due to power requirements, probably only hydraulic systems will be used. Figures based on energy savings with regenerative braking in mixed trips. Energy savings will mostly be achieved in urban areas (stop/start). Based on the same reference energy use of 16.2 MJ/km (0.58 MJ/tonkm) and energy-savings based on savings in busses, in urban areas the minimum energy use would be:

- 2010/2015: 13.0 MJ/vehkm (20% less energy use, urban areas)  
  0.50 MJ/tonkm (payload 25.7 ton)
- 2030/2040: 12.2 MJ/vehkm (25% less energy use, urban areas)  
  0.47 MJ/tonkm (payload 25.7 ton)

All estimates of fuel-use per tonkm based on an extra system weight of about 2,300 kg.

**Economic parameters**

Reference vehicle costs Dfl 220,000.
Reference maintenance costs Dfl 1.70/vehkm (Dfl 0.06/tonkm).

Extra investments for regenerative braking system:
Dfl 3,200/1,000 kg, so about: Dfl 32,000 - 64,000 per vehicle
No costs estimates are known for future situations
[cost estimates based on V.d. Graaf, 1994]

Maintenance costs: about 5% of investments costs (yearly) [Haspel, 1991]
Lifetime about 13 years.

**Environmental parameters**

Hydraulic systems do not cause emissions and do not need scarce materials but in general hydraulic systems are noisy. Free piston engines of course produce the same emissions as internal combustion engines, but due to the higher efficiency, less pollution per (ton)kilometre will be produced.
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3 ALTERNATIVE TRANSMISSIONS

In this chapter continuous variable transmission systems are described as an example of (future) alternative transmission systems. With these transmission systems, the use of transient (combustion) engines can be optimized at different vehicle speeds. The transmission systems can also be integrated with regenerative braking systems in electric or hybrid vehicles.

3.1 Description of alternative transmissions

**Definition**
Alternative transmissions are non-manual transmission systems which have a high (transmission) efficiency, or transmission systems which can lead to an optimal engine use, thus achieving a higher overall efficiency. As an example of alternative (automatic) transmissions, the Van Doornes continuous variable transmission system will be discussed in this chapter. In the parameter-section, improvements of energy efficiency by the development of high-efficiency transmission systems in general are described.

A Continuous Variable Transmission offers a continuum of gear-rations between certain boundaries. The Van Doornes CVT operates using hydraulic-powered pulleys and a flexible steel "push-belt".

**Explanation**
Characteristic for a CVT is the fact the transmission has no separate "gears": a continuum of gear-rations is available. In the CVT, a pushbelt is running between two pulleys (sets of cone-shaped discs). By changing the distance between the discs of the sets, another gear-ratio is obtained. Unlike most gearing systems which use a pull-belt (or chain) to change the gear-ratio, the Van Doornes CVT is using a push-belt, comparable to a flexible but strong steel "rod". The push-belt is a high-precision product consisting of two "strings" (each containing 10 strips of high-quality metal) and about 300 links. The CVT is controlled by an advanced electronic/hydraulic system that makes it possible to choose different driving styles (economic, sportive, speed/cruise control).

*Figure 3.1: Van Doornes CVT combined with an internal combustion engine*
Energy functions

In general automatic transmissions decrease the fuel-efficiency, but CVT-transmissions increase fuel efficiency about 10% for the current second generation CVT and up to 30% for a third generation "hybrid" CVT (coupled to a flywheel system) [VDT, 1994]. As this last estimate seems to be rather high, in the calculations a maximum increase of fuel efficiency of 15% is assumed. Table 3.1 shows some estimates of savings and costs for five different kinds of transmissions. The CVT is mentioned in the last line.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque Converter Lock-up</td>
<td>Open Converter</td>
<td>3.0</td>
<td>2.0 - 3.2</td>
<td>100</td>
</tr>
<tr>
<td>Electric Transm. Control</td>
<td>Hydraulic</td>
<td>0.5</td>
<td>0 - 0.6</td>
<td>48</td>
</tr>
<tr>
<td>4 Speed Automatic</td>
<td>3-speed auto.</td>
<td>4.5</td>
<td>1.8 - 4.0</td>
<td>450</td>
</tr>
<tr>
<td>5 Speed Automatic</td>
<td>3-speed auto.</td>
<td>7.0</td>
<td>3.5 - 5.0</td>
<td>650</td>
</tr>
<tr>
<td>Continuously Variable Transm.</td>
<td>3-speed auto.</td>
<td>8.0</td>
<td>3.0 - 5.5</td>
<td>650</td>
</tr>
</tbody>
</table>

Table 3.1: Energy-efficiency and costs estimates of transmission technologies

[IEA, 1993]

For passenger cars fuel savings of 8% on urban roads are possible. In non built-up areas, the benefits drop to 4% and on motorways there are almost no savings. For trucks transmission and powertrain developments (e.g. turbocompounding, integrated control), the fuel-efficiency can improve with 2-4% in urban areas. In non built-up areas the gains are only 1 to 2% and for light and medium trucks there are no advantages on motorways. It is remarkable that heavy trucks on motorways can save up to 4% with these new developed transmission systems [Hickman, 1991].

Penetration

It can be expected that within about 20 years (so 2015-2020) the larger part of the sold cars is standardly equipped with some form of CVT-transmission [VDT, 1994], although certain problems still have to be solved (noise, acceleration). For vans the system can be used for city distribution. CVTs will possibly be used in (small) trucks and busses in urban areas.

Competing technologies

There are different kinds of CVTs, but the Van Doornes CVT is the only one that is in use at some scale. Competing technologies are advanced, electronically controlled "handshift gearboxes" (for example used in trucks), the Torotrax gearbox and clutch-and-overrun systems (used in Volkswagens' ECO-Golf) [Wallentowitz, 1994].

State of development

CVTs are already in use in (small) production cars like Fiat Panda, Subaru Justy, Ford Fiesta, but recently also in bigger cars (Volvo). The second generation CVTs, which use less energy, offers more comfort and can be used for 3.5 litre ICES is now available. This CVT has an electronic controller, new types of (hydraulic) pumps and chains and an improved management program. Especially in trucks, high-tech electronically controlled gearboxes are used which have comparable energy-saving characteristics (like Eatons' SAMT) [Wieman, 1993].
Current R&D
The mechanical efficiency of a CVT is lower than the efficiency of a gearwheel-transmission: the reduction of energy use is achieved by optional and continuously "changing" gears, so the internal combustion engine can be used at a better operating point. The best results can be achieved in city-use. A part of the research is aimed at the improvement of the mechanical efficiency of the CVT system. In the coming 5 to 10 years, the third generation CVT will be developed. This system offers an integrated motor and CVT-control system and an improved design of pulleys and push-belt. These improvements will reduce the costs. On the longer term (10-15 years), a hybrid CVT will be available which has an advanced control system and is equipped with a flywheel system.

Bottlenecks
At the moment the maximal torque of the CVT is an important bottleneck, although progress is made. Another problem is the still unnatural behaviour of the transmission system as reported by users [Wallentowitz, 1994]. Due to the high-tech production methods and the high investments to develop the CVT, the production costs are rather high (compared with other technologies). Only when mass-production will be possible for the CVT, the costs will be equal to or lower than the current costs for transmissions.

Availability
The CVT is used in several production models; in 2010/2015 advanced hybrid CVTs will be available. The maximum transfer-power up till now is 120kW (1994), so CVT can, in theory, be used in busses. Maybe in 2010/2015 vans can be equipped by CVT. While in 2030/2040 light trucks and busses can use the system [Markus, 1994].

3.2 Parameters of alternative transmissions for passenger cars

Energy parameters
Reference energy use: 2.56 MJ/vehkm (energy efficiency: 19%, transmission efficiency 85%). Effective energy use: 1.71 MJ/seatkilometre (average: 1.5 available seats per passenger car).

Energy use:
1994: 2.30 - 2.43 MJ/vehkm; 1.54 - 1.62 MJ/seatkkm
(5%-10% reduction: CVTs, and improved automatic transmissions)
2010/2015: 2.30 MJ/vehkm; 1.54 MJ/seatkkm
(10% reduction: third generation)
2030/2040: 2.18 MJ/vehkm; 1.45 MJ/seatkkm
(15% reduction: improved CVT; transmission efficiency 95%)

All reductions compared with 4-speed manual gearing system.
Economic parameters

Reference vehicle costs are Dfl 22,000.

Extra investments (per vehicle) will be:

1994: Dfl 2,600 (VDT "Europe"-estimate)
2010/2015: Dfl 800 - 1,000 (VDT "Japan 1994" estimate)
2030/2040: Dfl 660

There will be no extra maintenance costs in comparison with conventional automatic or manual gearing systems [VDT, 1994; IEA, 1993].

Environmental parameters

Emissions

The alternative transmission systems do not produce any emissions. Due to the more "steady-state" behaviour of engines lower emission-rates can be expected.

Materials

For the construction of a CVT common materials are used.

3.3 Parameters of alternative transmissions for vans

Energy parameters

Reference energy use: 6.48 MJ/vehkm (energy efficiency: 20%); this can be compared to an energy use of approximately 3.73 MJ per ton-kilometre (payload 1.735 ton).

Energy use:

1994: (no applications for CVT)
2010/2015: 5.83 MJ/vehkm (10% reduction); 3.43 MJ/tonkm (payload 1.7 ton)
2030/2040: 5.18 MJ/vehkm (20% reduction); 3.05 MJ/tonkm (payload 1.7 ton)

Economic parameters

Reference vehicle costs are Dfl 45,000 (ICE-van) [Wieman, 1993].

Extra investments (per vehicle) will be:

1994: -
2010/2015: Dfl 1,400
2030/2040: Dfl 1,000

Costs estimates are based on specific power-ratio vans/passenger cars.
3.4 Parameters of alternative transmissions for busses

Energy parameters

Reference energy use: 13.2 MJ/vehkm (energy efficiency: 21%)
For 35 seats, this means 0.38 MJ/seatkm.

Energy use:

1994: (no applications of improved transmission systems)
2010/2015: 12.7 - 12.8 MJ/vehkm (3-4% reduction overall);
            0.35 - 0.36 MJ/seatkm
2030/2040: 10.6 (city) - 11.9 MJ/vehkm (10% reduction overall, 20% reduction
          for city busses); 0.30 (city) - 0.34 MJ/seatkm

1994: no advanced transmission system applications in busses
2010/2015: first advanced transmission-applications in (small) busses
2030/2040: possible applications in all busses, also other transmission improvements introduced

Economic parameters

Reference vehicle costs are Dfl 245,000.

Extra investments (per vehicle) will be:

1994: (Dfl 15,600)
2010/2015: Dfl 5,400
2030/2040: Dfl 4,000

Costs estimates are based on power-ratio busses/passenger cars.

3.5 Parameters of alternative transmissions for trucks

Energy parameters

Reference energy use: 16.2 MJ/vehkm (energy efficiency: 23%),
0.58 MJ/tonne-kilometre, (payload 28 ton).

Energy use:

1994: (no applications of advanced transmission systems)
2010/2015: 15.7 - 15.6 MJ/vehkm (3-4% reduction overall); 0.56 MJ/tonkm
2030/2040: 14.6 MJ/vehkm (10% reduction, transmission efficiency: 95%);
            0.52 MJ/tonkm

2010/2015: possible first advanced transmission applications for light trucks
2030/2040: CVT applications in light trucks, also other transmission improvements introduced
Economic parameters

Reference vehicle costs are Dfl 220,000.

Extra investments (per vehicle) will be:

- 1994: Dfl 52,000
- 2010/2015: Dfl 18,000
- 2030/2040: Dfl 13,200

Costs estimates are based on power-ratio busses/passenger cars.

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PART IV: 
COMBUSTION ENGINES AND VEHICLE CONSTRUCTION

- IMPROVED EXISTING INTERNAL COMBUSTION ENGINES
- FREE PISTON ENGINES
- VEHICLE CONSTRUCTION
PART VI
COMBUSTION ENGINES AND VEHICLE CONSTRUCTION

- Improved existing internal combustion engines
- Free piston engines
- Vehicle construction
1 IMPROVED EXISTING INTERNAL COMBUSTION ENGINES

In this chapter the improved internal combustion engines are discussed. Most road vehicles are equipped with internal combustion engines, but in general, internal combustion engines are relatively fuel inefficient. Only about 15% of the thermal energy is, in the end, used for the propulsion of the vehicle. An important advantage of internal combustion vehicles is the large driving range, the relatively low fuel-costs and the refuelling-speed. Therefore it is important to improve the energy-efficiency of this engines.

1.1 Description of improvements on internal combustion engines

1.1.1 Definition

In internal combustion engines the combustion process of an air-fuel mixture is directly used for the generation of kinetic energy (downward movement of the piston). In most internal combustion engines the up-and-down movement of the piston is transformed in a rotating movement (an exception is the free piston engine which is described in chapter 2 of this part). Distinction can be made between four stroke and two stroke engines, otto and diesel engines and engines for different types of fuel.

1.1.2 Explanation

Four stroke engines
In the first stroke, air or an air-fuel mixture is sucked into the cylinder by the downward piston movement. In the second stroke, the air or air-fuel mixture is compressed by the up-going movement of the piston (and, in a diesel engine, fuel is injected). Then the compressed air-fuel mixture is ignited. In the third stroke the piston is forced down by the combustion process. In the fourth stroke, gases are pressed out of the cylinder by the up-going movement of the piston.

In four stroke engines valves are used to control the flow of the air or the air-fuel mixture and the exhaust gases. In the past, two valves per cylinder were generally used, but in modern engines four or five valves for each cylinder are used. The valves are controlled by one or two camshafts, which can be located at the bottom of the engine (in that case the valves are opened and closed by rods and tappets) or on top. For the propulsion of passenger cars, three, four (most frequently used) or more cylinders are "coupled" in an engine.

Two stroke engines
In two-stroke engines, in one stroke the air-fuel mixture in the cylinder is compressed and simultaneously "fresh" air-fuel mixture is sucked into the lower part of the engine (oil sump). Then the fuel-mixture in the cylinder is ignited and during the second stroke exhaust gases are driven out of the cylinder by the "fresh" air-fuel mixture which is pumped from the oil sump to the cylinder (combustion chamber). The fuel inlet and the exhaust gas outlet are placed at the side of the cylinder; the inlets and outlets are "closed" and "opened" by the piston-movement, so in theory no valves are necessary. Two-stroke engines can be remarkably lighter than four-stroke engines because there is no necessity of valves, camshafts, rods and chains.
Diesel engines

In a standard diesel engine air is compressed until just before maximum pressure is reached and then diesel fuel is injected. At that moment, the combustion process spontaneously starts. In conventional engines, the diesel fuel is injected in a "pre-combustion chamber" which is connected with the cylinder by a relatively small hole. These engines are called "indirect injection diesel engines" (IDI-engines). In newly developed diesel engines, fuel is directly injected in the combustion chamber (Direct Injection, DI-diesel). For DI-engines, the piston-head has to be redesigned to make it possible to inject the fuel. The air that is brought into the cylinder can be compressed by an exhaust-gas driven "turbo" system. In general such a turbo only works at high engine speeds (rotations per minute, during acceleration for example) and provides for extra power for a few seconds.

Otto engines

In an otto engine the fuel-air mixture is ignited by a spark after it is compressed. The compression ratio is lower (less pressure) than in diesel engines. In general, gasoline engines can be lighter of construction than diesel engines with the same performance. The by-products of an otto engine are (up till now) less polluting than those of the diesel engine combustion process. Furthermore, in combination with a gasoline engine it is possible to use a catalytic convertor while it is until now not possible to use such a convertor in combination with a diesel engine. Most otto-engine vehicles used to be equipped by a carburettor, a "mechanical" device to mix fuel and air and to bring this fuel-mixture to the cylinders. In modern cars fuel is injected in the air flow, while the amount of injected fuel is controlled by an electronic system. The fuel can be injected in the throttle body (single point injection) or just in front of the inlet valves of the cylinders (multipoint injection, every cylinder with its own injector).

1.1.3 Energy functions

Passenger car and van: diesel engine

Diesel engines are more fuel-efficient than otto-engines, but diesel engines produce more emissions (NO\textsubscript{x} and soot-particles), are heavier and more expensive to produce; by improving diesel fuel (less sulphur), emissions will diminish, but CO\textsubscript{2}-emissions (and energy use) of refineries will increase. Power output from a diesel engine is controlled by the amount of injected fuel while the compression ratio (20-25 for a small naturally aspirated engine) stays the same. As there are no throttle losses, diesel engines are more fuel efficient at lower speeds (less than maximum power output) in comparison with gasoline engines [Feola, 1991; Hickman, 1991].

Possible improvements of diesel engines concern the following aspects (reducing both the use of energy and the emissions):

- combustion process and duration;
- point of injection, duration and pressure;
- supercharging (turbochargers, mechanical, turbocompound, processor directed supercharging);
- charge of the air cooling (exhaust emissions, smoke/particles);
- mechanical friction;
- electronic diesel control.
By precompressing the air, the combustion process can be improved. Furthermore, direct injection principally results in a better combustion process that causes fewer emissions. The fuel efficiency of DI-diesel is more than 15% to 20% better than the efficiency of an IDI-diesel. A disadvantage of IDI engines is that the combustion process is hard to control and rather noisy [Delsey, 1991].

The design of the combustion chamber (including valves, pistonhead etc.) is of great importance for the combustion process. As it is now possible to "peer" into the chamber while the actual combustion process takes place (laser-technology), it is possible to improve the design of the combustion chamber.

Possible improvements of fuel economy for diesel engines:

- high-speed compression-ignition engines: 20 - 30%
- compression ignition with turbocharging and intercooling: 25 - 40%

[Martin, 1991]

Total efficiency-improvements for diesel engines are estimated at:

- 5% for 1994,
- 20% for 2010/2015,
- 30% for 2030/2040.

Distribution in time based on distribution in time for internal combustion engines. These improvements in fuel efficiency are based on all possible developments mentioned above [V.d. Graaf, 1994; Flenker, 1991].

For a DI-diesel engine, a reduction of NOX-values from 12 to 7 g/kWh causes an increase of the fuel consumption by 8%. Compromises between fuel consumption on the one hand and emissions on the other hand have to be found [Flenker, 1991].

**Passenger car and van: otto engine**

In general, otto engines are less noisy than diesel engines. Gasoline engines, especially for light vehicles, have few or no advantages in energy efficiency for highway or road driving (28% to 32%) compared to the regular diesel engines. On the opposite, at low speeds and especially in urban traffic, the regular diesel engine offers an energy efficiency which is almost double (20-25%) of that of a gasoline engine (10% to 14%) [Delsey, 1991].

The control of power output from (most) gasoline engines is achieved by throttling the intake mixture by reducing the throttle-opening, so pressure losses occur. Low power output is thus obtained by reducing the effective compression ratio. At lower speeds, this will result in a lower efficiency in comparison with diesel engines.

Otto-engines can be made more fuel efficient by:

- applying of multipoint injection;
- reducing the amount of fuel in the air-fuel-mixture and increasing the compression (lean-burn principle);
- redesign of the combustion chamber.

Lean-burn technology offers a benefit in energy efficiency and in emissions control. Fuel consumption can be reduced by as much as 14%, although a range of between 5 and 8% is more realistic in production vehicles. Still, the emissions will be too high to meet the emissions regulations being introduced in Europe. Therefore, the catalytic converter is likely to be the preferred option for spark-ignition engines, instead of the current lean-burn (spark) engines. Where three-way catalysts are used, the fuel consumption might increase 5% [Martin, 1991].
In the tables 1.1.3a and 1.1.3b (below), the energy use of some experimental (prototype) cars is compared with a production vehicle.

### Table 1.1.3a:
**Comparison of energy efficiency between production and prototype cars**

<table>
<thead>
<tr>
<th></th>
<th>Renault 18 production</th>
<th>Renault EVE prototype</th>
<th>Renault EVE+ prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight</td>
<td>920 kg</td>
<td>845</td>
<td>845</td>
</tr>
<tr>
<td>$C_D$</td>
<td>0.39</td>
<td>0.24</td>
<td>0.225</td>
</tr>
<tr>
<td>$SC_D$</td>
<td>0.73</td>
<td>0.47</td>
<td>0.44</td>
</tr>
<tr>
<td>engine</td>
<td>gasoline 1400 cm$^3$</td>
<td>gasoline 1100 cm$^3$</td>
<td>diesel direct inj.</td>
</tr>
<tr>
<td></td>
<td>46 kW</td>
<td>39 kW</td>
<td>1600 cm$^3$</td>
</tr>
<tr>
<td>max. speed</td>
<td>150 km/h</td>
<td>157 km/h</td>
<td>165 km/h</td>
</tr>
<tr>
<td>fuel consump.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90 km/h</td>
<td>6.3 l/100 km, 2.1 MJ/km</td>
<td>4.1 l/100 km, 1.3 MJ/km</td>
<td>3.5 l/100 km, 1.2 MJ/km</td>
</tr>
<tr>
<td>120 km/h</td>
<td>8.4 l/100 km, 2.8 MJ/km</td>
<td>5.5 l/100 km, 1.8 MJ/km</td>
<td>4.4 l/100 km, 1.6 MJ/km</td>
</tr>
<tr>
<td>urban</td>
<td>9.4 l/100 km, 3.1 MJ/km</td>
<td>6.6 l/100 km, 2.2 MJ/km</td>
<td>5.8 l/100 km, 2.1 MJ/km</td>
</tr>
<tr>
<td>average</td>
<td>8.0 l/100 km, 2.6 MJ/km</td>
<td>5.4 l/100 km, 1.8 MJ/km</td>
<td>4.6 l/100 km, 1.6 MJ/km</td>
</tr>
</tbody>
</table>

[Delsey, 1991], calculations of energy use (MJ/km) added

### Table 1.1.3b:
**Comparison of energy efficiency between prototype cars**

<table>
<thead>
<tr>
<th></th>
<th>Peugeot ECO 2000 Gasoline prototype</th>
<th>Peugeot ECO 2000 Diesel prototype</th>
<th>Renault EVE+ prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight</td>
<td>458 kg</td>
<td>510</td>
<td>845</td>
</tr>
<tr>
<td>$C_D$</td>
<td>0.235</td>
<td>0.235</td>
<td>0.225</td>
</tr>
<tr>
<td>$SC_D$</td>
<td>0.38</td>
<td>0.38</td>
<td>0.44</td>
</tr>
<tr>
<td>engine</td>
<td>gasoline 750 cm$^3$</td>
<td>diesel d.i. 903 cm$^3$</td>
<td>diesel direct inj.</td>
</tr>
<tr>
<td></td>
<td>27 kW</td>
<td>29 kW</td>
<td>1600 cm$^3$</td>
</tr>
<tr>
<td>max. speed</td>
<td>151 km/h</td>
<td>163 km/h</td>
<td>165 km/h</td>
</tr>
<tr>
<td>fuel consump.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90 km/h</td>
<td>2.3 l/100 km, 0.8 MJ/km</td>
<td>2.1 l/100 km, 0.7 MJ/km</td>
<td>3.5 l/100 km, 1.2 MJ/km</td>
</tr>
<tr>
<td>120 km/h</td>
<td>3.2 l/100 km, 1.1 MJ/km</td>
<td>3.1 l/100 km, 1.1 MJ/km</td>
<td>4.4 l/100 km, 1.6 MJ/km</td>
</tr>
<tr>
<td>urban</td>
<td>3.5 l/100 km, 1.2 MJ/km</td>
<td>3.2 l/100 km, 1.1 MJ/km</td>
<td>5.8 l/100 km, 2.1 MJ/km</td>
</tr>
<tr>
<td>average</td>
<td>3.0 l/100 km, 1.0 MJ/km</td>
<td>2.8 l/100 km, 1.0 MJ/km</td>
<td>4.6 l/100 km, 1.6 MJ/km</td>
</tr>
</tbody>
</table>

[Delsey, 1991], calculations of energy use (MJ/km) added
In table 1.1.3c estimates of fuel savings by improvements on engines are shown:

<table>
<thead>
<tr>
<th>engine technology</th>
<th>baseline</th>
<th>estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% fuel saving</td>
</tr>
<tr>
<td></td>
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<tr>
<td>general</td>
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<tr>
<td>roller cam followers</td>
<td>flat followers</td>
<td>2.0</td>
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<tr>
<td>friction reduction by 10%</td>
<td>base 1987</td>
<td>2.0</td>
</tr>
<tr>
<td>accessory improvement</td>
<td>conventional</td>
<td>0.5</td>
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<tr>
<td>fuel system</td>
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<tr>
<td>throttle body fuel inj.</td>
<td>carburettor</td>
<td>3.0</td>
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<tr>
<td>multipoint fuel inj.</td>
<td>carburettor</td>
<td>5.0</td>
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<tr>
<td>valve train</td>
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<tr>
<td>overhead camshaft</td>
<td>overhead valve</td>
<td>3.0</td>
</tr>
<tr>
<td>4 valves per cylinder</td>
<td>2 valves</td>
<td>5.0</td>
</tr>
<tr>
<td>variable valve timing</td>
<td>fixed timing</td>
<td>6.0</td>
</tr>
</tbody>
</table>

The costs of improving the average fuel use from 8.3 l/100km to 5.4 l/100km (improvement of 36%) are approximately Dfl 1,500 a car [Ledbetter, 1991], but this improvement includes improvements on tyres, vehicle weight and air-resistance.

Passenger car, two-stroke engine

The Orbital Motor company (Australia) estimates the overall potential for fuel-economy improvement at 30% when compared with a conventional baseline automobile (including redesign of vehicle). Other manufacturers estimate improvements of about 5-8% engine-efficiency improvement and 10-13% overall energy-efficiency improvement [Brogan, 1991]. Potential problems with NOx-emissions (3-way catalytic convertor can not be used due to high oxygen content) and acceptance due to the type of noise (less sturdy noise) [Rutten, 1990].

Costs estimates of two-stroke engines are not available, but probably two-stroke engines will eventually cost as much or even less than four-stroke engines. As the moving parts of the engine (also the piston) have to be lubricated, for most existing types of two-stroke engines lubricant (oil) will be mixed with the fuel in advance. In some newly developed two-stroke engines, moving parts are lubricated by a special lubrication system, but still some lubricant will be spilled in the air-fuel mixture. This mixture of fuel, air and lubricants causes more pollutant exhaust emissions. Furthermore, during the combined inlet/outlet phase of the cycle, some fuel could escape by the exhaust outlet. In modern two-stroke engines, fuel injection systems and special lubricants (or ceramic materials) are used to reduce polluting emissions.
Trucks and busses, diesel engine

With the development of a "low heat rejection engine" for trucks, the efficiency of both the fuel energy and the mechanical power might be improved by 40% to 55%. Till now savings of only 3% to 4% have been demonstrated, while projections of 13-14% and even 20% have been made [Fulkerson, 1989; Sachs, 1992]. High-torque low-rpm engines have already been introduced. The costs of these engines are about the same or less than the engines they supplant; fuel use improvement of 10%-12% is possible. Electronic Truck engine control (ETEC) regulates engine fuel intake, maximum rpm, maximum road speed, power output and other parameters. The costs are Dfl 7,000 - 8,000. ETEC improves fuel economy with 20% in combination with high-torque low-rpm engines (added benefit 4%). Furthermore, injection systems will be improved (high pressure injection), turbocharging and aftercooling will be applied and the "breathing" of engines (by increasing the number of valves per cylinders from 2 to 4) can be improved [Seppen et.al., 1991].

<table>
<thead>
<tr>
<th>Table 1.1.3d: Engine improvements for trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td>costs [Dfl]</td>
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<tr>
<td>engine (control) technology</td>
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<td>lower rpm engines</td>
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<td>intercooler</td>
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<td>improved intake/exhaust</td>
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<td>synthetic lubricants</td>
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<tr>
<td>friction modified oil</td>
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<tr>
<td>total:</td>
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<tr>
<td>engines in development</td>
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<td>improved accessories</td>
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<td>turbocompound/adiabatic</td>
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<td>organic rankine cycle</td>
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<tr>
<td>total:</td>
</tr>
</tbody>
</table>

[Sachs, 1992]

To reduce the NO\textsubscript{x}-emissions, injection of diesel fuel can be retarded. This will lead to a 6-8% lower fuel economy (and possible higher emissions of particles) [Seppen et.al., 1991]. Part of the gains in fuel efficiency therefore has to be used for the reduction of NO\textsubscript{x}, if legislation is aimed at decreasing emissions of this type.

1.1.4 Penetration

Penetration of improvements will be very high if it is possible to comply with the emission standards. When this is no problem, a penetration of 100% is possible [Rutten, 1990].
1.1.5 Competing technologies

Possible competing technologies for improved internal combustion engines are electric vehicles:
- electric vehicles equipped with fuel cells (not yet fully developed, expensive, space-inefficient)
- electric vehicles equipped with batteries (heavy, expensive and relatively inefficient) [Rutten, 1990].

Furthermore, there is mutual competition between the various internal combustion engine technologies.

Options are:

**competing engines**
- Diesel: 6.2 l/100 km (in production)
- Otto: 11.1 l/100 km (in production)
- Gas turbine: 8.3 l/100 km (tests)
- Stirling engine: 8.6 l/100 km (tests)
- Steam (Rankine) engine: 5.8 l/100 km (estimated)
- Two stroke engines: 5.7-5.4 l/100 km (estimated) [Kinbom, 1991; Brogan, 1991 (two-stroke engine)]

**competing fuels:**
- diesel: 2.0 MJ/km (about 5.6 l/100 km)
- otto (gasoline): 2.3 MJ/km (about 7.0 l/100 km)
- CNG in adapted IC engine: 2.2 MJ/km
- Hydrogen in adapted otto engine: 1.9 MJ/km [IEA, 1993]

(note the differences in fuel consumption given by the different sources)

Below, some of these competing technologies will be described shortly.

**Gas engines**
Gas engines are mostly based on traditional ICEs. In gasoline engines converted to run on CNG, the gas is added to intake air through a variable valve in the inlet manifold or carburetor. Gas in the engine intake displaces air so that less fuel can be burned, while in gasoline or diesel engines small droplets of fuel are injected. The non optimal combustion process causes a fall in maximum power output (15-20%) in a typical gasoline or diesel optimized engine [Stephenson, 1991]. In CNG-optimized engines, the fall in full throttle output would be about 5-10% [USDOE, 1990]. The loss of power can be compensated by use of a larger engine or a turbocharger, adding to the costs and weight of engines. In a CNG-diesel engine, a spark or a small amount of diesel fuel is needed to ignite the fuel-air mixture. Dual-fuel diesel engines are about 20% more energy-efficient than spark ignition (CNG) engines.

Gas engines (LNG/CNG) can be 5-10% more fuel-efficient than gasoline engines, but gas engines are more expensive than standard ICEs and there are several technical problems (leaking of gas with gas regulators, difficulties with high engine temperatures) [IEA, 1993]. The advantages seem to be too small to use these engines [Hovers, 1992], especially because the storage and handling systems are heavy and complex. Natural gas can be transported in compressed (CNG) or liquid (LNG) form. A CNG vehicle requires large and heavy gas cylinders; steel gas storage systems have five times the volume and weight of gasoline tanks containing the same energy. By using advanced, but more expensive materials like carbon fibres, the weight of the steel tank can be reduced by 50%. The costs vary for different materials: Dfl 70/kg fuel for steel tanks,
DFL 140/kg fuel for aluminium, DFL 160/kg fuel for glassfiber and DFL 300/kg fuel for carbon fibre [Bergh, 1991]. Advanced gas storage facilities, using activated carbon, make it possible to store CNG under lower pressure (35 bar). Another advantage of these tanks is the lower weight. As LNG has to be (deep) cooled whole handled and stored, this is a hard method to use natural gas in vehicles.

**Gas turbines**

Gas turbines offer the potential for high fuel economy if operating temperatures can be increased beyond what is possible with all metal turbines. Advantages should be:

- smooth, quiet power,
- multi-fuel capability,
- low maintenance costs,
- low parts count,
- low exhaust emissions,
- high reliability,
- compactness,
- low weight.

[Brogan, 1991]

Gas turbines for automotive applications have to be developed further. Primary technical challenges include the development of:

- reliable high-temperature ceramical components for structures,
- an engine suitable for several low emission fuels,
- efficient heat recovery and management,
- a high efficient small turbomachinery,
- high temperature bearings,
- lubrication and scale-up of ceramic fabrication processes for large scale,
- cost effective production.

[Brogan, 1991]

The gasturbine engine is expected to achieve an efficiency of about 42% within the 100kW output range. The efficiency drops with the engine size [Kinbom, 1991]. The opinions on the potential of gasturbines differ; some say they will never be more energy-efficient than improved ICES [Rutten, 1990; French, 1991], others think there will be a promising future [Fulkerson, 1989; Brogan, 1991]. Solid figures to prove this last statement are not given. Cost estimates of gas-turbines are not available. The storage and handling problems are the same as with ICE-based gas engines when LNG is used; when diesel (or other fuel) is used, the storage poses no problems.

**Hydrogen fuel engines**

Hydrogen fuel can be considered as a long-term potential fuel (not before 2010). Hydrogen fuel can best be used in spark-ignited direct-injection engines. In the long term non-combustion fuel-cells may be used (in combination with an electric motor). The very low ignition energy ("explosive" fuel mixture) and wide flammability limits of hydrogen cause some problems in otto engines. Special measures are needed to regulate combustion in order to avoid backfire (combustion in the intake manifold), pre-ignition and knock. Proposed solutions are based on water injection, high-pressure hydrogen injection in the second half of the stroke, exhaust-gas recirculation and very lean burn. In lean burn conditions, knock and backfiring do not occur while the emission of NO\textsubscript{x} is zero. As with CNG, the storage of hydrogen poses problems. Tanks have to be heavy and bulky to hold an amount of energy comparable to diesel or gasoline tanks. Hydrogen can be stored under high pressure (200 bar), as a cryogenic liquid (-253°C) or chemically bound in metal hydride storage ("adsorption"). The energy-equivalent of 75 litres of gasoline is supplied by about one cubic metre of hydrogen at 225 bar. The cylinder weight would be around 1500 kg. Next to weight and volume problems, the storage of (cryogenic) hydrogen poses problems due to evaporation and boiling off during refuelling [IEA, 1993; Bergh, 1991].
Hydraulic and compressed air engines

Especially in busses and in equipment, hydraulic engines can be used. Compressed oil is used to power the vehicles; the oil is brought under pressure by an onboard (non-transient) combustion engine. (See also "Free piston engine").

Pneumacom (USA) made a prototype of a compressed air-powered vehicle. In this passenger car high-pressure air (20 MPa) powers two engines. The vehicle should be able to drive for 2.5 hours, there are no figures about range, speed and acceleration characteristics at all. The air is compressed by a compressor-station, outside the vehicle. With a natural gas-driven compressor, the pressure is at 20 MPa in only 4 minutes. No information is available about (total, chain) energy use and efficiency of the compressor and "air-motor" or the costs. The main purpose is to decrease local emissions (zero-emission vehicle) [Stienstra, 1994].

1.1.6 State of development, current R&D

Research on improvements of internal combustion engines is aimed at the combustion process, the motor weight, the internal resistance and the loss of energy (heat). It is important to note that:

- improvements are not only aimed at fuel reduction but also at emission reduction: some emission-reduction improvements use more energy;
- improvements are furthermore aimed at lighter and smaller engines, so more power is available with a same-size motor;
- the development process is more evolutionary than revolutionary.

This last point makes it difficult to estimate "extra" costs, because "extra" in comparison to what? Usually, all manufacturers will try to offer the same reduction in energy use or emission production: there will simply be no choice between efficient and less efficient motors (in comparable vehicles).

Improvement of ICE (diesel/otto): all engine manufacturers (VM Motori, Italy; Peugeot, Renault, France; BMW, Volkswagen Germany; Isuzu, Nissan, Japan)
Hydrogen fuel: Mercedes Benz, BMW-DLR (Germany), MITI (coordination, Japan).
Gas Turbines: Allison (GM), Garrett (Allied-Signal) and Volvo.
Automotive gas engines: Volvo, Entec.
Two-stroke engines: Blair (University of Belfast, GB) cooperating with BMW Technik (Germany), General Motors, Ford/Optoral (USA/Australia), Toyota, Fuji Heavy Industries (Japan).

Current projects on diesel engines

- **ECO-diesel**
  Volkswagen's Golf is equipped with an indirect (so traditional) injection diesel system (IDI) with turbo-charger and catalytic converter: especially designed to reduce emission. The technologies used are complex and not very durable. The Ökô-Polo is a.o equipped with a turbo charger and a soot-filter system; the car is very fuel-efficient. The Golf Ecomatic uses a system that switches off the diesel engine as much as possible, so saving fuel and energy.

- **intercooling**
  In the intercooling system, the temperature of intake air is decreased, so the compression process is made easier. More power can be obtained [Feola, 1991].

- **DI-diesel**
  By direct injection of diesel fuel, a higher fuel-efficiency (15-20%) can be obtained.
The engine runs less smoothly, so driving can be less comfortable. Other side-effects can be higher emission of NO\textsubscript{x} and soot particles and the production of more noise.

**Current projects on otto engines**
- **multi-valve technology**
The use of 3, 4 or 5 valves for each cylinder leads to a higher compression ratio and so to a higher specific power or a decrease in energy use: the energy use of 4-valve (per cylinder) engines can be 8% less than the energy use in 2-valve engines.
- **valve-steering management**
Improvement of the combustion process leads to less energy use or higher specific power.
- **(turbo) charging**
Improvement of the combustion process by increasing the compression ratio: extra power or a lower energy use can be obtained. The technology is rather expensive so, at the moment, it is only used in special cars. Combination of multi-valve technology with turbo charging improves efficiency. Optimization of turbocharger time response at all engine loads and speeds of rotation can be obtained by an accurate design of variable geometry radial turbine.
- **multipoint/singlepoint injection**
Multipoint injection (injection just in front of the inlet valves of each of the cylinders) or singlepoint-injection (injection in throttle body) in combination with electronic control improves the fuel-efficiency of engines due to a better air/fuel-mixture in all cylinders. Energy-efficiency of test-engines is comparable with diesel engines (this means a significant raise in otto-engine efficiency).
- **redesign of combustion chambers**
Improvement of combustion process.
- **ceramic elements**
Reduction of internal resistance (see also table: 10% efficiency gain expected), also lower mass of rotating elements, so possibilities of increasing motor speed. This will lead to higher exhaust gas temperatures, which can be used for turbo charging or energy-storing systems only. The net result of lightweight ceramic elements will be marginal [Ruten, 1990].
- **lean-burn engines**
Only useful in smaller cars because of the higher NO\textsubscript{x}-production. Lean burn engines can reduce other emissions and energy use. Problems are the high development costs and the irregular combustion process.

Note: most engine developers try to improve the fuel efficiency of the engines; this leads to a better "power to fuel-use" ratio. The net effect on the fuel consumption is dependent of the fact how many "power" is installed in an (average) car or, what types of engines are bought. In the past, the average fuel consumption of cars did not decrease significantly due to the fact buyers bought more powerful vehicles [Kroon, 1994].
1.1.7 Bottlenecks

From the point of view of fuel-efficiency, diesel engines are better than otto engines. From the point of view of emissions, especially NO\textsubscript{x} and soot-particles, otto engines are better. There seems to be no compromise, so this will be an important point of discussion. This also goes for the improvement of (diesel) engines. With gas-turbines the high engine temperatures and the gas-storage systems (if LNG is used) pose problems. With two-stroke engines it is very hard to meet emission standards.

1.1.8 Availability

All described technologies for otto and diesel engines are already in use or being tested. Automotive gasturbines are not commercially available. USDOE estimates they can be available in 15 years [Bogan, 1991], so if the desired developments really take place, they can be fully operational in the 2030/2040 period. Two-stroke engines can be commercially available around 2030/2040 when they meet emission standards [Wallentowitz, 1994].

1.2 Parameters of improvements of combustion engines for passenger cars

Energy parameters

Diesel engines

Reference energy use for diesel engines is less than for gasoline engines. At an overall-efficiency of 21% (estimated), the reference energy use is approximately 2.32 MJ/km (1.54 MJ/seatkm).

Energy use with improvements (diesel, related to 1994 diesel reference)

- 1994: 2.20 MJ/km (-5%, lubricants)
- 2010/2015: 1.86 MJ/km (-20, direct injection diesel engines)
- 2030/2040: 1.62 MJ/km (-30%, DI, supercharging, electronic engine control)

Otto engines

Reference energy use 2.56 MJ/km (energy efficiency 19%, gasoline engine); 1.71 MJ/seatkilometre.

Energy use with improvements (fuel-to-wheels efficiency):

- 1994: 2.43 MJ/vehkm (-5%, friction reduction, electr. engine management)
- 2010/2015: 2.12 MJ/vehkm (-17%, lean burn, high compression, 4 valves/cylinder, overhead camshaft)
2030/2040: 1.97 MJ/vehkm (-23%, electronic engine management, variable valve timing)
1.31 MJ/seatkm
[efficiency-estimates: Martin, 1991; IEA, 1993, distribution through the years of improvements: own estimate]

Two-stroke engines
Energy use (two-stroke), related to 1994 otto engines, overall improvements:
1994: 2.4 MJ/vehkm (-5%, engine in existing bodies)
1.6 MJ/seatkm
2010/2015: 2.2 MJ/vehkm (-13%, engines in redesigned body, low estimate)
1.5 MJ/seatkm
2030/2040: 2.0 MJ/vehkm (-30%, engines in redesigned body, high estimate)
1.4 MJ/seatkm
[estimates based on Brogan 1991, distribution through the years: own estimate]

Calculation of required energy for driving (ICE, excl. losses) based on "lower estimation" [Bossche, 1992]: Energy (Wh/vehicle tonkm) = 80 + (80 / vehicle mass); reference energy-efficiency for passenger cars is estimated. The calculated energy use for internal combustion engine vehicles is somewhat higher than the energy use calculated in "Cars and Climate Control" [IEA, 1993]. Their estimates are 2.3 MJ/km (gasoline-ICE) and 0.69 MJ/km (full electric vehicle). Result for ICES is comparable to, for example, 2.6 MJ/vehkm [Delsey, 1991].

Economic parameters
Reference vehicle costs Dfl 22,000 [Martin et al., 1992].
Reference maintenance costs Dfl 0.33/km or Dfl 0.22/seatkm [Kram et al., 1989].

Extra investment costs per vehicle:
1994: Dfl 100
2010/2015: Dfl 680
2030/2040: Dfl 1,000
[estimates based on gasoline engines IEA, 1993]

Extra investment costs per vehicle (two-stroke)
1994: ? (high development costs, not commercially available)
2010/2015: ? possible lower production costs (less complicated construction)
2030/2040: ? possible lower production costs (less complicated construction)
[no estimates given]

Technical life: more than car (body) life.
Maintenance costs: comparable to available internal combustion engines, maybe somewhat higher due to more complicated construction (diesel/otto) or maybe less due to less complicated construction (two-stroke engine).
Environmental parameters

Emissions
Production of carbon dioxide, nitrous oxide, soot (diesel, two-stroke), particles (diesel, two-stroke). Problem: higher fuel efficiency often causes more NOx-emission.
Noise: more noise production in case of DI-diesel and two-stroke engines.

Materials
In the improved internal combustion engines, no scarce materials are used.

1.3 Parameters of improvements of combustion engines for vans

Energy parameters

Otto engines
Reference energy use 6.82 MJ/km (energy efficiency 19%, gasoline engine); 3.93 MJ/loading tonkilometre.
Energy use with improvements (fuel-to-wheels efficiency):

<table>
<thead>
<tr>
<th>Year</th>
<th>Energy Use</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>6.48 MJ/vehkm (-5%, friction reduction, electr. engine management)</td>
<td>3.73 MJ/seatkm</td>
</tr>
<tr>
<td>2010/2015</td>
<td>5.66 MJ/vehkm (-17%, lean burn, high compression, 4 valves/cylinder, overhead camshaft)</td>
<td>3.26 MJ/seatkm</td>
</tr>
<tr>
<td>2030/2040</td>
<td>5.25 MJ/vehkm (-23%, electronic engine management, variable valve timing)</td>
<td>3.03 MJ/seatkm</td>
</tr>
</tbody>
</table>

Diesel engines
Reference energy use: 6.48 MJ/vehkm (energy efficiency: 20%); this can be compared with a energy use of approximately 3.73 MJ per tonne-kilometre (payload 1.735 ton).

Energy use with improvements (diesel)

<table>
<thead>
<tr>
<th>Year</th>
<th>Energy Use</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>6.16 MJ/vehkm (-5%, lubricants)</td>
<td>3.55 MJ/tonkm</td>
</tr>
<tr>
<td>2010/2015</td>
<td>5.18 MJ/vehkm (-20%, direct injection diesel engines)</td>
<td>2.99 MJ/tonkm</td>
</tr>
<tr>
<td>2030/2040</td>
<td>4.54 MJ/vehkm (-30%, DI, supercharging, intercooling)</td>
<td>2.61 MJ/tonkm</td>
</tr>
</tbody>
</table>

Figures for improvement of efficiency based on figures for diesel engine passenger cars.

Calculation of "net energy" (energy for driving without losses) is based on "lower estimation" [Bossche, 1992]: Energy (Wh/vehicle tonkm) = 80 + (80 / vehicle mass); reference energy efficiency is estimated. Compared to the reference energy use some authors calculate relative lower energy use (3.8 MJ/km at 646 kg of loading [Haspel, 1991] and 5.4 MJ/km at full load [Rijkeboer, 1994]) but based on fuel-consumption also relatively higher figures can be calculated (4.56 MJ empty [Wieman, 1994]).
**Economic parameters**

Reference vehicle costs Dfl 45,000 (ICE-van) [Wieman, 1993].
Reference maintenance costs Dfl 1.43/vehkm or Dfl 0.82/tonkm (interpolated cost estimate of Dfl 220/GJ, based on [Kram et al., 1989]).

Investment costs per vehicle (otto and diesel):

- **1994:** Dfl 280
- **2010/2015:** Dfl 1,900
- **2030/2040:** Dfl 2,800

Cost-estimates based on extra investments for passenger cars times the energy use ratio (approx. 2.8).

Technical life: more than car (body) life.
Maintenance costs: comparable to available engines, maybe somewhat higher due to more complicated construction.

(for environmental parameters, see 1.3 above)

### 1.4 Parameters of improvements of combustion engines for busses

#### Energy parameters

Reference energy use: 13.2 MJ/vehkm (energy efficiency: 21%); this can be compared to an energy use of approximately 0.38 MJ per seat-kilometre.

Energy use with improved engine:

- **1994:** 11.2 MJ/vehkm; 0.32 MJ/seatkm
  (-15%: intercooler, improved intake/exhaust, improved lubricants)
- **2010/2015:** 9.1 MJ/vehkm; 0.26 MJ/seatkm
  (-31%: as 1994 + electronic truck engine control and lower rpm engines)
- **2030/2040:** 8.18 MJ/vehkm; 0.23 MJ/seatkm
  (-38%: as 2010/2015 + drive train improvements)
  [reductions: Sachs, 1992, (distribution in time: own estimate)]

Mass of internal combustion engine bus 16,500 kg, base vehicle mass 16,240 kg (incl. electric motor(s), excl. ICE motor and tanks); reference energy efficiency is estimated. Number of seats: 35. Travel distance/year: 60,000 km [CBS, 1993].

#### Economic parameters

Reference vehicle costs Dfl 245,000.
Reference maintenance costs Dfl 4.88/vehkm (Dfl 0.14/seatkm).

Extra investments:

- **1994:** Dfl 2,400
- **2010/2015:** Dfl 8,900
- **2030/2040:** Dfl 16,000

Cost-estimates based on truck-costs times the energy use ratio (energy use of bus is approx. 0.8 times energy use of trucks)
Lifetime of engine: more than bodywork
Lifetime and replacement time of materials:
oil: 15,000 kms: 4 times a year (Dfl 100/year)
lubricants: 150,000 kms: 1 time every 2.5 year (Dfl 60/year)
intake/exhaust: 800,000 kms, 1 time every 13 year (Dfl 100/year)

Maintenance costs: probably little higher due to more complex construction

(for environmental parameters: see 1.5, below)

1.5 Parameters of improvements of combustion engines for trucks

Energy parameters

Reference energy use: 16.2 MJ/vehkm (energy efficiency: 23%),
0.58 MJ/tonne-kilometre, (payload 28 ton).

Energy use with improved engine:
1994: 13.8 MJ/vehkm; 0.49 MJ/tonkm (payload)
(-15%: intercooler, improved intake/exhaust, improved lubricants)
2010/2015: 11.2 MJ/vehkm; 0.40 MJ/tonkm
(-31%: as 1994 + electronic truck engine control and lower rpm engines)
2030/2040: 10.0 MJ/vehkm; 0.36 MJ/tonkm
(-38%: as 2010/2015 + drive train improvements)
[reductions: Sachs, 1992 (distribution in time: own estimate)]

Reference energy use of trucks based on average fuel consumption (a.o. [Wieman, 1994]), reference energy efficiency estimated. Mass of truck, including maximum loading, 35,000 kg. Base vehicle mass 6,270 kg (incl. electric motor(s) and a starting-battery package) [Wieman, 1994]; maximum payload (combustion engine) 28,000 kg. Travel distance/year: 60,000 km (50,000 truck, 90,000 tractor) [CBS, 1993].

Economic parameters

Reference vehicle costs Dfl 220,000 [Wieman, 1994].
Reference maintenance costs Dfl 1.70/vehkm (Dfl 0.06/tonkm); based on [Kram et al., 1989].

Extra Investments:
1994: Dfl 3,000
2010/2015: Dfl 8,000
2030/2040: Dfl 8,000
[estimates of cost based on Sachs, 1992 (distribution in time: own estimate)]

Lifetime of engine: more than bodywork
Lifetime and replacement time of materials:
oil: 15,000 kms: 4 times a year (Dfl 100/year)
lubricants: 150,000 kms: 1 time every 2.5 year (Dfl 60/year)
intake/exhaust: 800,000 kms, 1 time every 13 year (Dfl 100/year)

Maintenance costs: probably little higher due to more complex construction
Environmental parameters

As most trucks are equipped with diesel engines, the emission of soot, particles and hydrocarbons poses most problems. For diesel engines, higher fuel efficiency generally leads to an increase of emission of NOx. Improved (DI) diesel engines can be more noisy and this will certainly be a problem because present vehicles already pose problems.

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2 FREE PISTON ENGINES

In this chapter the free piston engine will be described. Free piston engines are newly developed internal combustion engines. The up-and-down movement of the piston is not transformed to a rotating movement, but is used directly. The return-movement of the piston (and the compression) is driven by compressed gas. Free piston engines are smaller, cheaper and more fuel-efficient than their conventional counterparts.

2.1 Description of free piston engines

Definition
Hydraulic Free Piston Engines (FPEs) produce an oil flow under pressure. The hydraulic cylinder is directly coupled with the FPEs, without rotating parts. The up-and-down movement of the piston is directly used and not transformed into a circular movement. The construction can be compared with a two-stroke engine, as there are no valves (in the combustion part of the engine).

Explanation
In a FPE, the piston is directly coupled to the hydraulic plunger of the pump system. By electronic control, it is possible to hold the piston for a shorter or longer period at the "dead point" of the movement. The return movement of the piston is driven by compressed gas; the flow of this gas is controlled by valves. In this way, it is possible to regulate the frequency of the piston movement, while the combustion process is not dependent on the frequency: emissions and energy use are the same for each piston movement. The development of high-speed hydraulic valves made it possible to steer the piston movement. At the moment, standard valves can be used. Because FPEs are relatively simple machines, construction costs can be about 30%-50% less than conventional, steady state internal combustion engines (Jongeneel, 1994). For the production of FPEs, ordinary materials and conventional components can be used (hydraulic valves, high-pressure injection systems and even electronic components, although the electronic steering system is not standard). The emission characteristics of FPEs are even better than the energy-use characteristics because of the optimal combustion process. GM and IW-TNO estimate a reduction of 80% of NOx and 75% of sulphur would be possible (compared to steady-state ICEs).

Figure 2.1: internal combustion engine (left) and free-piston engine, both combined with a hydraulic pump
Energy functions
The fuel consumption can be reduced from 20% up to 50% in comparison with conventional steady-state ICEs. Overall efficiency of dieselhydraulic aggregate 35%, the FPE: 45% [Knip, 1993].

Penetration
FPEs in combination with hydraulic traction can be used in so-called mobile equipment. In the Netherlands, the estimated energy use of this equipment is 35 - 40 PJ a year, (1991) [Achten, 1994], about half the energy use of all freight vehicles. Reliable estimates of the degree of penetrations in mobile equipment and other vehicles can not be given [Achten, 1994]. It is not very likely a large part of on-road vehicles (cars, vans, busses or trucks) will be equipped with a FPE-hydraulic motor combination; maybe there are some applications for hybrid electric vehicles.

Competing technologies
Other steady-state combustion engines (like in hybrid vehicles), gas turbines, Stirling engines and fuel cells (gas turbines, Stirling engines and fuel cells are in general more complex to build or require scarce materials).

State of development
Now only prototypes and test-applications are in use. In the next years (i.e. 1995 - 1996) new prototypes will be built. In general, new technologies used to improve diesel engines (hydraulic valves, fuel injection systems) can also be used in FPEs. As electronic motor management systems are widely used in present vehicles, the necessary electronic management system for FPEs is no longer an obstacle for the application of these engines.

Current R&D
At the moment research is done to improve and to scale up the prototypes to get higher specific power. Research is done by:
• IFP (Innas Free Piston) by INNAS (The Netherlands)
• Hydro motors: Volvo Cumulo

Bottlenecks
The construction of FPEs does not require special technologies or materials. As electronic motor management systems are widely accepted, this is no longer an obstacle to use FPEs [Achten, 1994]. Price, weight and above all noise are the main problems for FPEs in combination with hydraulic motors. Furthermore, possible problems are foreseen with servo valves for large oil volumes [Wallentowitz, 1994].

Availability
The first FPEs can be in the market between 1995 and 2000, but a large-scale use of FPEs will be only possible after 2005. In the meantime, further developments will take place.
2.2 Parameters of free piston engines for passenger cars

Energy parameters

Reference energy use (engines in hybrid passenger car; diesel engines):
1994: ICE, 0.087 l/km, 3.08 MJ/km (engine efficiency 23%)
      2.05 MJ/seatkm
2010/2015: ICE, 0.061 l/km, 2.16 MJ/km (engine efficiency 30%)
          1.44 MJ/seatkm
2020/2030: ICE, 0.060 l/km, 2.12 MJ/km (engine efficiency 30%)
          1.41 MJ/seatkm

Theoretical energy use:
1994: FPE, 0.067 l/km, 2.36 MJ/km (engine efficiency 30%)
      1.57 MJ/seatkm
2010/2015: FPE, 0.052 l/km, 1.85 MJ/km (engine efficiency 35%)
          1.23 MJ/seatkm
2030/2040: FPE, 0.040 l/km, 1.41 MJ/km (engine efficiency 45%)
          0.94 MJ/seatkm

In 1994 and 2010/2015 FPEs will almost certainly not be used in passenger cars.
In 2030/2040 FPEs could possibly be combined with the CUMULO system (a hydrostatic drive train plus pressure accumulators) or in combination with a linear generator in electric (hybrid) vehicles. For the calculations the electric-hybrid application is used.

Economic parameters

Reference vehicle costs Dfl 22,000.
Reference maintenance costs Dfl 0.33/km or Dfl 0.22/seatkm.

The INNAS developing company can not give estimates for investment and maintenance costs, so the below costs are estimates.

Extra investments (per vehicle):
1994:
2010/2015: about Dfl 2,400
2030/2040: about Dfl 1,600

Costs of FPEs are 70% - 50% of the costs of steady state ICEs [Jongeneel, 1994].
When a 30 kW engine costs about Dfl 3,500 [Martin, 1991] and a steady state ICE is about 90% of that costs (Dfl 3,150, estimate), a FPE would cost about Dfl 1,580 - 2,360.

Maintenance costs for FPEs will be lower in comparison with ICEs. At 75% (estimated), the maintenance costs will be Dfl 0.21/km or Dfl 0.14/seatkm in 2010/2020 and Dfl 0.20/km or Dfl 0.14/seatkm in 2020/2030.

Environmental parameters

Emissions
Type of emissions is comparable with steady state ICE, but the volume will be approximately 50 - 75% less (NOx). The use of a FPE in combination with a hydraulic motor cause a lot of noise: this can pose severe problems; fewer problems if a FPE is combined with an electric motor.
Materials
Use of common materials.

Note: probably there will not be a wide spread use of FPEs in passenger cars.

2.3 Parameters of free piston engines for vans

Energy parameters

Reference energy use (engines in hybrid van; diesel engines), ICE-drive:

1994: ICE, 0.127 l/km, 6.10 MJ/km (engine efficiency 23%)
4.93 MJ/tonkm
(restricted range for electric drive)

2010/2015: ICE, 0.136 l/km, 4.80 MJ/km (engine efficiency 30%)
2.94 MJ/tonkm

2020/2030: ICE, 0.136 l/km, 4.80 MJ/km (engine efficiency 30%)
2.86 MJ/tonkm

Theoretical energy use, ICE-drive:

1994: FPE, 0.097 l/km, 4.68 MJ/km (engine efficiency 30%)
3.78 MJ/tonkm

2010/2015: FPE, 0.117 l/km, 4.11 MJ/km (engine efficiency 35%)
2.52 MJ/tonkm

2030/2040: FPE, 0.091 l/km, 3.20 MJ/km (engine efficiency 45%)
2.13 MJ/tonkm

1994: no applications of FPEs in vans

2010/2015: maybe FPEs combined with CUMULO or in hybrid electric vehicles, especially in inner city distribution (fleetowners only)

2030/2040: FPEs combined with CUMULO engines in hybrid electric vehicles.

Economic parameters

Reference vehicle costs Dfl 45,000 (ICE-van) [Wieman, 1993].
Reference maintenance costs Dfl 1.43/vehkm or Dfl 0.82/tonkm
(interpolated cost estimate of Dfl 220/GJ, based on [Kram et al., 1989]).

Extra investments (per vehicle, estimated):

1994: -
2010/2015: about Dfl 7,000
2030/2040: about Dfl 5,000

Costs of FPEs are 70% - 50% of the costs of steady state ICES [Jongeneel, 1994].
If a 70 kW engine costs about Dfl 10,500 [Swen, 1992] and a steady state ICE is about 90% of that costs (Dfl 9,450, estimate), a FPE would cost about Dfl 4,725 - 7,090.

Maintenance costs of FPE are estimated at 75% of ICE-costs: Dfl 0.78/vehkm or Dfl 0.50/tonkm (payload) in 2010/2015 and Dfl 0.78/vehkm or Dfl 0.47/tonkm in 2020/2030. Costs based on costs for hybrid vehicles/diesel ICE vehicles.
Environmental parameters

Emissions
Type of emissions is comparable with steady state ICE, but the volume of emissions is 50% - 75% less (NOx).
The use of a FPE in combination with a hydraulic motors cause much noise: this can pose severe problems.

Materials
In the production of FPEs only common materials are used.

2.4 Parameters of free piston engines for buses

Energy parameters

Reference energy use (Engines in hybrid bus; diesel engines), ICE-drive:
1994: ICE, 0.420 l/km, 14.9 MJ/km (engine efficiency 23%)
      0.56 MJ/seatkm
      (restricted range for electric drive)
2010/2015: ICE, 0.289 l/km, 10.3 MJ/km (engine efficiency 30%)
           0.29 MJ/seatkm
2020/2030: ICE, 0.289 l/km, 19.3 MJ/km (engine efficiency 30%)
           0.29 MJ/seatkm

Theoretical energy use, ICE-drive:
1994: FPE, 0.322 l/km, 11.4 MJ/km (engine efficiency 30%)
      0.33 MJ/seatkm
2010/2015: FPE, 0.248 l/km, 8.83 MJ/km (engine efficiency 35%)
           0.25 MJ/seatkm
2030/2040: FPE, 0.193 l/km, 12.9 MJ/km (engine efficiency 45%)
           0.37 MJ/seatkm

1994: only prototypes (city buses)
2010/2015 & 2030/2040: FPEs combined with CUMULO system; especially useful in cities.

Economic parameters

Extra investments (per vehicle, estimated):
1994: -
2010/2015: about Dfl 18,000
2030/2040: about Dfl 12,000

Costs of FPEs are 70% - 50% of the costs of steady state ICEs [Jongeneel, 1994].
If a 135 kW engine costs about Dfl 27,000 [Swan, 1992] and a steady state ICE is about 90% of that costs
(Dfl 24,300, estimate), a FPE would cost about Dfl 12,150 - 18,230.

Maintenance costs of FPE estimated at 75% of ICE-costs: Dfl 2.86/vehkm or Dfl 0.08/seatkm in 2010/2015 and 2020/2030. Costs based on costs for hybrid vehicles/diesel ICE vehicles.
Environmental parameters

Emissions
Type of emissions comparable with steady state ICE, but 50% - 75% less (NOx).
The use of a FPE in combination with a hydraulic motor causes a lot of noise: this can
pose severe problems, especially because busses will (also) be used in urban areas.

Materials
Use of common materials.

2.5 Parameters of free piston engines for trucks

Energy parameters

Reference energy use (engines in hybrid bus; diesel engines), ICE-drive:
1994: ICE, 0.496 l/km, 17.5 MJ/km (engine efficiency 23%)
0.71 MJ/tonkm
(restricted range for electric drive)
2010/2030: ICE, 0.390 l/km, 13.8 MJ/km (engine efficiency 30%)
0.50 MJ/tonkm

Theoretical energy use, ICE-drive:
1994: FPE, 0.372 l/km, 13.1 MJ/km (engine efficiency 30%)
0.53 MJ/tonkm
2010/2030: FPE, 0.293 l/km, 10.4 MJ/km (engine efficiency 35%)
0.38 MJ/tonkm

2010/2015 only prototypes
2030/2040: FPEs combined with CUMULO system; from emission point of view,
especially useful in city-distribution.

Economic parameters

Extra investments (per vehicle, estimated):
1994: -
2010/2015: about Dfl 31,000
2030/2040: about Dfl 21,000

Costs of FPEs are 70% - 50% of the costs of steady state ICES [Jongeneel, 1994].
If a 230 kW engine costs about Dfl 46,000 [Swan, 1992] and a steady state ICE is about 90% of that costs
(Dfl 41,400, estimate), a FPE would cost about Dfl 20,700 - 31,050.

Maintenance costs of FPE estimated at 75% of ICE-costs: Dfl 1.09/vehkm or
Dfl 0.04/tonkm in 2010/2015 and 2020/2030. Costs based on costs for hybrid
vehicles/diesel ICE vehicles.
Environmental parameters

Emissions
Type of emissions comparable with steady state ICE, but 50% - 75% less (NOₓ);
The use of a FPE combined with a hydraulic motor causes a lot of noise: this can pose severe problems, especially because these trucks will probably be used in urban areas (distribution).

Materials
Use of common materials.

References
- Knip, J.K. (1993), Free Piston engines (in Dutch: De vrije zuiger motor), in NRC December 12
- Wallentowitz (1994), Review
3 VEHICLE CONSTRUCTION

In this chapter vehicle construction technologies are described that can contribute to more energy-efficient vehicles. The technologies include reduction of vehicle weight, reduction of rolling resistance and the reduction of air resistance.

3.1 Description of developments in vehicle construction

3.1.1 Definition

By decreasing the weight, air resistance and rolling resistance of a vehicle, energy can be used to drive the vehicle more efficiently. These measurements will decrease the fuel consumption and energy use.

3.1.2 Explanation

**Vehicle weight**

The vehicle weight can be decreased by using light materials like aluminum and plastics instead of steel and by redesigning the body work and engine. Especially when plastics are used, for the construction of the body work so-called space frames are used to obtain a strong and stiff bodywork.

The use of aluminium in cars is expected to increase:
- 1990: average 94 kilograms of aluminium in cars
- 2000: 115 to 140 kilograms of aluminium in cars
- 2015: estimates of about 10% of produced cars are full-aluminium cars

[Knip, 1993]

Full-steel vehicles weigh about 950 kg while the same aluminium vehicle weighs about 700 kg. A reduction of fuel consumption of 1.2 up to 1.8 litres per 100 km is possible [Knop, 1993].

Plastics are widely used in vehicles, for example in the interior. Other parts of the vehicle like bumpers and bonnets can also be made of plastics (weight reduction of elements by 50% in comparison with steel). To construct a lightweight but strong and stiff "space frame", lightweight body panels can be used, for example made of plastics (like BMW E1).

It is even possible to use plastics in the engine, as is shown in the "Polimotor". Replaceable elements are cylinderhead, crankcase, oilfilter, throttle body, camshaft etc. [Rutten, 1990]. Full-plastic vehicles are not likely to be build in mass production: plastics are relatively expensive and less fast to process (gluing, moulding etc.). Only for small series of vehicles or separate elements, plastics are economically useful. The weight of a full-plastic coach-work buss is 6,500 kg (1,200 kg coach work), less then the partly steel counterparts (10,000-15,000 kg) [Rutten, 1990; Krummenacher, 1991].

By a redesign of the construction, the weight of a truck-cab shell (except the doors) can be decreased from 226 kg to 151 kg [Lowe, 1985].

The use of lightweight engines (like two-stroke engines) also reduces the total weight of vehicles.
Air resistance
Air resistance of a vehicle is dependent on (a.o.) the "projected frontal surface" and the airdrag coefficient \(C_D\). The size (height and width) of a car determines the frontal surface, the design of a car the \(C_D\). In general, small cars have a higher \(C_D\)-value but a smaller frontal surface. The use of smaller engines (two-stroke ICE or electric motors) makes it possible to redesign the bodywork and thus reduce air resistance. The mean \(C_D\)-value is between 0.28 and 0.38; a reduction to 0.20 (large cars) and 0.25 (small cars) seems to be possible (average reduction of 30%) [Ryba, 1991; Monte Carlo, 1985; Kram, 1989]. For the design of the vehicle, no extra (consumer) costs can be calculated; the costs of special measurements (skirts, spoilers etc.) vary.

LOW AERODYNAMIC DRAG

WEIGHT REDUCTION & LARGE AND COMFORTABLE CABIN

based on Nissan Technology Newsline (10.1990)

Figure 3.2: possible vehicle improvements [Nissan, adapted]

Rolling resistance
The rolling resistance is determined by the road surface, the air-pressure in the tyres, the size and the design of the tyres and the materials used. Improvements of 20% - 35% by new types of tyres are possible. These new tyres mean an improvement of fuel efficiency of 5% - 7% (based on Citroën AX with Michelin tyres). The costs of these tyres are about Dfl 760 (four tyres), the same as present regular tyres [Michelin, 1993].

Note: improvements of vehicle construction are only partly aimed at the reduction of energy use while driving. Part of the improvements is aimed at decreasing the energy use in a car-life (aluminium use by Audi), to improve safety (tyres, bodywork, additional features like airbags) or to make materials better reusable. The aerodynamical design is partly dependent on fashion: not all modern cars are smooth, wind-tunnel moulded designs (four wheel drive terrain cars, pickup trucks).
3.1.3 Energy functions

Energy efficiency technologies available (according to vehicle manufacturers):
- Vehicle weight reduction: 10 - 20%
- Aerodynamic improvements: 5 - 10%
- Ancillary power requirement reductions: 5 - 8%
- Improvements in tyres and lubricants: 3 - 5%

[Martin, 1991]

<table>
<thead>
<tr>
<th>rolling resistance</th>
<th>baseline</th>
<th>IEA estimate [% fuel saving]</th>
<th>Manufacturers' estimates [% fuel saving]</th>
<th>IEA estimate costs [Dfl]</th>
</tr>
</thead>
<tbody>
<tr>
<td>aerodynamics</td>
<td>base</td>
<td>2.3</td>
<td>1.2 - 3.1</td>
<td>80</td>
</tr>
<tr>
<td>weight reduction (10%)</td>
<td>base</td>
<td>6.6</td>
<td>5.0 - 8.0</td>
<td>varies</td>
</tr>
<tr>
<td>electric power steering</td>
<td>conventional</td>
<td>1.0</td>
<td>0.5 - 1.5</td>
<td>90</td>
</tr>
<tr>
<td>advanced tyres by 10%</td>
<td>base</td>
<td>1.0</td>
<td>0.5 - 1.0</td>
<td>36</td>
</tr>
</tbody>
</table>

[IEA, 1993]

Estimates of costs of weight-reducing measurements are not given. These costs can be derived as follows: In a car of 800 kg, 600 kg of steel is used (75% of weight) [Streicher, 1992]. For a car of 1000-1100 kg, this means about 790 kg of steel. The price of steel is about Dfl 1,400 per ton, so the steel in this average passenger car costs about Dfl 1,100. Using aluminium, a reduction of vehicle weight to 800 kg is possible (200-300 kg or 24% less weight). In such a car approx. 540 kg of aluminium is used. The price of (raw) aluminium is about Dfl 2,600 per ton, so the aluminium in this car costs about Dfl 1,400. This means Dfl 1.08 per kg (reduced weight) or Dfl 11.30 per % reduced weight. The production of aluminium is energy-intensive, but the reuse is relatively cheap. Processing of aluminium is not as easy as steel processing; production costs will be higher. In the above calculation these higher processing costs are not included, so the real costs will be higher.

The aluminium Audi V8 costs Dfl 200,000 (taxes included) or DM 79,600. Its weight is 1565 kg, about 150 kg less than a comparable full-steel car [Becker, 1994].

Table 3.1a: Fuel efficiency estimates of vehicle construction improvements
### Table 3.1b: Aerodynamics, weight and tyres improvements for trucks

<table>
<thead>
<tr>
<th>Costs [Dfl]</th>
<th>Benefit in fuel economy [%]</th>
<th>Life of measure [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerodynamics:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- tractor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>full aero package</td>
<td>6,000</td>
<td>14</td>
</tr>
<tr>
<td>aero cab incremental</td>
<td>5,000</td>
<td>14</td>
</tr>
<tr>
<td>roof fairings</td>
<td>1,600</td>
<td>10</td>
</tr>
<tr>
<td>roof-top deflectors</td>
<td>1,000</td>
<td>7</td>
</tr>
<tr>
<td>gap seals-extenders</td>
<td>600</td>
<td>5</td>
</tr>
<tr>
<td>bumper air dam</td>
<td>500</td>
<td>1</td>
</tr>
<tr>
<td>- trailer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>skirts</td>
<td>4,000</td>
<td>5</td>
</tr>
<tr>
<td>front bubble, fairing</td>
<td>900</td>
<td>3</td>
</tr>
<tr>
<td>total:</td>
<td>10,000</td>
<td>19</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>weight reduction</td>
<td>6,000</td>
<td>1</td>
</tr>
<tr>
<td><strong>Tyres</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>low profile radials</td>
<td>1,730</td>
<td>3</td>
</tr>
<tr>
<td>super singles</td>
<td>1,300</td>
<td>8</td>
</tr>
<tr>
<td>total:</td>
<td>1,400</td>
<td>8</td>
</tr>
</tbody>
</table>

[Sachs, 1992]

The way vehicles are used, has a large influence on the energy-saving results. In case of improved vehicle construction (20% less aerodynamic drag/rolling resistance) the following reductions are possible:
- 2% in built-up areas,
- 5% (light trucks) - 6% (heavy trucks) in non built-up areas,
- 8% (light trucks) - 10% (heavy trucks) on motorways.

[Hickman, 1991]

### 3.1.4 Penetration

There are no practical barriers for a 100% penetration of the technologies described. Only cost-factors can lead to a lower degree of penetration. Aerodynamical improvements of small cars and vehicles used at lower speeds are less useful than improvements of larger cars and vehicles used at higher speeds.

### 3.1.5 State of development, current R&D

All measures as described can be used nowadays. Only the penetration is, mostly due to high costs, relatively low. Current R&D is aimed at:
- (further) improvement of tyres: lowering the rolling resistance while safety demands are increasing;
- research on lightweight materials and the way to use them efficiently in the production process;
- research on lowering the $C_0$-values and total air resistance while maximizing inner space.
3.2 Parameters of improvements on vehicle construction for passenger cars

Energy parameters

Reference energy use: 2.56 MJ/vehkm (energy efficiency: 19%)
Effective energy use: 1.71 MJ/seatkilometre (average: 1.5 available seats per passenger car).
Energy use with improvements:

- **1994**: 2.48 MJ/vehkm (-3%, tyres, aerodynamics)
  1.66 MJ/seatkm
- **2010/2015**: 2.30 MJ/vehkm (-10%, aerodynamics, weight, tyres)
  1.54 MJ/seatkm
- **2030/2040**: 1.89 MJ/vehkm (-26%, extra improvements)
  1.26 MJ/seatkm

2010/2015 estimate: [IEA, 1993], benefits of electric steering excluded
2030/2050 estimate: based on [Martin]

- 15% improvement of fuel efficiency due to weight reduction (Martin: 10 - 20%)
- 7.5% by aerodynamics ([Martin]: 5-10%)
- 3.5% by tyres ([Martin]: 3-5%)
- 0% by ancillary power ([Martin]: 5-8%)

In the calculation, no reductions for ancillary power have been included, because the lower rolling resistance, increasing safety-demands and increasing comfort demands will increase the use of extra equipment as anti-spin control/track control and air-conditioning systems.

Economic parameters

Reference vehicle costs Dfl 22,000.
Reference maintenance costs Dfl 0.33/km or Dfl 0.22/seatkm.

Extra investments:

- **1994**: Dfl 80 per vehicle
- **2010/2015**: Dfl 330 per vehicle
- **2030/2040**: Dfl 580 per vehicle

[Cost estimates 1994 and 2010/2015 based on IEA 1993, own estimates (weight reduction costs), costs for 2030 are extrapolated]

Technical life: car (body) life.
Maintenance costs: comparable with base situation.

Environmental parameters

Emissions
There are no specific emissions due to aerodynamical or weight measures. The use of (raw) aluminium is less energy-efficient than the use of (raw) steel, but the reuse of aluminium is far more energy-efficient than the reuse of steel.

Due to the measurements described, there will be no extra noise-pollution.
Materials
As aluminium can be recycled, there is less need for raw materials (like bauxite). To a lesser degree, (modern) plastics can also be recycled.

3.3 Parameters of improvements on vehicle construction for vans

Energy parameters
Reference energy use: 6.48 MJ/vehkm (energy efficiency: 20%); this can be compared to an energy use of approximately 3.73 MJ per tonne-kilometre (payload 1.735 ton).

<table>
<thead>
<tr>
<th>Year</th>
<th>Energy Use</th>
<th>Percentage Change</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>6.42 MJ/vehkm (-1%, tyres)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010/2015</td>
<td>6.35 MJ/vehkm (-2%, aerodynamics, tyres)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030/2040</td>
<td>6.03 MJ/vehkm (-7%, extra improvements)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.32 MJ/tonkm</td>
<td></td>
<td>(payload now 1.91 ton, 10% less vehicle weight)</td>
</tr>
<tr>
<td></td>
<td>3.00 MJ/tonkm</td>
<td></td>
<td>(payload now 2.01 ton, 20% less vehicle weight)</td>
</tr>
</tbody>
</table>

Figures for improvement of efficiency based on figures for passenger cars, with some changes for efficiency-improvements due to lower air resistance (estimates):

<table>
<thead>
<tr>
<th>Year</th>
<th>Percentage Change</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>0% (was 2% for passenger cars)</td>
<td></td>
</tr>
<tr>
<td>2010/2015</td>
<td>1% (was 2% for passenger cars)</td>
<td></td>
</tr>
<tr>
<td>2030/2040</td>
<td>4% (was 8% for passenger cars)</td>
<td></td>
</tr>
</tbody>
</table>

Further more, the weight-improvements are used to increase the loading capacity, so for this aspect only the energy use per ton km will change.

Economic parameters
Reference vehicle costs Dfl 45,000.
Reference maintenance costs Dfl 1.41/vehkm or Dfl 0.81/tonkm (interpolated cost estimate).

Investments:

<table>
<thead>
<tr>
<th>Year</th>
<th>Costs per Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>Hfl 80</td>
</tr>
<tr>
<td>2010/2015</td>
<td>Dfl 330</td>
</tr>
<tr>
<td>2030/2040</td>
<td>Dfl 580</td>
</tr>
</tbody>
</table>

(cost estimates 1994 and 2010/2015 based on IEA, own estimates (weight reduction costs), costs for 2030 are extrapolated)

Technical life: car (body) life.
Maintenance costs: comparable with base situation.

Environmental parameters
See: Parameters for passenger cars
3.4 Parameters of improvements on vehicle construction for busses

Energy parameters

Reference energy use: 13.2 MJ/vehkm (energy efficiency: 21%)
For 35 seats, this means 0.38 MJ/seatkm.

Energy use:
- 1994: 12.5 MJ/vehkm (-5%: some aerodynamical improvements, tyres)
  0.36 MJ/seatkm
- 2010/2015: 11.8 MJ/vehkm (-10%: 15% weight reduction of bodywork, tyres)
  0.34 MJ/seatkm
- 2030/2040: 9.9 MJ/vehkm (-25%: 35% weight reduction of bodywork, tyres)
  0.28 MJ/seatkm

Estimates of weight reductions based on Rutten, 1990, estimates of reductions by using other tyres and by improving of the aerodynamics based on Sachs, 1992, (distribution in time: own estimate).

Reduction of about 15% of weight of bodywork results in 7.5% reduction of energy use, based on the formulas used for fuel-cell calculations. Using the same method, at a reduction of about 35% of the weight of the bodywork, a 20% reduction of energy use can be calculated. The base weight of the bus (1994) is 16.5 ton, passengers included; the empty mass is about 10 tons (a bus can carry more passengers than there are seats).

Economic parameters

Reference vehicle costs Dfl 245,000.
Reference maintenance costs Dfl 4.88/vehkm (Dfl 0.14/seatkm).

Extra investments:
- 1994: Dfl 1,000
- 2010/2015: Dfl 1,600
- 2030/2040: Dfl 1,800

[estimates of costs based on Sachs, 1992 and own estimates (weight), distribution in time: own estimate]

Lifetime and replacement time of tyres: 130,000 kms: every 2.2 year (Dfl 640/year)
Maintenance costs: comparable with base situation.

Environmental parameters

See: Parameters for passenger cars
3.5 Parameters of improvements on vehicle construction for trucks

Energy parameters

Reference energy use: 16.2 MJ/vehkm (energy efficiency: 23%), 0.58 MJ/tonne-kilometre, (payload 28 ton).

Energy use:
- 1994: 14.1 MJ/vehkm (-13%, rooftop deflectors, gap-seals, bumper air dam) 0.50 MJ/tonkm
- 2010/2015: 12.6 MJ/vehkm (-22%, full aero package, low profile tyres) 0.45 MJ/tonkm
- 2030/2040: 11.8 MJ/vehkm (-27%, full aero package, super singles (tyres)) 0.41 MJ/tonkm (load capacity now 28.7 ton)

[efficiency figures based on Sachs 1992, distribution in time: own estimate, 1994 situation only indicative]

Weight-improvements of the truck are used to increase the loading capacity, so for this aspect only the energy use per tonkm will change (2030/2040).

Economic parameters

Reference vehicle costs Dfl 220,000.
Reference maintenance costs Dfl 1.70/vehkm (Dfl 0.06/tonkm, payload).

Extra investments:
- 1994: Dfl 2,100
- 2010/2015: Dfl 12,000
- 2030/2040: Dfl 12,000

[estimates of costs based on Sachs, 1992, distribution in time: own estimate]

Lifetime and replacement time of tyres: 130,000 kms: every 2.2 year (Dfl 640/year)
Maintenance costs: comparable with base situation.

Environmental parameters

See parameters for passenger cars.
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