TRANSPORT AND SUSTAINABILITY

- WITH SPECIAL EMPHASIS ON GROCERY DISTRIBUTION

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Preface

This report is a slightly modified version of the report that has served as formal basis for the acquisition of the Ph.D. degree. The Ph.D. study has been carried out at the Department of Physics and the Department of Buildings and Energy at the Technical University of Denmark during the period from December 1992 to June 1997. No specific grants have been received for the Ph.D. study, which instead has been based on different projects.

In addition to this report, a number of publications have been produced in the course of the work - as listed in the reference list.

Supervisor has been Professor Niels I. Meyer from the Department of Buildings and Energy.

Kaj Jørgensen
December 1997

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Introduction

It is generally acknowledged that the present development of the transport sector is the key problem in any strategy for sustainable development, but the views are much more diverse as to what could and should be done to improve this situation.

According to one line of thinking, technical improvements of the transportation means can to a great extent rectify the problems - frequently adding that technical fixes also will have to play this role since little can done to more fundamentally change the direction of the transport sector. In some cases, it is even argued that the technical improvements are not only potentials but that they will materialise, more or less automaticcally, in the course of time.

In contrast, others emphasise that technical improvements cannot have this role - sometimes rejecting the technical improvement potentials altogether. Therefore, it is necessary to compare welfare benefits and costs - if the costs (e.g. the environmental impacts) are to high, the benefits (i.e. increased transportation) has to be restricted.

The point of departure for this report is the latter perception with the addition that increased transport is only to some degree meeting a demand - at least an explicit demand - and hence cannot in every respect be seen as a welfare benefit. In addition, much transport is generated by in social structures social structures, transport systems etc. The study of the development of the grocery sector in the post-war period, in which the motor vehicle was introduced on a large scale in Denmark, illustrates this (cf. Chapters 4, 5 and 7).

During the post-war period, profound changes have taken place in the grocery sector, with respect to the retail and wholesale trade structures as well as the shopping patterns. In the course of this development, the sector has gone from a structure based on neighbourhood specialist shops to one with much fewer and larger shops, each aimed at a broader range of needs and each serving much greater areas. A similar centralisation trend can be seen in the manufacturing and wholesale trade of groceries.

The development has been closely linked to the technological development of both retail shop equipment and, not least, transport technologies. The passenger car and the medium and heavy duty trucks are key technologies, without which the development would not have been possible in its present form. Thus, it illustrates the role of the car in the development of modern consumer society in Denmark, in particular the paradox of the car, namely that it is at the same time a necessity for the existence of the modern welfare society and a threat to it.

The case study points to a considerable growth in transport related to grocery distribution, in spite of the fact that the grocery consumption in quantitative terms has only increased moderately. As a result, fuel consumption and emissions show a strong increase, too.

The second main topic of the report is the assessment elements of a strategy for sustainable transport. In keeping with the above, such a strategy requires a comprehensive approach, covering these main factors:

- the development of transport demand, determined partly by social factors (social structures, economical issues, transport structures etc.) and partly by the behaviour of individuals;
- system efficiency and organisation, i.e. the efficiency of the transport and energy system;
- technical factors in conjunction with transportation means (e.g. fuel consumption and emission factors).

While the analysis covers in principle this topic as a whole, it does not go into details with every aspect of it. Rather, it takes the third factor as starting point, raising the question what, in the framework of individual behaviour and structural factors, technical progress can do to promote sustainable development in transport - and, not least, what are the limits to this path towards sustainable development.

In other words, the study of the potentials raises the question to what extent it is possible to achieve sustainable development by means of technical improvements only. This could be seen in quantitative terms, measuring the technical improvement potentials against the targets for reduction of fuel consumption and emissions. But there is also a qualitative dimension to the issue, whether the technical improvements are addressing the problems of the transport sector in an adequate manner - or mainly relieving some negative aspects of an unfortunate development.

The focus is on technical improvements of road vehicles, i.e. neither modal shift nor improvement of other transportation means (e.g. trains). This is because the objective of the study is to investigate potentials and limitations of the existing vehicles. The improvement potentials would, naturally, be much higher if modal shift and improved public transport were included, but the same limitations with regard to achieving sustainable development and traffic growth would apply in this case, albeit at a different level.

List of Abbreviations

AFC	Alkaline Fuel Cell
APU	auxiliary power unit (onboard power generator in hybrid vehicles)
CH2	compressed hydrogen (i.e. hydrogen stored as a compressed gas)
CH4	methane
CI	combustion ignition engine (conventional diesel engine)
CNG	compressed natural gas (i.e. natural gas stored as a compressed gas)
CO	carbon monoxide
CO2	carbon dioxide
DMAFC	Direct Methanol-Air Fuel Cell
FC	fuel cell
HC	(total) hydrocarbons
ICE	internal combustion engine
LH2	liquefied hydrogen, i.e. hydrogen stored as a cooled down liquid
LNG	liquefied natural gas, i.e. natural gas stored as a cooled down liquid
LPG	liquefied petroleum gas (oil-derived auto gas, consisting mainly of butane and/or propane)
NaS	sodium/sulphur batteries
NaNiCl	sodium/nickelchloride batteries
NiCd	nickel/cadmium batteries
NiMH	nickel/metal hydride batteries
NMHC	non-methane hydrocarbons
NOx	nitrogen oxides
N2O	nitrous dioxide (laughing gas)
PAFC	Phosphoric Acid Fuel Cell
PbA	lead/acid-batteries
PM	particle mass

PNGV	Partnership for New Generation of Vehicles (an American government/industry programme to promote cleaner vehicles[1])
RMI	Rocky Mountain Institute, Colorado, USA
SFC	specific fuel consumption
SI	spark ignition engine (conventional gasoline engine)
SO2	sulphur dioxide
SOFC	Solid Oxide Fuel Cell
SPFC	Solid Polymer Fuel Cell (also known as Proton Exchange Membrane Fuel Cell)
THC	total hydrocarbons, i.e. the sum of NMHC and CH4
ZEV	zero emission vehicles (that is, zero emissions from the vehicle exhaust pipes only)

1 *See Section 8.6.*

Summary

The post-war period has strong growth in transport demand, especially in automobiles (passenger cars, vans and trucks) and linked to these growing environmental problems. At the same time, there has been increased environmental awareness - in the form of more attention to environmental issues at broader and broader levels - resulting in conflicts between growth and environment. Concerning certain environmental impacts it has been possible to achieve environmental improvements despite the traffic growth, but in other areas it has been recognised that it is difficult to achieve improvements on the background of continuing traffic growth.

A case study of transport in conjunction with grocery distribution illustrates the problems. The study analyses the development of the grocery distribution from the 1950s to the present, covering the whole of the supply chain from suppliers to the shops and from the shops to the homes of the consumers. Only domestic transport is covered. The study shows that the transport demand on the shopping side has increased nearly 4 times during this period, whereas the transport demand on the wholesale side (bringing the commodities to the shops) has increased almost 3 times. This is despite the fact, that the quantities of the groceries consumed have only increased moderately, by weight and monetary value.

Thus, the transport efficiency of grocery distribution has deteriorated substantially during the period. In connection with this development, the total fuel consumption and CO2-emissions of grocery distribution has increased 2.5 times - with the strongest growth on the shopping side. Other emissions (NOx, HC, CO, PM) have increased between 2 and 4 times.

This development should be seen on the background of substantial changes with respect to both structures and behavioural patterns of the grocery sector. As regards the structural changes, the most important trends in this context have been the following:

- considerable centralisation trends at retail, wholesale, manufacturing levels, resulting in a 60% reduction of the number of grocery shops in Denmark
- the development of a range of new shop types - characterised by self-service, large turnover demand, changed localisation patterns, different assortments (new products, different aims of shops)
- vertical and horizontal integration
- competition between shops in different areas and between different shop types

The principal changes of shopping patterns have been:

- reduced loyalty towards nearest shopping option - because prices, assortment, organisation links rather than distance serve as the most important criteria for selection of shops or suppliers.
- shopping patterns have gone from visiting a range of shops within walking or cycling distance in the 1950s to one based on fewer shop trips to shops located at greater dis-

tances. Today visits to supermarkets, or similar shops, perform a vital part of most shopping patterns, thus making "supermarket access" a key characteristic of the typical shopping pattern. This means that the number of supermarkets, variety stores etc. (i.e. large supermarkets with a high percentage of non-food turnover) is a more relevant measure of the centralisation of the centralisation process than the total number of retail shops.

The market orientation of the grocery shops have changed during the period: neighbourhood shops - located in, or adjacent to residential areas - have closed down being replaced by more central locations. On top of this, regionally oriented shops, frequently located outside the city centres, attract customers from huge catchment areas. The neighbourhood shops - accounting for nearly 100% of the grocery turnover in the 1950s - have been reduced to 15-20% today, whereas centrally located shops (such as supermarkets) account for about 70-75%. The regionally oriented shops' market share of the grocery sector is less than 10%.

At first, the introduction of the motor vehicle resulted in greater freedom, allowing those with car access more shopping options. In turn, however, increased closing down of neighbourhood shops reduced the choice, especially for people without car access (almost half of the households in Denmark). That is, structural adaptations have undermined the gains of the motor vehicle, thereby adding further pressure on non-automobile households.

It is not possible to link this development to either structural or behavioural changes. Instead, it is linked to both aspects and these, in turn, are interrelated to a great extent.

On the distribution side, the reduction of the number of retail shops, in principle, provide for better planning opportunities regarding the distribution of commodities to the shops. But this, according to the study is more than offset by the longer distances the goods have to travel before reaching the shops.

The report investigates the potentials for reduction of the energy demand and emissions by means of technical improvements of vehicles. The assessments are based on fuel cycle considerations covering both the energy system (that is, the system providing the fuel to the vehicle) and the vehicle system (the system on board the vehicle transforming the fuel to useful work).

In general, there are substantial potentials for improvements of the energy efficiency of the transportation means - and even greater potentials for CO2-reductions. To reap the full potentials, it is probably necessary to break with the present technological development trend.

The study of the conservation potentials is based on different "technology levels" with the following estimated energy conservation potentials (in comparison with the present stock average):

- Average Sold Technology (AST): 5% increase for passenger cars; 10% increase for light goods vehicles; and a 5% reduction for heavy goods vehicles;
- Best Sold Technology (BST): 25% reduction for passenger cars; 15% reduction for light goods vehicles; and a 10% reduction for heavy goods vehicles;

- Developed Technology (DEV), representing technologies close to commercialisation: 30% reduction for passenger cars; 25% reduction for light goods vehicles; and a 15% reduction for heavy goods vehicles;
- Efficient Technology (EFF), representing incremental improvements of existing vehicles needing a certain technical development before commercialisation: 60% reduction for passenger cars; 50% reduction for light goods vehicles; and a 25% reduction for heavy goods vehicles;
- Present Alternative Fuel Vehicle (AFV1), the most efficient alternative fuel technology currently on the market: 50% reduction for passenger cars; 40% reduction for light goods vehicles; and a 20% reduction for heavy goods vehicles;
- Advanced Alternative Fuel Vehicle (AFV2), which is similar to AFV1 except that more advanced technologies are gradually being introduced: 75% reduction for passenger cars; 70% reduction for light goods vehicles; and a 50% reduction for heavy goods vehicles;
- Advanced Vehicle (ADV), presuming breakthrough technologies in comparison with the present technological development but based on near-term drive train technologies: 80% reduction for passenger cars; 70% reduction for light goods vehicles; and a 45% reduction for heavy goods vehicles;
- Hypercar Level (HYP), equivalent to the ADV level, except that more advanced drive systems, based on fuel cells are applied: 90% reduction for passenger cars; 80% reduction for light goods vehicles; and a 60% reduction for heavy goods vehicles.

In addition, there are further potentials for reduction of emissions, not least of CO2, in conjunction with shift to alternative fuels. In principle, zero emissions can be achieved if the fuel is based on renewable energy. In practice, there are restrictions on the use renewable fuels, too - particularly due to the land use impacts in conjunction with the solar energy to useful fuels. Bio-fuels are seen as particularly problematic in this respect whereas fuel cycles based on electrical or hydrogen propulsion (preferable using fuel cells) are considered the preferred option.

The following reservations are identified with regard to the practical implementation of the improvements:

- Further regulatory instruments are needed to ensure the implementation, since the practical development does not point to substantial improvements (if any improvements at all).
- The implementation of the improvements takes time, in particularly due to slow penetration of the vehicle stock. The demand for rapid change is in conflict with an objective of a smoother transformation, which will allow learning from experiences and democratically and social responsible developments.
- The technical improvement potentials do not solve all problems, and they should not be perceived as a substitution of other transport planning measures, especially not in the longer term. In particular, the technical potentials do not promise a scope for "green growth" as claimed by some.
- Some of the technologies studied imply conflicts with other considerations - of which this study particularly focuses on land use aspects.

Generally, it is concluded that a shift to fuels based on renewable energy does not substitute the need for economising with the resources - be it by means of technical efficiency or through other transport planning measures.

The time perspective of the penetration of the improvements in the vehicle stock has been investigated by means of a dynamical model (TECIMP), taking as its starting point the present vehicle stock and its distribution on age intervals. On that basis, it calculates the penetration if the improvements are introduced in connection with natural replacement of the vehicle. In most cases, it takes many years, or even decades, before the improvements have penetrated the stock entirely. The model take into consideration that newer vehicles drive more, and consequently the penetration of the driving is more rapid. However, this only advances the penetration by 2-3 years.

Sammenfatning

I tiden siden 2. verdenskrig har der været en kraftig vækst i transportarbejdet, ikke mindst for del af det der er blevet udført af motorkøretøjer (person-, vare- og lastbiler). I den forbindelse har der været stigende miljømæssige problemer i forbindelse med trafikken, men samtidig også stigende miljøbevidsthed omkring problemerne. På visse områder er der opnået miljøforbedringer til trods for væksten, men på andre områder står det klart at det er meget svært at opnå miljøfremskridt så længe vi har den kraftige trafikvækst.

Et case study af transporten i forbindelse med distribution af dagligvarer i Danmark illustrerer problemerne. Det beskriver udviklingen i distributionen af dagligvarer i Danmark siden 1950'erne, idet både distributionen fra leverandør til butik og fra butikkerne og ud til de enkelte hjem dækkes. Dog er kun national transport dækket. Analysen viser at transportarbejdet i forbindelse med indkøb er steget næsten 4 gange fra 1960 til i dag, mens transporten i forbindelse med distributionen til butikkerne er steget næsten 3 gange. Dette til trods for at mængden af dagligvarer - hvad enten denne måles i kg eller faste priser - kun er steget moderat siden 1960.

Med andre ord er transport effektiviteten forringet betydeligt i perioden. Samtidig er det samlede brændstofforbrug og de samlede CO_2-emissioner i forbindelse med dagligvaredistributionen beregnet at være steget 2,5 gange - med den stærkeste vækst på indkøbssiden. Andre emissioner - NOx, kulbrinter, kulilte, partikler - er beregnet at være steget mellem 2 og 4 gange.

Denne udvikling skal ses på baggrund af at der er sket betydelige ændringer hvad angår såvel strukturelle forhold som den enkeltes adfærdsmønstre. De vigtigste tendenser for så vidt angår de <u>strukturelle</u> ændringer er:

- betydelige centraliseringstendenser på både detail- engros- og producentniveau, som bl.a. har resulteret i en 60% reduktion af antallet af dagligvarebutikker i Danmark fra 1960 til i dag
- udviklingen af en række nye butikstyper - karakteriseret ved selvbetjening, store omsætningskrav, ændrede lokaliseringsmønstre, ændrede og større sortimenter
- vertikal og horisontal integration
- konkurrence mellem butikker i forskellige geografiske områder og mellem forskellige butikstyper.

De vigtigste ændringer hvad angår <u>indkøbsmønstre</u> er:

- reduceret loyalitet over for den nærmeste indkøbsmulighed - fordi det er priser, sortiment og organisatoriske forbindelser snarere end fysisk nærhed der fungerer som kriterium for valg af butik eller leverandør
- indkøbsmønstrene er gået fra hovedsageligt at bygge på besøg i en række forskellige butikker i gå- eller cykelafstand i 1950'erne til i dag at være baseret på færre besøg i bu-

tikker i større afstand. Det er dog stadig sådan at gennemsnitsdanskeren kommer i dagligvarebutikker næsten dagligt. I dag er supermarkeder, eller tilsvarende butikker, en vigtig del af de fleste menneskers indkøbsmønstre, hvorfor adgang til supermarkeder er en vigtig egenskab ved indkøbsmønstrene. Derfor er antallet af supermarkeder og lignende måske et mere relevant mål for butikstilgængelighed end det totale butiksantal.

Dagligvarebutikkernes markedsorientering har ændret sig i perioden, idet nærbutikker - lokaliseret i eller nær ved boligområder - er blevet lukket i stort tal og erstattet af butikker på mere centrale placeringer. Derudover er der kommet en række regionalt orienterede butikker, der sigter mod at tiltrække kunder fra et meget stort opland (oftest udover den by de ligger i). Nærbutikkerne - der i 1950'erne tegnede sig for næsten 100% af dagligvareomsætningen - er i dag nede på en omsætningsandel på 15-20%, mens de centralt lokaliserede butikker (f.eks. supermarkeder) tegner sig for 70-75%. De regionalt orienterede butikker dækker mindre end 10% af dagligvareomsætningen.

Først førte udbredelsen af bilen til større frihed på dagligvareområdet, idet den tillod husstande med biladgang friere valg af butikker. Men dernæst førte den stigende butiksdød blandt nærbutikkerne til en reduktion af valgmulighederne, specielt for husstande uden bil. Det vil sige at de strukturelle tilpasninger har undermineret gevinsterne ved motorkøretøjerne, hvorved der er blevet lagt yderligere pres på de billøse husstande.

Det er ikke muligt at forklare disse udviklingstræk med enten strukturelle eller adfærdsmæssige forhold. I stedet må man inddrage begge aspekter, der iøvrigt på hinanden indbyrdes.

På distributionssiden giver reduktionen af butiksantallet i princippet bedre muligheder for at planlægge distributionen af dagligvarer til butikkerne. Men dette bliver mere end opvejet af at lastbilerne tilbagelægger meget større afstande før de når butikkerne.

Rapportens undersøgelser af de tekniske potentialer for reduceret energiforbrug og emissioner, baseres på energikæde-overvejelser, der dækker såvel energisystemet (der omdanner primærenergi til drivmiddel og leverer dette til køretøjet) og køretøjssystemet (d.v.s. det system ombord i køretøjet der omsætter energien til nyttigt arbejde).

Det konkluderes at der eksisterer betydelige muligheder for energibesparelser og endnu større potentialer for reduktion af CO2-emissioner. For at høste disse potentialer er der formentlig nødvendigt at bryde med den nuværende teknologiske udviklingstendenser i bilproduktionen. Dette hænger sammen med at den gradvise forbedring af de eksisterende køretøjer næppe fører til at de fulde potentialer erkendes.

Analysen af besparelses-potentialerne bygger på en inddeling i forskellige "teknologiniveauer" med følgende energibesparelsespotentialer (sammenlignet med det nuværende gennemsnit for bestanden):

- "Average Sold Technology" (AST), der repræsenterer gennemsnittet af de solgte køretøjer: 5% stigning for personbiler, 10% stigning for varebiler og 5% reduktion for lastbiler
- "Best Sold Technology" (BST), svarende til de bedste køretøj på markedet: 25% reduktion for personbiler, 15% reduktion for varebiler og 10% reduktion for lastbiler

- "Developed Technology" (DEV), som repræsenterer teknologier der er tæt på kommercialisering: 30% reduktion for personbiler; 25% reduktion for varebiler; og 15% reduktion for lastbiler

- "Efficient Technology" (EFF), der repræsenterer teknologier som er videreudvikling af eksisterende køretøjer men som kræver en vis teknisk udvikling for at kunne kommercialiseres: 60% reduktion for personbiler, 50% reduktion for varebiler, og 25% reduktion for lastbiler

- "Present Alternative Fuel Vehicle" (AFV1), der er den mest effektive teknologi i dag for køretøjer baseret på alternative drivmidler: 50% reduktion for personbiler, 40% reduktion for varebiler og 20% reduktion for lastbiler

- "Advanced Alternative Fuel Vehicle" (AFV2), der svarer til AFV1 bortset fra at mere avancerede drivsystemer gradvis indføres: 75% reduktion for personbiler, 70% reduktion for varebiler og 50% reduktion for lastbiler

- "Advanced Vehicle" (ADV), der bygger på køretøjer med teknologispring sammenlignet med den aktuelle teknologiske udvikling på området, men som bruger drivsystemer der forventes på markedet inden for en overskuelig fremtid: 80% reduktion for personbiler 70% reduktion for varebiler og 45% reduktion for lastbiler

- "Hypercar Level" (HYP), der svarer til ADV-niveauet bortset fra at der benyttes avancerede drivsystemer baseret på brændselsceller: 90% reduktion for personbiler, 80% reduktion for varebiler og 60% reduktion for lastbiler.

Derudover er der yderligere reduktionsmuligheder for emissioner (ikke mindst af CO2) ved at skifte til alternative drivmidler. For drivmidler baseret på vedvarende energi kan der i princippet - omend ikke altid i praksis - opnås emissionsfri transport. I praksis vil der også være restriktioner på VE-baserede drivmidler, bl.a. som følge af de arealkrav der er i forbindelse med konverteringen af solenergien til drivmidler. Biobrændstoffer vurderes at være de mest problematiske i så henseende, mens energikæder baseret på el- eller brintdrift (helst baseret på brændselscelle-teknologi) repræsenterer de bedste muligheder.

I forbindelse med vurderingen af mulighederne for at realisere disse potentialer er der følgende vigtige forhold:

- Der er behov for nye - og skærpede - styringsinstrumenter, da der ikke er meget der tyder på at forbedringerne kommer af sig selv,

- Det tager tid at implementere de tekniske forbedringer, ikke mindst på grund af langsom indtrængning i køretøjsparken. Der er en konflikt mellem ønsket om hurtig svar på miljøproblemerne på den ene side og ønsket om så vidt muligt at undgå spring i udviklingen. Sidstnævnte er bl.a. nødvendigt for at give de bedste muligheder for at lære af erfaringerne

- De tekniske forbedringspotentialer løser ikke alle problemer, og de bør ikke ses som erstatning for andre transportplanlægnings-initiativer, specielt ikke på længere sigt. Det konstateres specielt at de ikke, som det ofte hævdes, giver basis for "grøn vækst" - d.v.s. en udvikling hvor miljøproblemerne ved væksten holdes i ave af forbedret teknologi,

- Flere af de undersøgte teknologier indebærer konflikter med andre hensyn - af hvilke specielt spørgsmålet om arealanvendelsen studeres nærmere i rapporten.

Generelt konkluderes det at et skift til drivmidler baseret på vedvarende energi ikke overflødiggør behovet for at økonomisere med ressourcerne, hvad enten dette sker gennem tekniske forbedringer eller gennem andre transportplanlægnings-foranstaltninger.

Tidsperspektivet for de tekniske forbedringers gennemslag i køretøjsbestanden er undersøgt ved hjælp af en dynamisk model (TECIMP). Denne tager udgangspunkt i den nuværende køretøjsbestands aldersfordeling, og beregner på den baggrund hvor hurtigt den nye teknik kan udbredes ved naturlig udskiftning. Som regel tager det adskillige år - ofte endda flere årtier - at få forbedringerne til at slå fuldt igennem i bestanden. Modellen tager hensyn til at nye biler har en større årskørsel end ældre, hvorfor gennemslaget i årskørslen er hurtigere. Forskellen er dog kun 2-3 år.

1 Methodology

The report investigates energy and environmental impacts of transport and the scope for reducing the negative impacts. The main emphasis is on energy consumption and CO2-emissions, and the study covers both structural, behavioural and technical aspects.

For the analysis, the following simple model of the factors determining the energy input and the emissions is used (Nørgård 1993; Ministry of Environment and Energy 1995):

$$E = S \cdot I \cdot P$$

where

E = total energy consumption or emissions

P = population

I = energy or emission intensity

S = energy service provided

The energy (or emission) intensity is the energy consumption (or emission) per unit of service - that is, the inverse efficiency.

In transport, the per capita energy consumption and emission - $S \cdot I$ - can be expressed in the following terms:

$$S \cdot I = D \cdot M \cdot CU \cdot e$$

where

D	= transport demand	[passenger-km or tonne-km per capita]
M	= distribution on transport modes (modal split)	
CU	= capacity utilisation of vehicle	[passengers or tonnes]
e	= specific energy use or emissions	[MJ or gram per km]

These factors reflect demand side aspects (D), transport system aspects (M and CU) and the technical standard of the vehicles (e). Since e is determined partly by the vehicle design and partly by the fuel and energy source used, it describes the energy system aspects[2]. Indeed, the study aims to combine two different approaches that could be termed a transport system approach and an energy system approach. The former focuses on the development of the transport system and the mechanisms shaping the transport demand, perceiving the energy system mainly as a means for providing the fuel, while the latter focuses on the energy system and its development logic, perceiving the transport sector as one energy demand sector among others. It is the hypothesis of this study that combining these two approaches provides more information than the sum of the parts.

The study is based on an fuel cycle approach in which the whole chain from primary energy source to final use is included (DeLuchi et al 1987; DeLuchi 1991b; Ecotraffic 1992). It covers the energy system providing the fuel, the vehicle responsible for the final use and the transport system linking up the two. This approach is used regardless of whether the primary energy source is fossil fuel based or based on renewable energy. While the former exhausts limited resources, the latter employs land (and other resources) to convert the solar energy to fuel[3]. Thus, in both cases the fuel cycle efficiency is of prime importance. The studies do not include Life Cycle Analyses, i.e. analyses covering the energy use and emissions in conjunction with the life cycle of the technologies used.

The correlations between transport and energy are approached from two different angles in the report:

- a study of the development of transport in conjunction with distribution of groceries exemplifies the historical development of the overall correlations
- a study of the potentials for technical improvement of transportation means.

The study of the technical potentials for decreasing the energy consumption and emissions focuses on two main groups of remedies: improvement of efficiency and fuel shift.

A key concept in the analysis is "mobility", a term which is widely used but rarely defined. A detailed discussion of the term is beyond the scope of this report, but the following clarification is needed. Most significantly, a distinction should be made between mobility perceived as the actual motion or/and the capability of moving - in other words, a distinction between the actual transport or the potential for transport (Berge et al 1992). Frequently, mobility is simply understood as the former, i.e. as the actual movement of humans or goods measured as transport demand (passenger-km, tonne-km) or number of trips. On that basis, there has been a strong growth in mobility, especially if measured as transport demand.

Another widespread understanding, not necessarily separated from this, is linking the term to a welfare perception, emphasising the capacity for movement and the notion of "being mobile" - seeing increased mobility as a positive welfare change. In this case, also, the usual perception is that mobility has increased, due to the access to motorised transportation

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2 *In the real world, the elements are neither as well-defined nor mutually independent as could be indicated by the model. Rather, there are different feed-backs and inter-relationships that make it impossible to determine each element independently.*

3 *Generally, fuel is used as a generic term to cover both fuels in a conventional sense (i.e. chemical fuels) and electricity.*

means, particularly automobiles. These immensely increase the travel options as compared to walking and cycling, hence the notion of increased mobility. However, if mobility is understood as freedom of choice, this freedom should include the option of not having to go longer to perform a certain task. In other words, imposed transport detracts from the freedom of choice just as imposed limits on transport. In this case, it is less certain that the mobility has increased.

In this report, the term "mobility" is used to cover the potential for transport, whereas the actual motion is termed transport or transport demand. In accordance with Berge et al (1992), the term "mobility" covers these aspects: the physical ability to move, the time needed to move and the access to transport facilities.

Instead of mobility, or as a supplement, the term "accessibility" is perhaps a more appropriate concept - that is, emphasising the individual's access to functions and facilities rather than the actual motion. This not only reflects characteristics of the individuals but also of the surroundings. Accessibility may be provided by supply-side measures (provision of transport facilities), or by demand-side changes to reduce or eliminate the need for transport. The demand for transport may be reduced by localisation of functions or by substituting transport by other communication means (e.g. telecommunication).

2 The Post-war Period in Denmark

The objective of this chapter is to provide a background to the study of the grocery sector development and the potentials for technical improvements: Section 2.1 outlines important development trends during the post-war period, concentrating on aspects of particular importance for this study, while Section 2.2 focuses on the transport development. Finally, Section 2.3 covers the development of environment and environmental awareness and the role of technology in this respect.

The purpose of the chapter is not to carry out a historical and/or social study, but simply to provide a setting for the studies of the grocery sector and of the development of fuel consumption and emissions.

The principal reference, unless otherwise noted, is Jørgensen (1995a).

2.1 Societal Changes During the Post-war Period

In short, the post-war period (at least from the late 1950s onwards) can be characterised by the popular term "welfare society"[4] and the breakthrough of consumer society, based on mass consumption and industrialised production. Denmark experienced a strong, and uninterrupted, growth in industrial investments between 1958 and the early 1970s, with annual growth rates in the order of 6-7%. This industrial boom was supported by low prices on resources, including primary energy, favourable financing and tax deduction schemes and work force education - and by the rapidly expanding markets due to the spreading of mass consumption (i.e. consumption of mass produced commodities).

The main trend of the period has been one of economic expansion and of strong growth in private and (especially) government consumption. In this context, the most important aspects of the higher material living standard are an increase in housing area per capita (and housing standard in more general terms, including a higher percentage of single family houses), and an increased possession of durable goods, such as household appliances, television sets and, not least, motor vehicles

In conjunction with the higher living standards, food and other basic goods account for a decreasing percentage of the total spending, thereby reducing the role, in quantitative terms, of the grocery sector investigated in this report. Still, the sector continues to be significant, accounting for more than half of the total retailing. It also plays an important role in the development of transport patterns, underlining the ambiguous role of the motor vehicle in society: at the same time providing freedom and dependence on the car. Thus, the sector serves as

4 *Or "welfare state" if emphasising that the welfare facilities have mainly been implemented through governmental intervention.*

a case study of the phenomenon Ivan Illich terms "radical monopoly of the industry", which is occurring when an industry becomes the dominant means of satisfying needs through compulsory consumption of high-powered commodity - in this case motorised transport - restricting the conditions for using low-powered transportation means, such as walking and cycling (Illich 1974).

The economic growth in part has been achieved by transferring informal activities to the formal economy, in the form of either market or public sector relations[5]. Beyond this, the economical growth has been based on productivity increases, through expanding division of labour, both within the factories and between these - and increasingly having an international dimension. Combined with the rapidly growing mobility[6] of the post-war period, the division of labour means that the production process is no longer linked to a certain place, resulting a greater demand for transport. Indeed, a key feature of the present society is specialisation on many different levels (e.g. between factories, between urban and rural communities). Consequently, access to transport facilities - notably road transport - has become a crucial locational factor.

During the period, there has been a moderate population growth in Denmark, namely a total increase of about 25% between 1960 and today. This development is projected to continue during the coming decades[7], albeit at a lower rate. The household structures - that is, household sizes and compositions - have changed considerably. The average household size has decreased substantially, mainly during the 1960s and 1970s. The growth has been a particularly strong for 1 and 2 person households, including single-parent households.

The percentage of married women working outside the home has more than tripled since the 1950s, while the percentage of unmarried women in the labour market has remained roughly constant. As a result, in the typical family there is no longer an adult staying home full-time. In line with this, most children are in institutions during working hours: in the 1950s 5% of children under 3 years and 12-15% of the 3-6 year olds were in institutions, while today the percentages are 50% and 75% respectively. In general terms, a higher share of everyday life has the form of organised programmes, frequently linked together by transport.

It is a widespread perception that strained time budgets are a key characteristic of present day families, in spite of shorter working weeks, longer holidays etc. At the same time, however, the household as a whole spend more time at work because of an increase in the percentage of two-income households, and everyday life is dominated by organised activities to a much greater degree.

Equally profound changes have taken place with respect to the development of settlement and spatial structures. Generally, the settlement patterns today reflect a mono-functional us-

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5 *This exemplifies the development of "modernised poverty", in the words of Illich, that is, the difficulties of surviving in the affluent modern society without "being plugged into" the market or the public sector (Illich 1974).*

6 *See the subsequent section.*

7 *This represents an upward adjustment of the population prognosis, which was until 5 years ago anticipating a minor decrease in population.*

age pattern, dividing the land into areas used for different purposes: housing, industrial facilities, shops, offices etc. There has been a significant movement away from the rural areas, which has reduced their share of the population from about 25% to approximately 15%. The small and medium-sized towns (1000-10000 inhabitants) have increased their share considerably, while villages (200-1000 inhabitants) have roughly maintained their position in both absolute and relative terms. Greater Copenhagen has maintained its share of population, but with a strong movement from its central areas to the suburbs. The same trend can be seen in other large cities.

The development, to a great extent, is a consequence of the increased level of the division of labour described above. In addition, it has been reinforced - intentionally and unintentionally - through physical planning, in part spurred by environmental objectives[8]. A third force behind the development could be termed consumer demand, though not necessarily reflecting an explicit demand from all consumers, nor even their majority. An example of this force is the demand for cheap and quick shopping opportunities. Many urban areas have been characterised by sub urbanisation in conjunction with the advance of owner-occupied single family housing. Thus, the demand for more per capita dwelling space has to a great degree been linked to a scattering of the urban areas[9].

Finally, the period has been characterised by internationalisation and even globalisation. This trend has been developing during most of the period and has a variety of different aspects:

- a standardisation of lifestyles, consumption patterns etc.[10]
- a breakdown of barriers to international trade, promoting free trade (e.g. EU, the Single Market, WTO etc.)
- removal of barriers to international capital movements
- development of international corporate chains
- globalisation of the division of labour through the widespread use of subcontracting
- global shopping.

2.2 Mobility - Transport Growth, Traffic Speeds and Time

The post-war period has seen the large-scale introduction of private cars in Denmark as well as in the rest of the industrial world, cf. Figure 2.1. Only in the USA, the widespread introduction of the motor vehicle took place before the Second World War[11]. World-wide, there

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8 *In the 1960s and early 1970s a principal environmental policy instrument was the separation of the population from polluting industries by means of high chimneys and land use planning.*

9 *Heavily subsidised through the taxation system.*

10 *This trend was noted, in a European context, by Georg Henrik von Wright in a text from the early 1960s, here quoted from Wright (1978).*

11 *In the early part of the automobile history - the first decade of the century and before - the USA was in fact lagging behind Europe, mainly due to the lack of suitable roads. But*

(the note continues)

was a strong growth in the vehicle stock in the 1950s and 1960s, but when the markets in the richest countries started to saturate, the global growth rates started to decline (Renner 1988; Lowe 1994). Hence, despite strong growth rates in many developing countries, the absolute number of vehicles in these countries are not - as yet - of significance in a global context. The development of the global passenger car stock in the course of the post-war period can be divided into the following stages (Brown et al 1995):

- Early 50s - rapid growth: annual growth rates around 10%, having increased from zero;
- Mid 50s to 1973/74 - high, steady growth: annual growth rates between 6% and 8%, with an average of 7.2% (corresponding roughly to a doubling every decade);
- 1973/74 to mid 80s - declining growth: annual growth rates gradually decreasing to around 3% (in the wake of the oil crises in 1973/74 and 1978);
- Mid 80s onwards - moderate, steady growth: annual growth rates remaining constant at 3-4%.

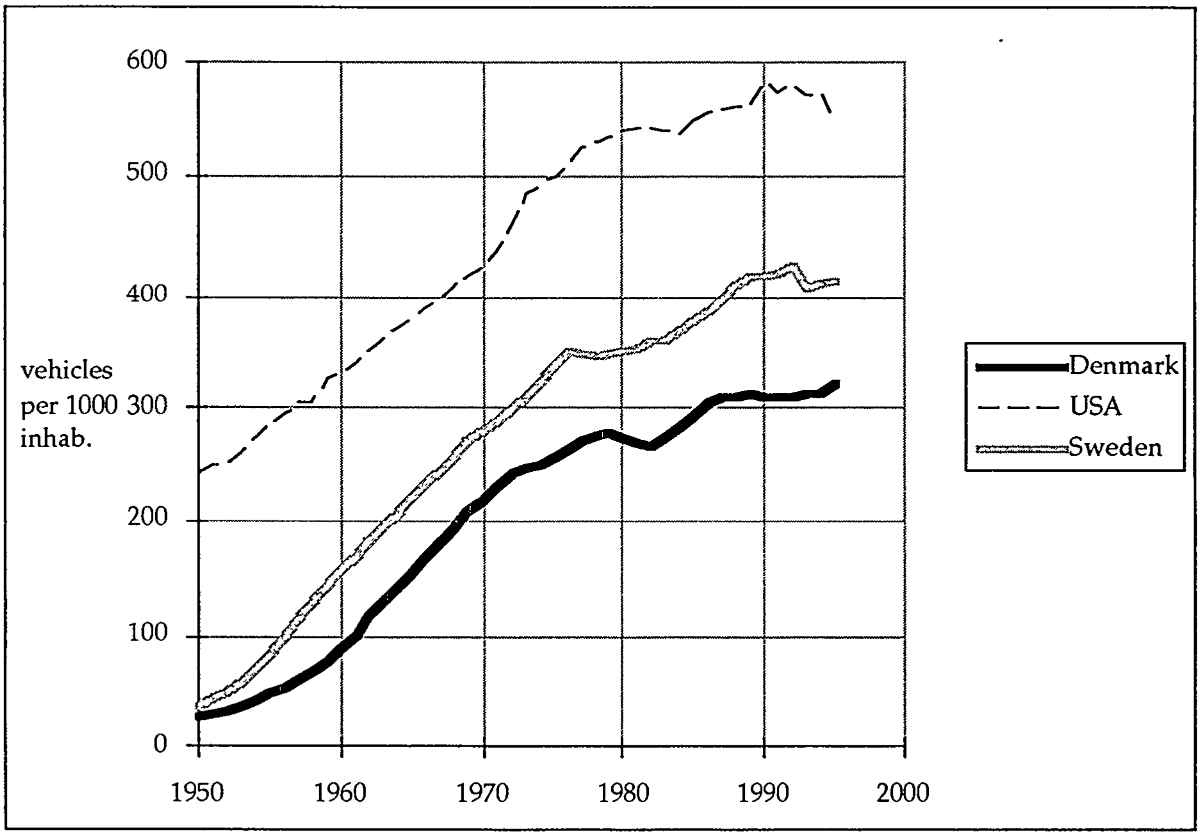

Figure 2.1. Passenger car densities in Denmark, Sweden and the USA (Automobil-Importørernes Sammenslutning 1995).

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the introduction of mass produced vehicles, initiated with the Ford Model T, put the USA in the lead (Tengström 1991; Tengström 1993a).

The remaining motor vehicle types (trucks, vans, busses) have followed roughly the same development, except that the growth rates around 1950 were even higher. Also, the period of high, steady growth was sustained a little longer than that of passenger cars, namely to around 1980, albeit at slightly lower growth rates (approximately 6% per annum).

In most prognoses, the growth is set to continue, albeit at lower annual rates - namely in the range of 1.8-2% per annum (Tengström 1991). Most of the growth, in absolute terms, will continue to take place in highly motorised countries in the coming decades.

The present Danish passenger car density is 315 per 1000 inhabitants, or just over half of the US level. Thus, Denmark has a relatively low car density, and even today only half of the households own a car (Danmarks Statistik 1995)[12]. About 70% of the population live in households owning an automobile, placing it in a position to enable the changes in structures and consumption patterns described later in this report. These changes in turn has turned the car into a necessity for many households.

12 *According to the Danish Travel Survey, the percentage of car owning households is higher, namely 340 passenger cars per 1000 inhabitants, and correspondingly the vehicle stock is larger than that recorded by Danmarks Statistik (Christensen 1993; Christensen & Jensen 1994). This probably reflects that the number of vehicles is being overestimated in the Travel Survey, rather than the number recorded by Danmarks Statistik being too low - since the latter is based on data from the central office for motor vehicle registration.*

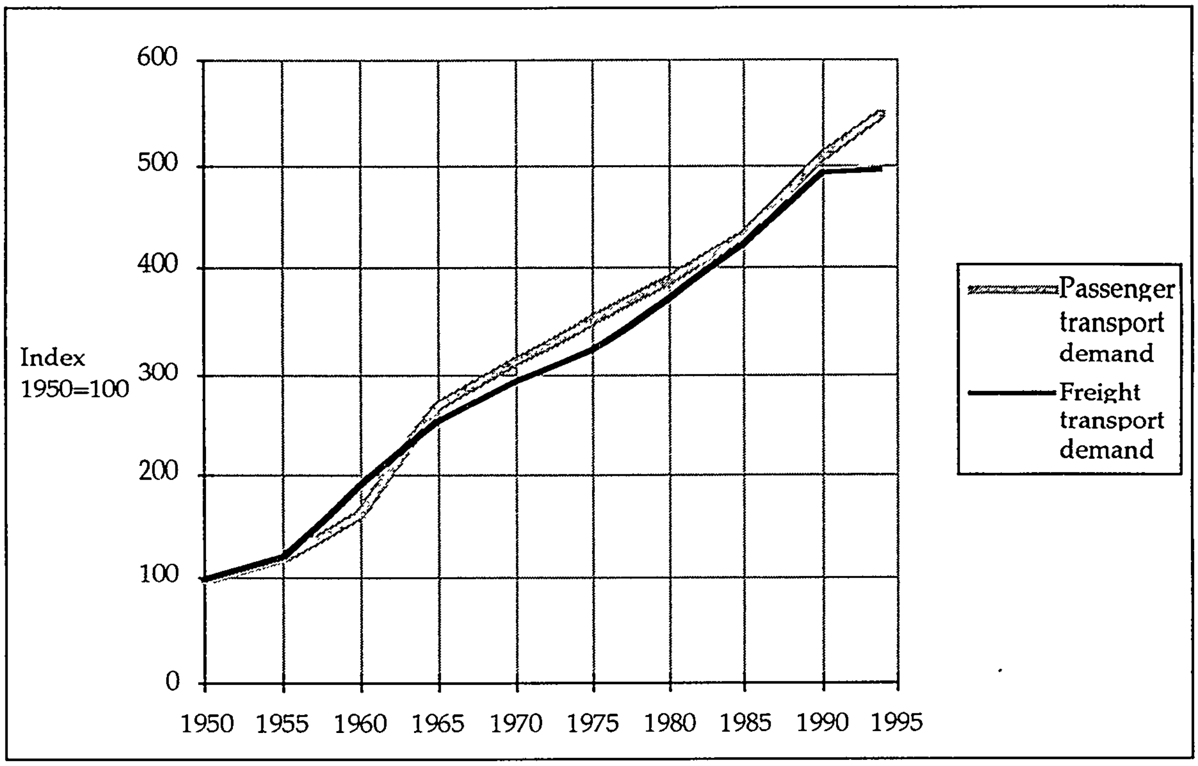

Figure 2.2. Indexed development of national passenger and freight transport demand (measured as passenger kilometres and tonne kilometres) in Denmark since 1950 calculated as an index with 1950 as 100 (Jørgensen 1995a). The contributions to passenger transport from cycling before 1980 and to freight transport from pipelines in 1994 have been estimated.

During the whole of the post-war period, except for a few interruptions in the wake of the oil crises of the 1970s, there has been a strong growth in both passenger and freight transport, cf. Figure 2.2[13]. This graph shows that the passenger transport has increased 5,5 times and the freight transport demand 5 times.

The development of the mobility patterns[14] during the post-war period has been characterised by both quantitative and qualitative changes:

- longer daily travelling distances;
- motorisation, i.e. a greater share of motorised transport being covered by motor vehicles;
- higher annual driving per vehicle (there is faster growth in driving than in vehicle stock);
- higher engine power (acceleration, speed);
- higher levels of required travelling standards (comfort etc.);

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13 *The interruptions are concealed in the graph due to the use of 5-year intervals.*

14 *The term "mobility" is defined in the chapter on methodology (Chapter 1).*

- flexibility to travel at any time in any direction.

There was a particularly strong growth of the transport demand in the 1960s, whereas the development before and after this decade has mostly been curbed by economical crisis[15]. In the 1950s, the vehicle stock grew stronger than transport demand[16], probably reflecting the fact that the automobile typically was not acquired for utility but rather as a status symbol in the hope of upward mobility in society[17]. In the 1960s, the spreading of the automobile undercut its position as prestige item and instead increasing engine power became the target of social status - leading to increasing differentiation of cars into vehicle classes. Today, engine power also has become everyone's possession, since even small vehicles are now equipped with powerful engines, and therefore the focus may switch to other items, such as equipment (Sachs 1984)[18].

In the 1970s, against beginning saturation of the vehicle market, the driving per vehicle started to increase and this has continued into the 1980s.

The development has been characterised not only by growth in quantitative terms (in transport demand, car use etc.) but also by a fundamental change in the role of transport in everyday life of modern households. Vilhelmson (1990) distinguishes between three different approaches to mobility, each of which are linked to certain lifestyles. In the main, they replace each other in the historical order given here, but they can be present at the same time, too. The three approaches are:

1. Geographical stability: an approach taking the conditions in the immediate surroundings of the home as point of departure. Daily life and needs are restricted to what can be met in the local community, where both the working day and spare time are usually spent. The most clean-cut examples of this approach, which is based on high self-sufficiency and a low degree of specialisation, are from the pre-industrial agrarian societies.
2. Geographical commuting: a further development of the geographical stability approach, in which the space covered by the activities are extended to reach certain more distant goals. The mobility, however, is typically limited to certain well-defined tar-

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15 *In the late 1980s, there was curb on consumer spending, particularly limiting the access to financing in the form of loans or credit. From the early 1990s, these restrictions have been lifted and currently financing opportunities are abundant at relatively low cost.*

16 *Compare with Section 6.1.*

17 *Indeed, the main application of the automobile in the fifties and early sixties - in Denmark and elsewhere - was leisure driving (Lund 1975; Sachs 1984; Hjorthol 1990)*

18 *Wolfgang Sachs terms this process - that is, the cultural attraction of a prestige item being so strong that is creates material conditions undermining its original attraction - "the aging of desire" (Sachs 1984). Fred Hirsch also has analysed the inherent contradiction of this process (Hirsch 1976). Sachs points to the role of the strong inflation in the 1960s and 1970s in reinforcing the development - pushing the upward mobile to "run just to stand still". In Denmark, with its "curbed automotive traffic" (Vibe-Petersen 1993) - i.e. low car densities and relatively small vehicles - the mass character of powerful automobiles is less pronounced than in countries such as Germany. Therefore, the aging of desire, in this field, is probably deferred somewhat, but on the other hand Denmark, as a non-manufacturer of automobiles, must follow international trends, albeit with an option to choose different segments of the vehicle supply.*

gets (usually the working place), leading to repetitive transportation patterns. These require transportation means with higher velocity, but not necessarily great flexibility. Also the transport demand is mostly confined to one member of the household (the male adult). This approach was expanding during the late fifties.

3. Geographical flexibility: an approach characterised by high mobility for all members of the household, with nearly all daily activities being linked to travel, a high percentage of which is covered by car. In this case, everyday life is characterised by the reproductive activities, such as child care, care, production and distribution of food etc., being handed over to specialised institutions, while the working life is based on flexible working hours and a scattered localisation of working places.

The private car has been the main catalyst in this process, particularly with regard to enabling steps 2 and 3.

In a Norwegian study, the following simplified five step scale has been used to characterise the Norwegian historical development of transport patterns in the post-war period (Hjorthol et al 1990):

1. Just after the Second World war, only the male adult typically worked outside the home, and mostly in the immediate neighbourhood, while children were being taken care of at home by their mother until starting in school.
2. In the 1950s, many families moved to new peripheral housing estates, while most of the job sites remained in the city centres, resulting in an increased demand for commuting. Mostly, this demand was covered by public transport, while the few private cars typically were acquired for leisure purposes.
3. By the end of the 1960s, women also began to work outside the home, typically in low-qualification jobs in the immediate vicinity, e.g. in shops or industrial plants, and children were still at home. Men's jobs moved from the urban centre, leading to more diversified transport patterns, and creating a greater demand for flexible, high-velocity transportation means such as the private car.
4. In the next step, women were getting jobs requiring higher formal qualifications, often in the public sector, resulting in longer distances to work. As a consequence, children spend the daytime in child care institutions. Many families moved to suburbs, further increasing commuting distances.
5. Can be seen as step 4 in full bloom, with all members of the family, in effect, being car users, whether driving themselves or using other in the family as driver. In some cases, the car is used to protect family members (notably children) from consequences of heavy traffic - for example, traffic accidents - an frequently there are conflicts between family members about transport patterns, leading to more than one car in some families.

This model is closely connected to the development in the structural factors, notably locational patterns and household structures. It describes a steady movement towards still greater car dependence and car usage, without crises or set-backs. Thus, it focuses on certain factors, presuming that the development is allowed to progress freely according to its own logic. In practice, however, the various obstacles and limits are likely to occur - e.g. oil supply constraints, environmental constraints and congestion[19].

In addition, the model focuses on average/dominating trends disregarding more or less the variations from these trends. In Denmark, for instance, even today only about half of the households have access to a car.

Nevertheless, the main trend has been that of the motor vehicle becoming more and more integrated into daily life. At first, it was used mainly for leisure activities, then increasingly for commuting, and now it plays a vital role for the planning of everyday life, even affecting the activity patterns of families that do not have access to a car.

At the same time, there has been increasing concern about the negative aspects of auto-centred transport, summarised in the following under three headings: unequal distribution; externalities; and internalities.

The unequal distribution of traffic refers to the fact that there are great variations today in different people's possibilities to exploit the benefits of motorised transport. According to the national Danish Travel Survey, 50% of the total passenger travel of the persons covered by the survey[20] is performed by 10% of the population, while the 50% with the lowest mobility only accounts for 7-8% of the travel (Ministry of Transport 1994b).

Moreover, this does not only relate to poor management or can be seen simply as a development stages, since it is linked to basic characteristics of individual motorised transport. This system provides freedom to the individual, but only in so far as this opportunity is not distributed to too many other individuals. Thus, this transport system has its own inherent limits.

The externalities or external effects of traffic are the impacts on its surroundings (the physical and social environment) that are not normally valued by the formal economy, including the influence on land use and urban development, environmental and health effects, noise, safety problems etc. (Freund & Martin 1993; Knoflacher 1993; Whitelegg 1993). Concern about these impacts date almost as far back as the motor vehicle itself, notably linked to safety aspects related to the increased speeds (Sachs 1984; Tengström 1991; Tengström 1993a).

In the 1950s and 1960s, the attention was directed towards the impact on urban development and land use in conjunction with the provision of infrastructure for the rapidly expanding traffic: roads, bridges etc.[21] This reflects the very space-consuming nature of modern car transport, inevitably leading to conflicts with other considerations (Knoflacher 1993).

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19 *This problem is treated in a forthcoming publication by the author (Jørgensen 1997).*

20 *The age group between 16 and 74 years. Thus, the impact of low mobility groups - children and old age persons - is not included.*

21 *As could be expected, the earliest examples of this resistance to the development of modern traffic were seen in the USA, particularly in San Fransisco (Flyvbjerg 1993).*

Noise, air quality and safety have played an important role in the debate about traffic's externalities during most of the history of the motor vehicle (Sachs 1984). Concern about fuel consumption, on the other hand, has mostly been confined to periods of crisis or/and price increases. Even though the vehicles have become more efficient, this is - at least in part - offset by higher standards (comfort, safety, performance).

In addition to the externalities, there are also, using Ivan Illich' term[22], the "internalities" of traffic, that is, mechanisms undermining the apparent benefits of motorised transport from the inside (Illich 1974). Illich generally considers these internalities to be responsible for declining marginal utility of consumption growth, in this case the growth of motorisation. He claims that beyond a certain threshold velocity - about 25 km/hour - a further increase is even counterproductive. Above this level, a further increase in velocity costs society more time than it saves, which means that above this threshold no one can save time without forcing others to lose time.

In the following, some of the most important internalities countering the time savings from increased velocity are listed (Illich 1974; Vilhelmson 1990; Tengström 1992; Knoflacher 1993; Whitelegg 1993, Jørgensen 1995c, Jørgensen 1996f).

The first of these is generally known under the heading "the thesis of constant travelling time". It is based on many empirical studies indicating that increased travel speeds do not lead to time savings, but rather longer distances being covered. Indeed, a large number of studies in different countries show that the time spent on private transport is roughly one hour, regardless of transportation means (speed) and geographical location or historical time. Some transport researchers even talk of "law of constant travel time and trip rates", whereas a modified version assumes that travel time accounts for a constant percentage of the spare time[23]. It is probably more correct to speak of inertia to change, rather than an unavoidable "natural law".

Secondly, through structural changes, adapting to the higher individual speeds, the longer distances are enforced on others, with or without access to fast transportation means. These changes take different forms, such as: the transformation of society into mono-functional areas[24]; emptying of the immediate neighbourhood of various functions, including a reduction in the number of retail shops, service facilities, schools etc.[25]; and changing in everyday patterns. Moreover, the heavy traffic means that streets in many cases cannot be used for children playing, hence, resulting in a need for planned leisure activities (needing transport) and a need for transport of children to school - thus, the car is seen to be necessary for protection against consequences of car traffic. Whereas the automobile initially was bought

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22 *Illich uses the term in the introduction to (Illich 1978) about such phenomenons as "time-consuming acceleration, sick-making health care and stupefying education"*

23 *That is, the time not occupied by work.*

24 *Supported by a movement of people from city centres to suburbs - frequently to avoid the negative impacts of the dense traffic. This particularly took place during the 1960s and 1970s.*

25 *The restructuring of the grocery sector constitutes an example of this adaptation to higher velocities (see Chapter 4 and 5).*

as a status symbol, providing access to new targets in space, now it is usually acquired out of necessity - the "masters of space and time awaken to find themselves slaves of distance and haste" (Sachs 1984).

Altogether, the result is that the everyday life is atomised in space and time. In conjunction with the constant travel time thesis, it can be said - quoting the Austrian transport researcher and planner Hermann Knoflacher - that time remains constant, while space changes (Knoflacher 1993).

Thirdly, for most people, the door-to-door velocity is much lower than the speeds in the high-speed sections of the traffic system (motor ways, high-speed rail, flying) due to the time needed - but mostly neglected - to get to and from these sections. The high velocities presume concentration of traffic volume (because of the investments needed) and a reduction of the opportunities to get on or off the high speed section (train stations, bus stops etc.), and they cannot be transferred to the whole of the traffic system. Besides the high-speed traffic sections, there are always other more time-consuming sections, either due to lower speeds (e.g. urban traffic) or because of the imposing of longer transport distances[26]. In addition, the "peripheral activities" such as parking, walking to and from the vehicle,·starting up etc. are frequently neglected.

Fourthly, high-speed traffic enforce time waste on other users of the transport system through the priority given to it at the expense of local traffic and those moving slower. For example, this happens when high-speed trains short circuit many stations or when pedestrians and cyclists have to wait to cross heavy traffic roads. Thus, some may gain speed, but others lose time in the same process.

Fifthly, many of the benefits of the automobile are undermined when too many exploit the opportunities, that is, they are conditional on being restricted to the relatively few. Congestion in urban traffic is the most prominent example of this, leading for instance to mean velocities around 16 km/h around the clock in Central London (Department of Transport 1995).

Finally, when calculating the costs of the car in time rather than in money, including the indirect time consumption - i.e. the time needed to earn the money to pay for the car and its use and the time needed attending to it (washing it, taking it to repair, parking it etc.) - the speed, calculated as kilometres covered per invested hour, is much lower than the direct velocity of the vehicle. Ivan Illich, launching this principle, calculated an average speed of less than 10 km/h for the typical American car driver, while a number of other studies lead to passenger car speeds in the range of 10-15 km/h for one person in the vehicle and up to 20 km/h for the typical capacity utilisation (Illich 1974; Nørgård 1979; Tengström 1992; Whitelegg 1993; Jørgensen 1996f).

It is a widespread perception that everyday life of today's households is governed by tight time budgets, and therefore that the car is necessary to make the ends meet[27]. But 2-3

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26 *Particularly relevant in conjunction with high-speed public transportation for which the higher speeds are conditional on the elimination of stations and stops.*

27 *Indeed, the principal motivation for acquiring a car is probably necessity as opposed to the emphasis on the freedom of the car used in the 1950s.*

working days a week are used to earn money for the car, and therefore an equivalent effect could be achieved by a reduction of the working week. This, obviously, neglects that there may be other reasons for working than to earn money, and also it is difficult for many to reduce the work week. Nevertheless, it illustrates the problem, namely that in many cases the acquirement of a car is not a rational solution from an overall assessment.

In particular, the thesis of constant travel time plays a key role with regard to the formulation of policies and development of regulatory instruments. One of its consequences is that it tends to act as a counter force to attempts to reduce travel distances by reducing the need for travel by means of planning measures, if speed is not reduced. Then the time saved in one part of the system may instead be used for other travelling purposes. For instance, there are indications that balance between job seeking persons and job opportunities in a municipality, which reduces the need for commuting, does not necessarily lead to a reduction in the actual commuting (Thost 1995), and similarly, a reduction in the need for travel between home and job by telecommuting or changes in the working procedures (e.g. a shorter working week) may just result in the time savings being spent for other travelling purposes. Following from this, the reduction of the overall travel demand is conditional on a reduction of the travel velocities.

Since the first widespread recognition of these problems, in the 1950s, it has been attempted to relieve the problems by technical means without putting restraints on traffic itself: safety belts, engine adjustments, filters/catalytic converters, noise abatement etc.

Traffic planning has been used in a similar way. At first, it was mainly seen as a means to secure the passage of the motorised traffic - that is, to ensure that the traffic system could handle the rapidly growing traffic in the post-war period. Later, when realising the problems in connection with traffic, traffic planning to some extent changed its scope, aiming rather to reduce the most urgent problems and to ensure reasonable solutions - but still without creating obstacles to traffic as such. Traffic in urban areas have been seen as the major problem, but even here the desire to ensure decent conditions for everybody is balanced off against growth desires (power centres) and against the fear of denying car-dependent shoppers and the like access to the city. Also, the greater emphasis on planning for all is not an unequivocal trend, especially not outside of city centres, where the main trend still is the building of motor ways, fixed links etc. (Gaardmand 1991).

Summing up, the post war period has be characterised by strong transport growth and strong increases in the standards required from transport (speed, flexibility etc.). Closely linked to this development, the motor vehicle has become the dominant way of travelling in both passenger and goods transport. However, there have been interruptions of the motor vehicle growth due to the impact of various obstacles and limitations. Especially during the oil crises of the 1970s there were signs of trends being reversed.

2.3 Growth and Technological Development - Progress and Problems

The post-war economical expansion has been based on higher productivity (output per labour input) achieved by means of increased division of labour and widespread application of new technology (including motorised transport). It has lead to higher living standards and to a greater range of opportunities being, in principle, available to the individual.

Generally, there have not only been increases in opportunities but also many opportunities have been cut off. Notably, Ivan Illich points to the paradox of "modernised poverty": "the experience of frustrating affluence which occurs in persons mutilated by their overwhelming reliance on the riches of industrialised productivity. Simply, it deprives those affected by it of their freedom and power to act autonomously, to live creatively; it confines them to survival through being plugged into market relations" (Illich 1973).

In other words, the development not only provides opportunities it removes them, also. The development has provided access to super markets with much greater commodity assortments than we knew in the 1950s. But at the same time it has denied present day consumers the opportunity of shopping locally - and this has not happened through explicit decision.

On the cost side, the development has resulted in higher energy consumption, pollution problems and increasing transport demand. In particular, transportation's contribution to the deterioration of the environment has been substantial, as could be expected on the background of its high growth rates. In some fields, the consequences of the growth have been offset, totally or in part, by improved technical standards and by planning efforts. In others, however, the negative impacts of transport increase and continue to do so.

The most urgent environmental problem, and probably the most difficult to solve, is the increase in emission of greenhouse gases, but other environmental problems remain. In particular, the problem of reducing the emissions of NOx and particle mass (PM) at the same time remains one of the big challenges of diesel engine development. Also, hydrocarbons cause concern, not so much because of the total emission quantities (which are being reduced) as of their complex composition.

In addition to the emissions, congestion and traffic safety are two major concerns. As regard the latter, considerable reductions have been achieved over the years in the total fatality figures, mainly through better protection of persons within the cars. Congestion is one of the fundamental problems of a space-consuming traffic mode such as private cars. The "freedom of the car" presumes that not too many exploits this opportunity.

Thus, as detailed in the previous section, the development has not just provided opportunities and progress, but also problems and concern. Given the conflicts between the continuing growth on the one hand and the goals and objectives of any planning policy for sustainable development, it is natural to look to technical solutions to improve fuel economy, reduce emissions and noise, increase traffic safety, enable more vehicles to be squeezed into the traffic system, etc. In several areas, technology is seen to promise a solution to these problems, e.g. in the form of introduction of three-way catalytic converters, promotion of very fuel efficient vehicles, use of information technology to relieve congestion problems etc.

This issue - the contribution of technology to the creation of a sustainable transport system - should be seen in wider context, namely the general post-war debate on energy and environment - and the role of technology in this context.

In the 1950s, popular environmental movements occurred in the USA, protesting against the consequences of the exploding traffic, albeit confined to the consequences for the local urban environment (smell, noise) and the impact of the traffic infrastructure on the urban development (Flyvbjerg 1993). From the early 1960s, popular warnings about environmental problems began to occur on a wider scale (Carson 1962; Commoner 1966), and during the sixties, there were a number of environmental issues related to environment and health.

From the early 1970s onwards, several studies, publications and international meetings have pointed to the evolution of a more comprehensive and fundamental ecological crisis, closely related to the development of the post-war economies. Of particular interest in this context are the Club of Rome study "The Limits to Growth" (Meadows et al 1972; Meadows et al 1974; Mesarovic & Pestel 1974; Meadows et al 1992) and Barry Commoner's analyses (Commoner 1966; Commoner 1971; Commoner 1976). The former focused on the consequences of growth in a limited world[28], while Commoner analysed the drastic technological changes of agricultural and industrial production and transportation, substituting cheap energy for expensive labour. The general conclusion of these and many other analyses was that he environmental problems should not just be seen as the result of isolated mistakes or confined to limited geographical areas. Instead, they should be seen as global in character, linked to the limits of nature. Thus, sustainability should be the goal rather than tall chimneys or filters so predominant in the environmental policies of that time. In other words, environmental considerations should be an integrated part of planning efforts - the energy and traffic system should be adapted to the demands imposed by the environment rather than trying to clean up afterwards (Eriksson & Hesselborn 1990; Naturvårdsverket 1993; Naturvårdsverket 1993).

A key issue is the extent to which the environmental problems can be reduced by technical means, in a world of growth. Historically, the potentials for improved energy efficiency and increased renewable energy utilisation were ignored almost completely until the 1970s. Instead fossil fuels in centralised power and heating supply systems were seen as the main solution to cover the apparently insatiable energy demand. Hence, there was presumed to be a fixed link between energy demand and the level of economical and material growth, which meant that energy supply technologies were seen as necessary to ensure modern welfare.

In opposition to this view, a different approach developed from the 1970s onwards, according to which there are wide possibilities for altering the relation between economical level and energy demand by technological means. A number of researchers have substantiated huge potentials for energy efficiency improvements, corresponding to a reduction of the energy demand by about two thirds or more without lowering the living standards (Lovins 1973; Nørgård 1979; Steen et al 1981; Nørgård 1991; Nørgård & Viegand 1994). In addition, many studies have shown that the use of fossil fuels may be reduced dramatically, or even phased out altogether, over two or three decades if the energy efficiency measures are combined with utilisation of renewable energy (Blegaa et al 1976; Lönnroth et al 1978; Hvelplund et al 1983; Johansson et al 1983; Jørgensen 1985; Jørgensen et al 1986; Meyer & Nørgård 1987; Benestad et al 1991; Brinck et al 1992; Meyer et al 1993).

Based on these findings, alternative energy planning research environments developed in many countries, not least in Denmark, aiming to promote sustainable[29] energy solutions. The

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28 *Based on system dynamics modelling theories (Forrester 1961a; Forrester 1961b; Forrester 1971).*

29 *Although the term "sustainable development" to many is inseparably connected to the "Brundtland Report" (World Commission on Environment and Development 1987) it was used long before that.*

overall objective was to promote "solar paths" as alternatives to the application of nuclear power and fossil fuels (including coal). Most solar paths were based on the two above-mentioned cornerstones (with varying emphases)[30]:

- improved efficiency of resource utilisation, through reduction of energy losses and emissions.
- exploitation of renewable energy, taking advantage of the fact that the earth is not a closed system, as it receives huge quantities of energy in the form of solar radiation.

Generally, the plans have aimed to counter the technological determinism, according to which nuclear power and/or fossil fuel fired power stations were unavoidable - that is, to show that the solar path would not necessarily compromise the standard of living. At the same time, many of the plans stressed the strategical perspective of the technological choices: it was not just a matter of selecting between different technologies, but also between two incompatible paths, one heading towards nuclear power (breeder reactors in the longer term) and one leading in the direction of solar energy and energy efficiency[31] (Lönnroth et al 1976; Lönnroth et al 1978). That is, a sustainable path (at least potentially) and a path which is incompatible with sustainability. Another important difference between the two paths is the capacity of the solar for promoting more decentralised development options than those offered by the former option.

Thus, the main focus was on technical potentials of the "solar path" for providing a long-term solution for the environmental problems without having to lower our material living standards[32]. This was initially a mainly defensive position, arguing that it is possible to avoid nuclear power without having to sacrifice the welfare society, but later it has formed the basis for an technological optimism. According to the latter view, it is possible to combine growth and sustainability through immense improvements of the efficiency of the energy system and utilisation of renewable energy. In Denmark, this perspective has been advanced by e.g. (Clemmesen 1995). Internationally, it is reflected in the subtitle of (Weizsäcker et al 1995): "double welfare and halved consumption of nature".

At the same time, there has also been a more critical approach pointing to the limitations in addition to the potentials. Technology should not replace changes in behaviour and attitudes but rather serve as a supplement. Moreover, many technological solutions create problems and

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30 *The logical sequence is to start off with efficiency, and next to introduce renewable energy to cover the remaining demand (in which case efficiency is a means to increase the coverage rate of renewable). This sometimes results in renewables being seen as the more visionary step, as opposed to "merely making the system more efficient", cf. (Scheer 1993). A more appropriate view would be to see them as back-up to demand side measures.*

31 *Amory Lovins used the phrase "soft energy paths" to designate both solar and energy efficiency technologies (Lovins 1977).*

32 *For instance, the 1976 Alternative Energy Plan took as its point of departure that it should meet the same energy demand as the official energy plan, but just apply different energy systems and energy resources (Blegaa et al 1976). This was seen as a political necessity to gain support for the plan.*

dilemmas in addition to solving these. A general conclusion on these thoughts could be the technology improves within certain limits, but improvement potentials are not unlimited.

Overall, many of the problems are indications of more fundamental shortcomings of our society, therefore technology cannot be used to solve the problems.

3 The Framework: Transport and Sustainability

The overall objective of this study is to investigate the scope for sustainable development in the Danish transport sector, using grocery distribution as a case. Therefore, this chapter outlines the framework for this, that is the requirements to and background for sustainable development. The objective is not to carry out a thorough analysis of the concept, but rather to define the use of it in this context, particularly with respect to establishing the targets for improvement used in the study.

3.1 Traditional Environmental Policy or Sustainability

The concept "sustainability" has been widely used and abused in recent years, frequently without proper distinction being made between traditional environmental policies and sustainable development policies. Thus, a few words about the concept are required though it is beyond the scope of this report to provide a detailed discussion.

Basically environmental sustainability implies that we ensure the needs of the present generation without deteriorating the opportunities of future generations. This may be subdivided into the following main items (Daly 1991; Meadows et al 1992; Nørgård 1993):

1. Renewable resources should not be applied at a higher rate than that of its regeneration;
2. Pollution should not be generated at a higher rate than the natural environment is capable of absorbing and neutralising;
3. Non-renewable resources (e.g. fossil fuels) should not be utilised, or (in a "softer" definition of the concept) should not be used at a higher rate than human capital can replace natural capital lost, e.g. through fossil fuel utilisation. The latter version implies, for instance, that it is acceptable to utilise fossil fuels if it is used to invest in energy conservation or renewable energy systems.

In other words, policies for sustainable development are based on the aim to stay within environmental constraints. As a consequence, policies should be aiming at remaining below absolute emission and energy consumption targets. Moreover, with these targets being based on assessments of the carrying capacity of nature and human beings rather than the viability of their implementation, they are frequently quite radical. On top of this, there is at present a very uneven global distribution of emissions, and any attempts to rectify this would further increase the reduction requirements in the rich, high-emitting, countries such as Denmark.

Traditional environmental policies, on the other hand, typically limit the scope to relative improvements in comparison to the present state or to a projected development of the environmental state. In line with this, they are frequently restricted to improvements of the system efficiency[33] rather than the reducing the absolute emission and consumption figures.

A key issue is whether limits play a role in determining the development of the economies or whether these operate as systems in balance (Meadows et al 1973; Jacobs 1991; Meadows et al 1992).

3.2 Efficiency and/or Sufficiency

Traditionally, a strong link was presumed to exist between living standard and energy consumption, but from the beginning of the 1970s onwards, there has been an increasing acknowledgement of the improvement potentials. Today, this has frequently lead to a very strong confidence in the potentials of improved efficiency and resource flows based on renewable energy - assuming that it is possible, in principle without limits, to combine sustainability with continuing growth (also known as "green growth")[34].

Here "efficiency" is defined in general terms as the ratio between output - or desired consequences - and input - or undesired consequences. The desired consequences are the satisfaction of certain human demands and the undesired consequences can be the environmental problems such as resource depletion and pollution[35] (Nørgård 1995).

The efficiency of transport systems depends on the technical state of the transportation means, the split on different transport modes (the modal split), and on the utilisation of the transportation means. If the demands are measured as passenger-kilometre or tonne-kilometre these factors are sufficient to determine the efficiency, but this, in some cases, provide a misleading picture. For instance, it would not reveal poor journey planning leading to excessive driving, since this is counted as demand. Therefore, the number of trips frequently is an important supplementary measure of the demand, which means that the journey length should be included among the factors determining the efficiency. A proper measure of the transport need should not take the transport demand as given since the issue is to perform certain task, not to carry out a certain amount of transport[36].

Thus, it is clear that there are many ways in which the transport system efficiency can be improved, enabling economic growth without similar growth in the undesired consequences, but

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33 *In this context efficiency is defined as the ratio of desired to undesired consequences, the desired consequences being the satisfaction of human demand, while the undesired consequences are the negative environmentral impacts linked to the flow of resources (Nørgård 1995). Thus, in this definition, inefficiency can denote both high consumption of limited resources - especially fuels, but it could also be land, labour, materials etc. - and different forms of pollution.*

34 *Cf. the title of a report published by a research institute linked to the Danish trade union movement (Clemmesen 1995), claiming not only that it is possible to combine continuing economical growth and sustainable development, but also that economic growth in fact improves the conditions for sustainability.*

35 *Hence, efficiency is understood as either energy efficiency or environmental efficiency, whereas economical efficiency (cost effectiveness) generally is not included.*

36 *See also Section 2.2.*

given the limits of nature - that is, the constraints on resource utilisation and emissions in absolute terms - the proponents of green growth, in effect, assume that is possible to improve efficiency infinitely, and enough to offset the effects of the growth.

A more even global distribution of wealth and of the projected population growth would further increase the required efficiency improvements in the rich countries such as Denmark. In transport, bringing the rest of the world up to the transport standards would correspond to a global growth by a factor 3 to 6, whether using Danish or American standards as target, and moreover the population is envisaged to double over the next 40 years.

Moreover, exponential growth will limit the opportunity to exploit finite resources as a means for promoting a long-term sustainable development. On top of this, it is highly questionable whether continuing consumption growth is desirable in the rich countries.

This means that the objective of improving efficiency should be combined with increased focus on the notion of "sufficiency", addressing not only the standards of the means but also the goals (Nørgård 1991; Sachs 1993).

3.3 Setting Targets

This report does not deal with all aspects of sustainable development, but concentrates on two problems: energy consumption, and particularly the use of fossil fuels; and global environmental problems, especially the contribution to the global warming[37]. The main problem in this context is the emission of CO2. Other environmental problems are touched on in the report without being treated in details[38].

The notion of "sustainable development" presumes that targets are (in principle) based on critical loads, i.e. taking the carrying capacity of the ecosystems as point of departure, rather than setting targets in relative terms, as in most conventional environmental policies. This procedure inevitably is subject to considerable uncertainty, especially for the global warming problems. During recent years, however, climate researchers have approached a higher degree of certainty (IPCC WGII 1995), and in any case, waiting for complete certainty to be achieved will probably make it too late to take action due to the long time constants.

The definition of Critical Load used in this report is based on (Nilsson & Grennfelt 1988; Jørgensen 1991; Brinck et al 1992): The highest quantitative estimate of exposure to one or more pollutants which do not - in the short or long term - result in significant harmful effects on the

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37 *Today, the issue of the depletion of the ozone layer plays a marginal role in conjunction with the transport sector in Denmark, though this may change if Danish cars are equipped with air-conditioning.*

38 *A key problem - which is reinforced by some of the technical solutions being advanced in the transport sector - is the complexity of today's society, not least because of the number of materials and chemical processes. A considerable part of these are not very well-known when analysed in isolation, and even less when placed in the actual surroundings. In addition, many environmental problems are characterised by great complexity and long time delays before the effects can be determined.*

most sensitive systems of the biosphere or the atmosphere or human beings, according to present knowledge.

As regards the impact on the global climate, the key factor is the concentration of greenhouse gases in the atmosphere. The most radical target is to require that it remains at present level or perhaps even that it should be reversed to a pre-industrial level, which would require huge reductions of the emissions (Emborg & Juul-Kristensen 1989). A more viable path would be to "limit the damage", i.e. to retain the concentration increase within certain boundaries. For example, the IPCC points to a reduction of the global CO_2-emissions with a view to keep the increase under a doubling of the pre-industrial concentration. Moreover, an equal distribution of the global CO_2-pollution would require much greater reductions in the rich countries such as Denmark.

If a 50% global reduction target is applied and combined with a target of equal per capita emissions all of the globe, this would result in a requirement of a reduction target for CO_2-emissions in Denmark of more than 90% (if assuming a doubling of the world population).

A variety of different targets, based on different sustainability criteria, have been established regarding the emissions of CO_2:

In the Danish Transport Action Plan of 1990 - and confirmed in "Traffic 2005" from 1993 and the present national energy plan "Energy 21" - the reduction targets for CO_2 are: a stabilisation by 2005/2010[39] at the 1988 level and a 25% reduction by 2030 (Ministry of Transport 1990; Ministry of Transport 1993a; Ministry of Environment and Energy 1996). The reduction targets of the general energy planning are stricter aiming at a 20% reduction by 2005 and a 50% reduction by 2030[40] (Ministry of Energy 1990; Ministry of Environment and Energy 1996).

In addition to the emission of pollutants, there is a resource consideration to be taken into consideration. During the last decade or so, there has been much emphasis on the greenhouse problems, to the extent that the resource aspect in many cases is forgotten. Nevertheless, sustainable development presumes that finite resources are not depleted or (in the weaker definition) are being applied for promoting sustainable energy systems with emphasis on energy conservation, utilisation of renewable energy and application of efficient energy systems. It should remembered in this context, that the 50% reduction target frequently termed "the Brundtland target" does neither refer to the reduction of CO_2-emission nor to the reduction of the fossil fuel consumption but to the total energy consumption including renewable energy (World Commission on Environment & Development 1987).

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39 *In 1990, the target year was 2010, whereas later this has been coordinated with the general energy planning targets, which means that the year is now 2005.*

40 *It has been a issue of much debate whether the latter is actually a target or an "aiming point".*

4 Development of the Grocery Sector of Denmark

This and the following chapter contain an analysis of the Danish grocery sector, covering the distribution chain from manufacturers/importers via wholesalers and retail shops to the individual households[41]. In other words, both the transport of groceries to the retail shops and the shopping transport is covered and evaluated as a whole. International transport, including import transportation, is not covered by the analysis, i.e. the increase in the consumption of imported products is not reflected in the findings.

The term "groceries" refers to commodity categories such as food, drink, tobacco and certain household articles. It is a common characteristic of groceries that their value is determined by the flow of products through the household (i.e. the consumption of production), whereas the value of the remaining product categories - durable goods, clothes,. books - is linked to the possession of the products (i.e. to the stock of products) (Nørgård 1979).

For the analysis the grocery sector is divided into the following subsystems (Jørgensen 1995a):

A. The wholesale system, responsible for the distribution of goods to the retail shops (domestic transport only), whether this is carried out by wholesalers or by other agents, such as manufacturers or by retail organisations. Structurally the wholesale system is determined by the grocery manufacturing sector and by the organisation of the wholesalers proper.

B. The retail system, consisting of the retail shops in the grocery sector.

C. The consumer system, covering the distribution of groceries from the retail shops to the individual households, i.e. the shopping transport.

The transport demand in conjunction with distribution of groceries is roughly the sum of A and C, since the distribution of goods between shops is limited, and hence there is virtually no transport work carried out within the retail system. Furthermore, only a small percentage of the distribution does not pass through the shops. Hence, when analysing the transport effects is possible to distinguish between transport to the shops (the wholesale system) and transport from the shops (the consumer system).

This chapter covers the sector as a whole, whereas Chapter 5 concentrates on the consumer system (the distribution of groceries from shops to individual homes). Chapter 7 contains an analysis of the historical development of the fuel consumption and emission effects of grocery distribution.

41 *The grocery project has been treated in the following publications: (Jørgensen 1993a; Jørgensen 1995a; Jørgensen 1995b; Jørgensen 1995c; Jørgensen 1995l; Jørgensen 1996g)*

4.1 Overview

The post-war restructuring of the Danish retail trade sector has resulted in a considerable real-term growth of the total turnover (in conjunction with the increase in private consumption) and also in far-reaching qualitative changes. In the grocery sector, however, the quantitative expansion has been moderate: in total, the turnover has increased 35-40% from 1960 to 1993 (whether measured by weight or in fixed prices), and roughly half of this increase is due to population growth. Today the grocery sector accounts for about 60% of the total retail turnover.

But this conceals radical qualitative changes, which can be characterised by means of the following keywords, cf. (Jørgensen 1995a; Danstrup 1984):

- centralisation of all links of the distribution chain (manufacturing, wholesale and retail sale);
- integration with a large part of the retail shops participating in chains, buying associations or similar wholesale collaboration arrangements, linking the individual retail shops much closer to specific wholesalers than used to be the case;

The turning point of the restructuring was the late 1950s and early 1960s. Before this time the grocery distribution networks were mainly locally based, with retail shops serving the communities in which they were located, and wholesalers, and to some extent even manufacturers, serving bounded geographical areas. Thus the networks were decentralised, centred around towns and cities. Today we have a nation-wide and centralised distribution network, with the major part of the manufacturing and wholesale taking place through organisations covering Denmark as a whole, and with retail shops being increasingly disconnected from their communities (Jørgensen 1995a).

This development is frequently perceived as a consumer-led process ("the development of the grocery sector is following the demands of the consumer"), but in practice it is a complex set of interactions between structure and behaviour, closely linked to the technological development. In particular, the development and widespread introduction of the automobile has played a vital role as a condition for - and consequence of - the development, which would have been unthinkable without on the one hand the passenger car for shopping transport and on the other hand the delivery truck for distribution of goods to the shops.

4.2 Structural Changes in the Retail System

The principal features of the development of the retail system since the 1950s have been (Jørgensen 1995a):

1. concentration on fewer, larger retail shops;
2. development of new shop types;
3. development of competition between shops;
4. the almost complete disappearance of the independent grocer's shop, having been replaced by more or less integrated chains and collaboration between shops and wholesalers.

Each of these features are treated in more details in the following.

The concentration trend has resulted in a dramatic decline in the number of grocery retail shops. Since 1960 the number has been reduced by about 60%, as can be seen from Figure 4.1. The traditional grocer's shop, served from a counter, has virtually disappeared, while the number of most specialist retail shops (butchers, bakeries etc.) has been cut by about 75-85%. The only major exception from this development has been the newspaper and magazine shops, the number of which has increased about 3 times since 1958[42]. This, however, can be explained by a change in the role of these shops from specialist shops to a sort of neighbourhood shops (cf. Section 4.4). Moreover, retail shops have been concentrated in city centres and shopping streets, at the expense of shops in the residential areas and in rural areas.

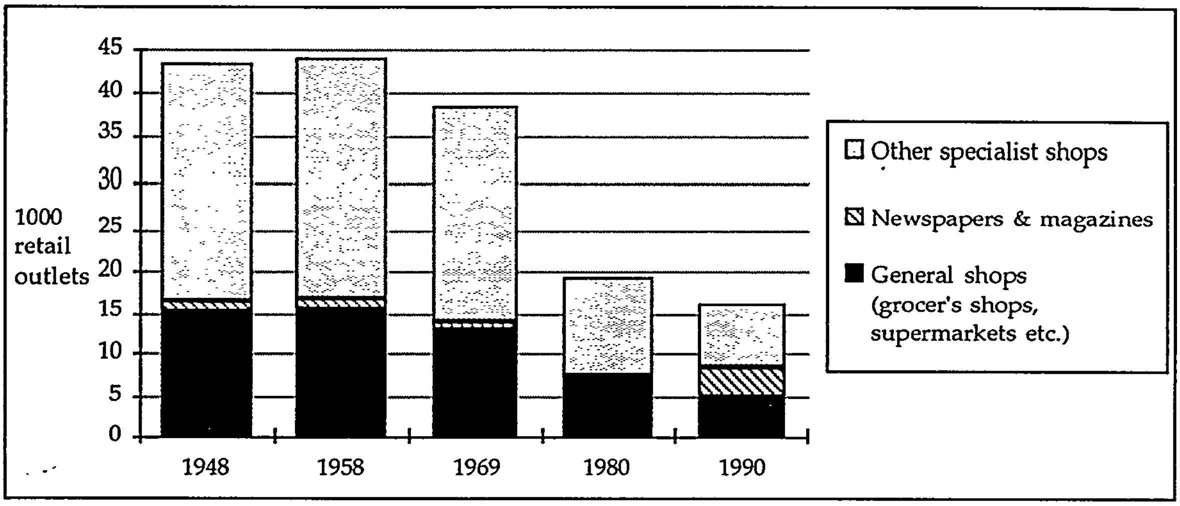

Figure 4.1. Development in the number of grocery retail shops in Denmark (Jørgensen 1995a).

Secondly, a range of new shop types have been introduced, to the extent that the majority of the types of shops dominating the scene in the 1990s have emerged (in a Danish context) from the 1950s onwards. Most of the new shop types can be seen as variations on the supermarket, introduced in Denmark at a large scale in the early 1960s.

The new shop types are generally characterised by (Danstrup 1984; Jørgensen 1995a; Stockmann 1993):

- new technology and new organisation principles (self-service; pre-packed products) with the principal objective of reducing the demand for labour;
- their aim to cover, in principle, all grocery demands (serving as "one stop shops"), as opposed to the traditional grocer's shop with mainly traditional groceries (flour, coffee etc.); as a consequence the assortments are generally much higher, requiring higher investments, in most of the new shop types;

42 *A considerable part of these shops are located on gasoline stations.*

- higher turnover demands following from the investments in new technology and larger assortments. For instance, today's supermarkets typically have a turnover which is 10 to 25 times higher than that of the grocery shop of the 1950s (in fixed prices).

The new shop types are treated in more details in Section 4.3.

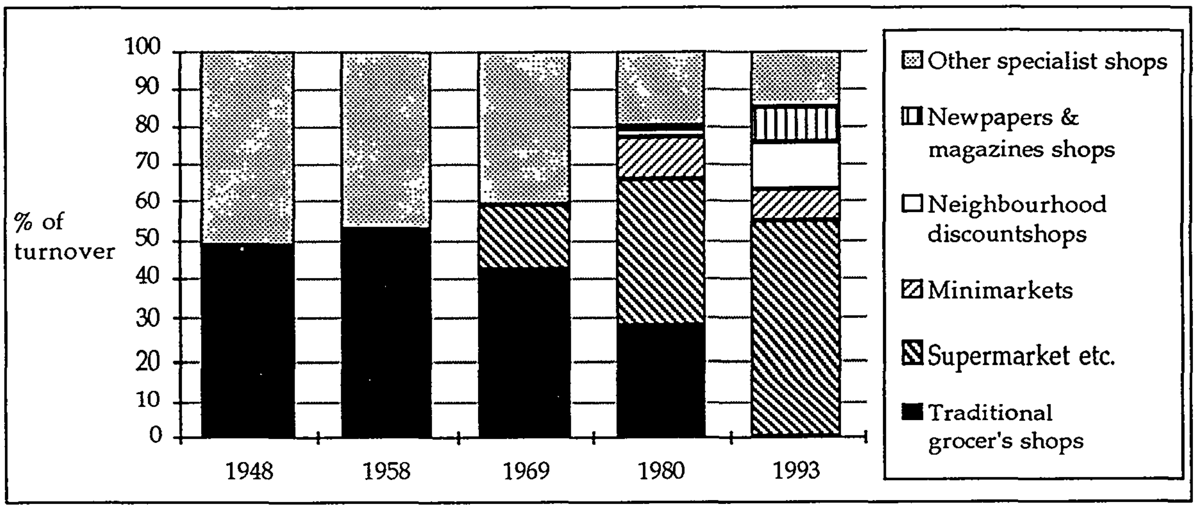

Figure 4.2. Distribution of grocery turnover according to types of shops (Jørgensen 1995a).

Thirdly, from the 1950s onwards competition has evolved between grocery shops in different geographical areas, and also between different shop types. Before the 1950s customers were nearly 100% loyal towards their shops (i.e. placed all of their shopping in the same shop), being forced to choose shops in their neighbourhood due to a lack of mobility. Moreover, there was relatively little competition between different lines of business in the grocery sector, in part because several shop types had monopoly of certain products (e.g. milk and meat). The relatively small area served by each shop reduced the need (and possibility) for competition between shops.

Therefore, when the supermarkets emerged on the scene they, in effect, introduced competition between shops, partly because their introduction coincided with the expansion of the private car in Denmark, and partly because they competed directly with other shops, not only the traditional grocer's shops but also, and perhaps even more pronounced, with respect to specialist shops. This also meant that price was introduced on a large scale as competition parameter in grocery trade (supermarkets were initially introduced as low price shops.

Today's retail shops may be divided into three main categories according to their market orientation:

- shops on central locations serving local communities beyond the immediate neighbourhood;
- shops with regional market orientation (distances of 25-50 km or more), often, but not necessarily, placed on out-of-town locations;

- neighbourhood shops serving the immediate surroundings (using distance as competition parameter).

Each of these three types of market orientations are treated in more detail in Section 4.4. Figure 4.2 show the distribution of the total Danish grocery turnover according to shop types.

Finally, the period has seen a virtual disappearance of the independent grocer's shops. In the 1950s, almost every grocer's shop was independent of chains and links to certain wholesalers, whereas today a considerable integration has taken place, which has lead to nearly all of the general grocer's shops being either part of an integrated chain or linked to a wholesaler.

Although the overriding trend of the period has been towards larger shops, with less service and with strong emphasis on low prices there have also been counter-trends, for instance, to cater for less mobile customers (especially the half of the Danish households without a car) or customers demanding higher standards rather than low prices.

The decline has been particularly pronounced in rural areas and villages, where the larger grocery shops (supermarkets etc.) have virtually disappeared, cf. Figure 4.3 and 4.4. These areas at the same time are the most vulnerable to such changes, due to the long distances to alternative shopping options. In small and medium-sized towns, on the other hand, there is an above-average number of large grocery shops per by capita, though the coverage measured by turnover is slightly lower in small towns (because the shops here are relatively small). In the Greater Copenhagen area, there is a lower than average coverage, which possibly can be explained - at least partly - by the higher and more comprehensive supply of specialist shops.

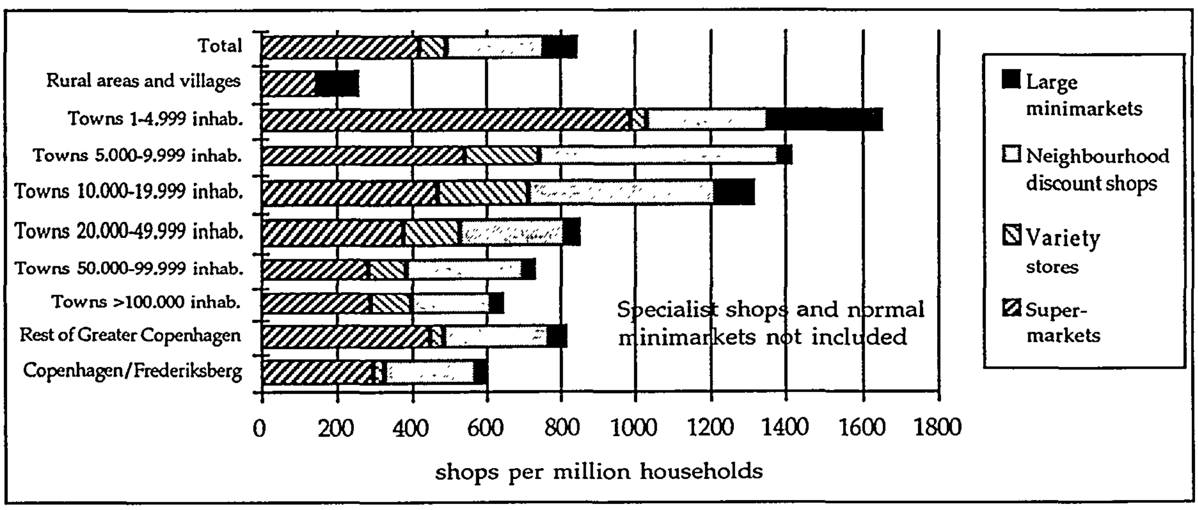

Figure 4.3. Number of large grocery shops per million households in different types of settlements (Jørgensen 1995a).

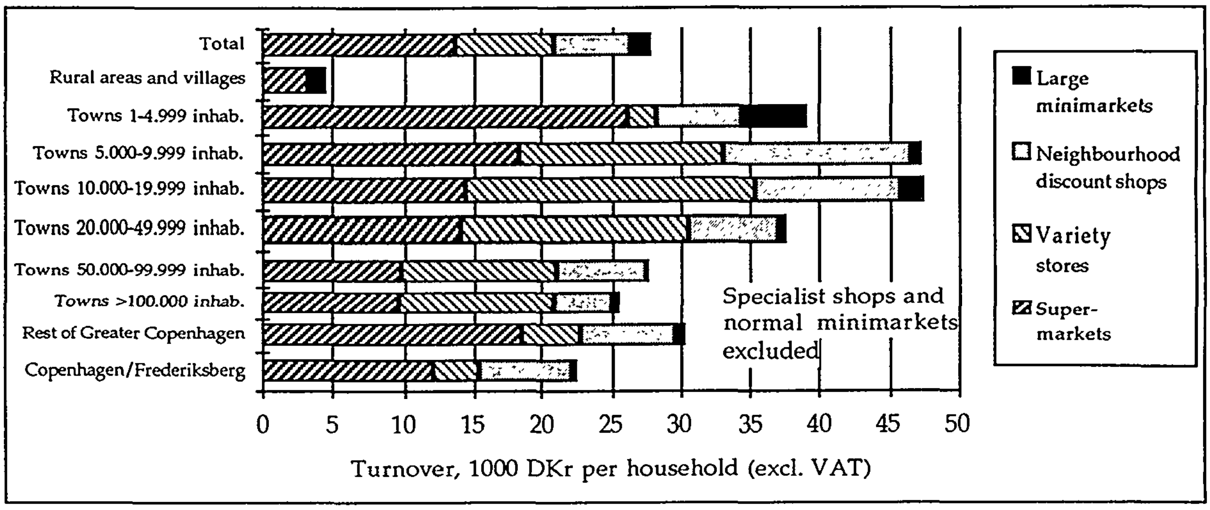

Figure 4.4. Approximate annual turnover in large grocery shops per million households in different types of settlements (Jørgensen 1995a).

4.3 The Grocery Shop Types

The most important new shop type in the grocery sector is the self-service supermarket, introduced in Denmark in the early 1950s, and spreading rapidly during the 1960s and 1970s. Today it is the predominant type of grocery shop, with about 29% of the total grocery turnover. Indeed, most of today's shop types in the grocery sector may be considered as variations on the supermarkets[43], either taking the development a step further (as the variety store) or a step back towards the smaller shops (as the mini markets).

The supermarkets have been the most important carrier of the transformation process. They have replaced not only the traditional grocer's shops but also the specialist shops to a large extent. Initially, they were introduced as a low price alternative based on low level of service, but generally this is not the case any longer. The average turnover is in the range of 30 to 75 million Danish Kroner (DKr), equivalent to the total annual grocery consumption of approximately 600-1500 average households. In fixed prices, this is between 10 and 25 times the size of a traditional grocer's shop of the late 1950s. Based on the assumption that the households on average cover 15% of the grocery demand in the shop, the typical supermarket turnover corresponds to an catchment area of approximately 10-25.000 inhabitants.

Today's supermarkets are completely different from the traditional grocer's shop, not only because of the self-service and size of the shops but also because of their aim to be genuine general shops, that is "one stop shops" covering, in principle, all of the grocery demand. In

43 *Sometimes the term "supermarket" is used in a much broader sense, covering several of the other shop types mentioned in the following. In this report, the term is used in a narrower sense, which could be interpreted as "supermarket proper".*

contrast, the pre-supermarket grocer's shop covered only the so-called colonial produces (coffee, sugar etc.).

The so-called variety store or double supermarket, is a large supermarket in which the non-food turnover accounts for more than 20% of the total turnover. This shop type was introduced in the early 1960s as low price competitors to the department stores, acting, in effect, as low cost department stores applying the service levels of supermarkets. It experienced a rapid expansion during the 1960s and early 1970s, but in the following 10-15 years very few new variety stores were established.

The 1990s, so far, has seen a particularly strong development in the establishment of these shops, especially in the Greater Copenhagen area. Today they are responsible for about 23% of the grocery turnover. Their annual turnover per shop is in the range of 100 to 200 million DKr (about 2000-4000 average households) and equivalent to the total turnover of about 35-70 average traditional grocer's shops (in fixed prices). Based on an assumed average coverage rate of 15% the catchment area needed per shop would contain 30-60.000 inhabitants - that is, either a rather large town or located in the Greater Copenhagen area.

The neighbourhood discount shops probably represent the most profound change in Danish grocery trade during the last couple of decades,. They are retail shops based on a low cost strategy, achieved through minimal service and shop standard, and a very limited assortment of primarily "problem-free commodities" (i.e. commodities with a high turnover rate). Thus they only cover a part of the grocery demand (typically 60-70%), and they are usually placed near other shopping facilities to provide the remainder of the demand. Introduced in the late 1970s as a low cost supermarket, many of these shops have since re-adjusted their market orientation, moving towards a neighbourhood profile, including location closer to residential areas. They typically have a turnover of 15-30 million DKr, equivalent to about 300-600 average households and 5-10 traditional grocer's shops. Most of these shops also have expanded their assortment compared to the early discount shops, taking in more and more commodity categories that were initially left out to save costs - a phenomenon called "trading-up" by retail analysts. Based on a 15% coverage rate the catchment area needed per shop corresponds to a population of 5-10.000.

According to retail sector development theories this development is to be expected. The Wheel of Retail theory explains the development as follows. The new shop types are introduced as low-cost alternatives with limited assortment, limited service and shop standard, but are forced to "trade up" (i.e. to expand the assortment and service) because of the competition. This, then, leaves room for new low-cost shops. Supermarkets have followed this development, and neighbourhood discount shops apparently are in the process of doing it. The cyclic Wheel of Retail theory have been developed into the "spiral motion" theory, which take into account that the surrounding society is in constant development. See (Agergaard et al 1968; Jørgensen 1995a).

Today, neighbourhood discount shops account for about 15% of the annual grocery turnover, and their market share is expected to continue increasing. Their pricing policy give them a substantial impact on the structure and consumption patterns of the grocery trade in general.

The very large hyper markets were introduced in Denmark in the early 1970s and have so far played a more limited role in Denmark than in many other countries. They can be seen as a variation on the variety store, with an even larger assortment and an even higher share of non-food commodities, and consequently demanding even higher annual turnover per shop. Therefore, they are generally aimed at regional markets, attracting customers by means of their large assortment and a clear low price profile. They are aimed at automobile households, requiring a high number of parking spaces. To minimise costs they are usually located at out-of-town places near good road connections.

Today the hypermarkets account for about 8% of the grocery turnover, that is, a relatively small percentage compared to the situation in many other countries. This can be explained by planning restrictions, and possibly the extent of the neighbourhood discount shops. The typical turnover per shop is in the range of 500-1000 million DKr, equivalent to about 10-20.000 average households. This corresponds to a catchment area per shop with 150-300.000, which, in effect, presumes orientation towards regional markets.

Currently, there is a stop for establishment of new hypermarkets and large shopping centres.

The mini market can be defined as a small supermarket with a limited assortment and a distinctive local orientation, but unlike the discount shops they do not have a low cost profile. They expanded in the 1970s in the wake of the oil crisis (and the resulting higher gasoline prices), and were supported by changes in legislation removing monopolies on milk and meat trading. In the 1980s, their market share and number of shops roughly halved, and today they account for about 8% of the grocery turnover divided on some 2500 shops.

The average mini market turnover is 3.5 million DKr, and nearly all of them have turnovers of less than 15 million DKr, equivalent to the grocery consumption of up to 300 average households, and corresponding to the total turnover of up to 5 traditional grocer's shops. The catchment area needed per shop corresponds to a population of up to 4500, which in most cases can be found in the immediate neighbourhood of the shop. New shops, generally, require a turnover in the upper end of the range, that is, between 10 and 15 million DKr. There are about 200 so-called "large mini markets" - mini markets near the borderline to supermarkets proper - with an average turnover of 14-15 million DKr.

A special development has been seen in connection with the category "newspapers and magazines shops", which has experienced a substantial growth in the number of shops during the last 10-15 years, especially as a result of the establishment of shops at filling stations. Today, many filling stations, and even gasoline companies, obtain a larger turnover from sale of groceries than from gasoline sale[44].

The shops in this category have developed into a kind of "micro markets", i.e. small shops with long opening hours and assortments, which are determined by the commodities that were exempted from the opening hours regulations in the Danish Shops Act, in force until 1995. These shops are mainly oriented towards emergency and impulse buying. The 1995 Shops Act allows small grocery shops (with a turnover of less than approximately 12.5 million DKr) to stay open all week, including Sundays, with no restrictions on the assortment,

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44 *Thereby, they are going full circle, since the first pumps selling gasoline in Denmark were established by traditional grocer's shops.*

except alcoholic drinks, and this already has resulted in many small grocery shops staying open on Sundays.

The newspapers and magazines shops account for about 9% of the total grocery turnover, as opposed to around 2.5% in 1980. The average turnover of newspapers and magazines shops in 1994 was 2.9 million DKr, but this figure is increasing since the growth is in large shops with a turnover over 5 million DKr (Dansk Dagligvareleverandør Forening 1994). Today, only 13% of the newspapers and magazines shops have a turnover over 5 million DKr, while this share is envisaged to grow to almost 20% in just 5 years. 60% of the shops have a turnover of less than 3 million DKr, which means that it can be covered by the immediate neighbourhood of the shop. These figures cannot be compared directly to the other shop types, due to the very small amount per customer.

The remaining grocery specialist shops (e.g. baker's shop, greengrocer's, and butcher's) have experienced an even stronger decline in the number of shops than the sector as a whole, namely by about 75% since 1960. In addition, their market share has dropped from around 50% to about 15%, and their function has changed from main suppliers of the commodities not covered by the grocer's shops - frequently based on monopolies - to supplementary suppliers to supermarkets, variety stores etc.

Mostly, the turnover of grocery specialist shops is under 5 million DKr, but since each shop covers a part of the grocery budget and each transaction in the shop typically is relatively small it is not possible to estimate a catchment area similarly to the other shop types.

4.4 Classification of Today's Grocery Shops

Section 4.3 gives a survey of the most important grocery retail shops, while this section details the market orientation classification presented in the previous section[45], dividing the shops into three categories: centrally located shops oriented towards local markets; regionally oriented shops; and neighbourhood shops.

The first category, the centrally located shop oriented towards local markets, may be considered the base case of the three market orientation types. It normally serves more than one community, albeit in the main limited to one town with hinterland, and therefore they are typically placed in central locations with good access for traffic. Their orientation implies a need for a much higher turnover than that of the traditional grocer's shop.

The most important examples of this category are the supermarket, the variety stores, and the neighbourhood discount shops, particularly in the initial phase[46]. These shops are responsible for the fact that, on the one hand, most people in urban areas have shops within 4-5

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45 *As explained in Section 4.2 "market orientation" is a characteristic of today's grocery shops, as opposed to the typical grocery shop of the 1950s, which was mostly oriented towards its immediate neighbourhood, in which it met limited competion.*

46 *The neighbourhood discount shops to some extent have developed towards the third category (see below).*

kilometres at the maximum, but on the other hand they have rarely got them in the immediate neighbourhood, that is within walking distance.

Secondly, the regionally oriented shops (hyper markets), most directly exploit the availability of the private car, and the diminishing customer loyalty, since they are oriented beyond markets in one town, addressing markets at a distance of 25-50 km or more. Moreover, they are established at out-of-town locations, and thus they are almost totally dependent on customers with car access, aiming to attract customers by means of low prices and large assortments. Denmark got its first hyper market around 1970, but the influence of this shop type has been limited - compared to many other countries - by local resistance against the shops. This resistance, however, appears to be declining, in which case hyper markets may gain an increasing share of the market. The same applies to shopping centres aimed at a regional market.

Despite a limited role in Danish grocery trading so far the hypermarkets potentially have substantial impacts for transport and environment, due to their size, typical location and market orientation.

The third category, the neighbourhood shops, were dominating in the 1950s, when both the traditional grocer's shops and most specialist grocery shops were oriented towards local communities. Today it is mainly a counter-trend directed at customers with limited mobility. Its principal competition parameter is short distance from home to shop.

The most significant examples of this category are the mini markets and the newspaper and magazine shops, in so far as they have developed from specialist shops to small neighbourhood shops. A major part of these shops are placed at petrol stations, and thus to some extent they are oriented towards motorists rather than the neighbourhood. Finally, the neighbourhood discount shops are in the process of developing into neighbourhood shops to a greater extent than supermarkets proper, placing greater emphasis on finding locations near residential areas. These shop types have in common that they are mainly oriented towards supplementary and emergency shopping rather than basic grocery shopping.

In broad terms, the first-mentioned category accounts for about 70-75% of the grocery retail turnover in Denmark, while the second accounts for about 10% and the third for 15-20% (Jørgensen 1995a).

4.5 Manufacturing and Wholesale System

The wholesale distribution network is determined by the development at both the manufacturing and the wholesale levels. The distribution network has developed from being primarily a locally based structure - with the major part of the supply coming from wholesalers located relatively close to the retail shops - to a structure based on nation-wide distribution systems (Jørgensen 1995a; Krarup 1986a; Krarup 1986b). Grocery wholesale in Denmark today is dominated by about five relatively large general wholesalers, and while twenty years ago even relatively small towns had their own distribution terminals or depots, today each wholesaler usually has one or two terminals covering the whole of the country. There has been a similar concentration process at the manufacturing level, both among the primary producers (farmers, fishermen etc.) and in the food industry (dairies, slaughterhouses etc.).

Although a few significant wholesalers are mainly supplying retail shops within regional markets, nationally oriented wholesalers account for the major part of the supply. Because the major part of the retail shops are attached to chains or buying associations the choice of wholesalers is generally based on this affiliation rather than geographical proximity. In addition to supply through wholesale dealers, there is a varying, but significant, supply directly from manufacturers to retail shops (often invoiced through the wholesalers). The distribution systems used for direct supply have seen structural changes along the same lines as those among the wholesale dealers, albeit to a varying degree in different sectors.

The centralised distribution networks mean longer distribution paths, but also, in principle, opportunities for better planning. Distances have been increased by the reduction of nodal points (manufacturers, wholesalers, terminals etc.) in the network, by the specialisation of manufacturing plants, and by the associations between shops and wholesalers. In other words, the distance between the nodal points increase, and the closest nodal point are not necessarily chosen.

In principle, the transport demand can be divided into inter-regional/national, regional and local distribution, with different vehicles being applied for different purposes, but in practice there is not a very distinct separation of the three. As an implication of the reduction of the number or local storages, terminals and depots the same vehicles (typically delivery trucks) are used for inter-city transportation and local distribution. The result is that over-sized vehicles, with poor capacity utilisation, are employed in local distribution.

The distribution may be carried out either by wholesalers, by the manufacturers delivering directly to retail shops, or by (mainly smaller) retail shops collecting the commodities in self-service wholesale storages. The last-mentioned accounts for a very small percentage of the total distribution. A common daily driving pattern of one of the big wholesale dealers or a manufacturer is a total driving distance of 200 to 300 km, of which about 30-40% is local distribution driving, with the journeys to and from the area accounting for the remaining 60-70% (Krarup 1986a; Krarup 1986b).

On average the products are estimated to be transported about 50-80 km per journey (including their share of the empty driving), but frequently they are transported 2-3 times during the distribution chain (Danmarks Statistik 1993a).

5 The Grocery Consumer System

This chapter focuses on the last stage of the distribution of groceries, in which they are transported to the individual households. This distribution is, in the main, performed by the consumers through their shopping in the retail shops, though there are other paths as well (such as direct transport from producers/distributors to the home, delivery services, consumption in restaurants etc.).

5.1 Consumption and Shopping Patterns

The product assortment has changed fundamentally from mainly anonymous products sold by the pound to assortments dominated by pre-packed products, with a significant percentage of proprietary articles, and generally a much greater range of products. For instance, the number of dairy products has increased by more than an order of magnitude, and import of fruit and vegetables has increased the product range and has made the term "vegetable or fruit of the season" virtually meaningless. This means that the assortment has become one of the factors on which customers base their choice of shops, whereas 30 years ago proximity was the predominant decision criteria. In addition to product diversification within the well-known product categories, totally new product categories have been introduced. Notably, the introduction of refrigerated and frozen food has changed both distribution system, retail shops and shopping patterns (Krarup 1986b).

Table 5.1 illustrates the distribution of the grocery consumption on different product categories. The average Danish household consumes about 1600 kg of groceries at home annually - 1400 kg of which are food, drink and tobacco products - plus about 4-500 kg of packing (only the packing reaching the consumer). The largest single item is refrigerated fresh food (dairy products, meat, fish etc.) with about 500 kg/household, followed by fresh vegetables and fruit and non-cooled beverages with 250 kg each. Frozen food accounts for only 75 kg (5% of the total), in spite of the fact that Denmark is second only to the USA with respect to consumption of frozen food.

The general shopping pattern has changed due to the centralisation initiated with the advent of the supermarket, and, furthermore, the competition between shops, using price as the principal competition parameter. In addition, the increased consumer mobility means that the customer loyalty towards shops has decreased considerably.

In the 1950s, the consumer usually visited a number of specialist retail shops, located within walking distance, to cover the daily need for groceries. As few had refrigerators or freezers some products had to be bought on a daily basis, and there were often delivery services.

Per household	Net weight kg/year	Gross weight kg/year	% based on net weight	% based on money
Tinned goods, flour, coffee etc.	195	230	11	11
Bread and cakes	125	130	7	7
Non-refrigerated drink	255	495	15	9
Fresh fruit and vegetables	255	260	15	7
Refrigerated fresh food	505	535	29	23
Frozen food	75	85	4	5
Tobacco articles	5	5	-	7
Non-food groceries	215	235	12	18
Total in households	*1620*	*1970*	*93*	*86*
- catering etc.	120	130	7	14
Total, incl. catering	*1740*	*2100*	*100*	*100*

Table 5.1. Estimated distribution of grocery consumption according to product categories in average Danish household (Jørgensen 1995a). The net weight is the commodity as it is delivered to the consumer, excluding packing, while the gross weight includes the weight of the consumer packing, i.e. the packing in which the product is delivered to the consumer.

Today, most of the daily shopping needs are normally covered through visiting one general shop, much larger (and with a greater assortment) than the grocer's shops of earlier days, but also located at a greater average distance from the home of the consumer. Also a greater proportion of the shopping is carried out in conjunction with the journey between work and home, as a consequence of changed working patterns, and less time is generally devoted to shopping than earlier, which probably is the main reason that specialist shops have not been able to compete with supermarkets (Jørgensen 1995a).

New values and priorities among shoppers have lead to different criteria for choice of shops: distance have decreased in significance, while prices, assortment ranges and product quality have gained importance. Prices have played a dominating role during most of the period from the early sixties until today, resulting in the rapid growth of neighbourhood discount shops and hyper markets, and (perhaps more importantly) in a strong emphasis on competition on prices in other shop types, particularly super markets and variety stores.

The assortment range has been another important criteria in most of the grocery retail trade, though exceptions to this rule exist (the neighbourhood discount shops). Thus shop types with a smaller range have found it difficult to attract customers, unless they have had a pronounced low-price profile. Among other consequences this has lead to a need for many consumers to go to the shop to select the products themselves, with a decline in the delivery services as a result.

Finally, quality conscious consumers are a minor fraction, but important in the overall context. For instance, they are responsible for low-price shops having to upgrade to attract new customers.

5.2 Shopping Transport Patterns

The development of the grocery sector is potentially leading to increased transport distances for two main reasons. First, the average distance between shop and consumer has increased, and, secondly, consumers do not necessarily choose the shop closest to their home anymore. The longer distances, moreover, result in a reduction of the share of shopping opportunities within walking distance. In addition, delivery services have virtually disappeared, which means that heavier loads have to be carried home by the consumer, forcing or tempting many to use motorised transport for the shopping trips.

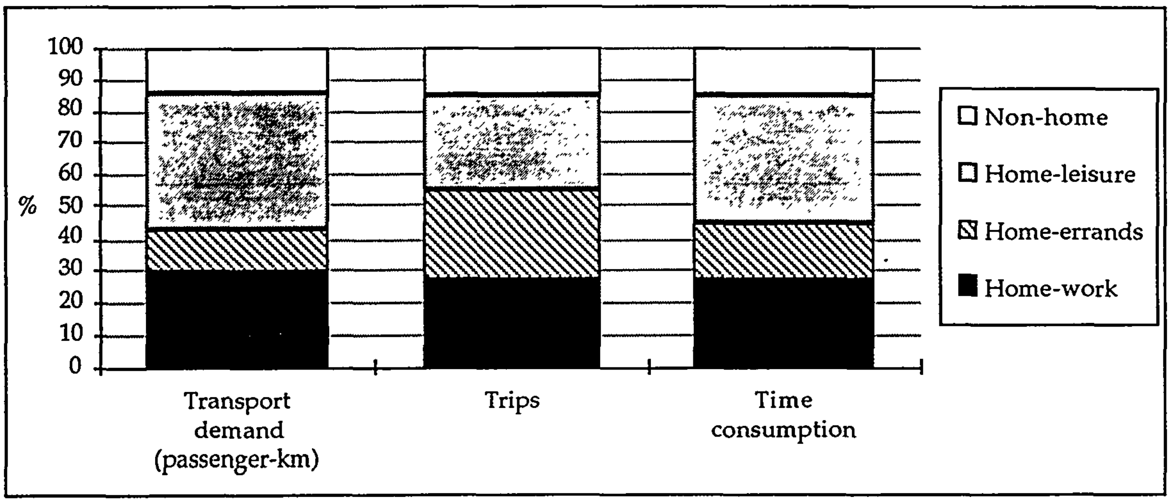

Figure 5.1. Passenger transport patterns - in three forms of transport demand (passenger-km), trips and time consumption - distributed on trip purposes (Ministry of Transport 1994b; Jørgensen 1995g).

The transport demand for errands, including shopping, increased by almost 50% between 1981 and 1992 (Christensen 1994). Figure 5.1 illustrates the share of transport demand, trips and time consumption accounted for by transport for errands in the year 1992 (Ministry of Transport 1994). Its share of the transport demand and time consumption is 14-17%, and about 28% of the trips. In other words, the trips for errands are generally very short, namely half the length of the average trip, which means that in all likelihood there is a high proportion of cold starts.

With respect to transportation means, 66% of the transport demand for errands in the 1992 investigation was executed in cars as drivers, as compared to 59% for passenger transport as a whole. The fractions covered by walking and cycling are about 50-100% higher than the general average, whereas the percentage covered by public transport is only half that of passenger transport in general. The limited length of the average errand trip applies to all transportation means.

The average payload per grocery shop visit (i.e. per trip to and from the shop) can be estimated to be in the range of 10-15 kg, excluding packing. The variation in all likelihood is substantial between different transportation means and shop types.

6 Vehicle Stock, Fuel Consumption and Emissions

This chapter contains a survey of the vehicle stock and its fuel consumption and emission patterns, providing a background for computing the fuel consumption and emissions of grocery distribution in the following chapter. While the scope is not limited to grocery distribution, the emphasis of the survey is influenced by the conditions of the grocery sector, including the fact that the main focus is on road transport.

There has been a strong and almost uninterrupted transport growth - passenger and tonne kilometres - during most of the post-war period. Besides the increase in transport demand measured in passenger or tonne kilometres, the most important aspects from an energy and environment perspective has been the increase in speed and the increase of motorised transport. Each of these factors - transport quantity, speed[47] and quantity - should, all other things being equal, contribute to a growth in fuel consumption. Furthermore, as a consequence of the demand for acceleration and speed, engines have become much more powerful, which in general leads to less efficient operation. Thus, a strong growth should be expected in the transport sector fuel consumption - much stronger than the one that has been seen in practice. This reveals that a considerable technical development of the vehicle efficiency has taken place during the period to counter these factors, though not sufficient to avoid an increase in the fuel consumption.

6.1 Development Trends for Vehicles and Transport in the Post-War Period

Figures 6.1 and 6.2 illustrate the development of the vehicle density for different vehicle categories in Denmark. Passenger cars grew almost constantly by about 12% per annum from around 1950 to the mid-sixties, after which the growth percentages started to decrease. Between 1980 and 1982 there was even a reduction in the passenger car stock (in the wake of the second oil crisis) and, after a period with relatively strong growth in the mid-eighties, the stock has remained roughly constant since 1988.

In the 1950s, 2-wheelers (mainly scooters) gave a significant contribution to the boom in individual passenger transport, providing more affordable motorised transport than passenger cars. From 1960 onwards, there was a rapid decline in the 2-wheeler stock. Since then there has been a moderate, but relatively constant, growth, and over the last 15 years the stock has increased by about 40% (mainly motorcycles). Still, the 2-wheeler density is less than 10 vehicles per 1000 inhabitants, as compared to 325 for passenger cars.

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47 *Speed contributes to the fuel consumption through the air resistance, which is proportional to the square of the vehicle speed.*

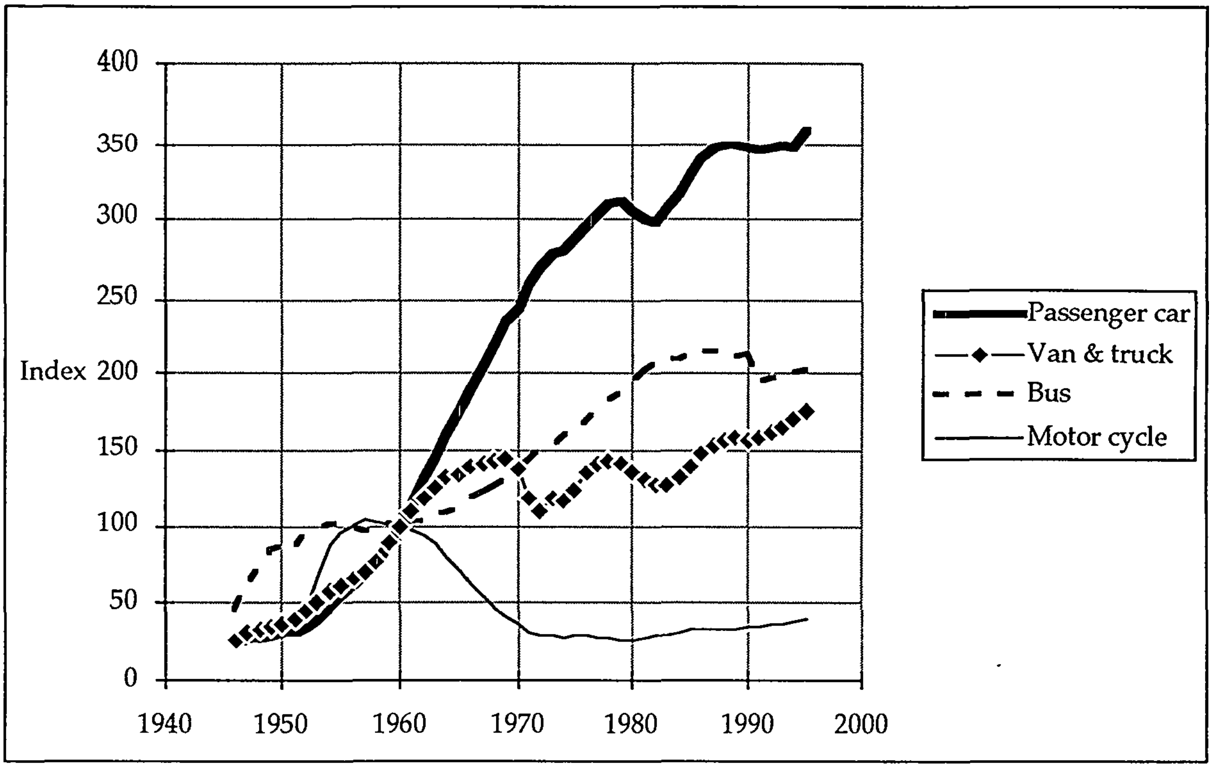

Figure 6.1. Development of motor vehicle densities (vehicles per 1000 inhabitants) in Denmark, with 1960 equal to 100 (Automobil-Importørernes Sammenslutning 1995).

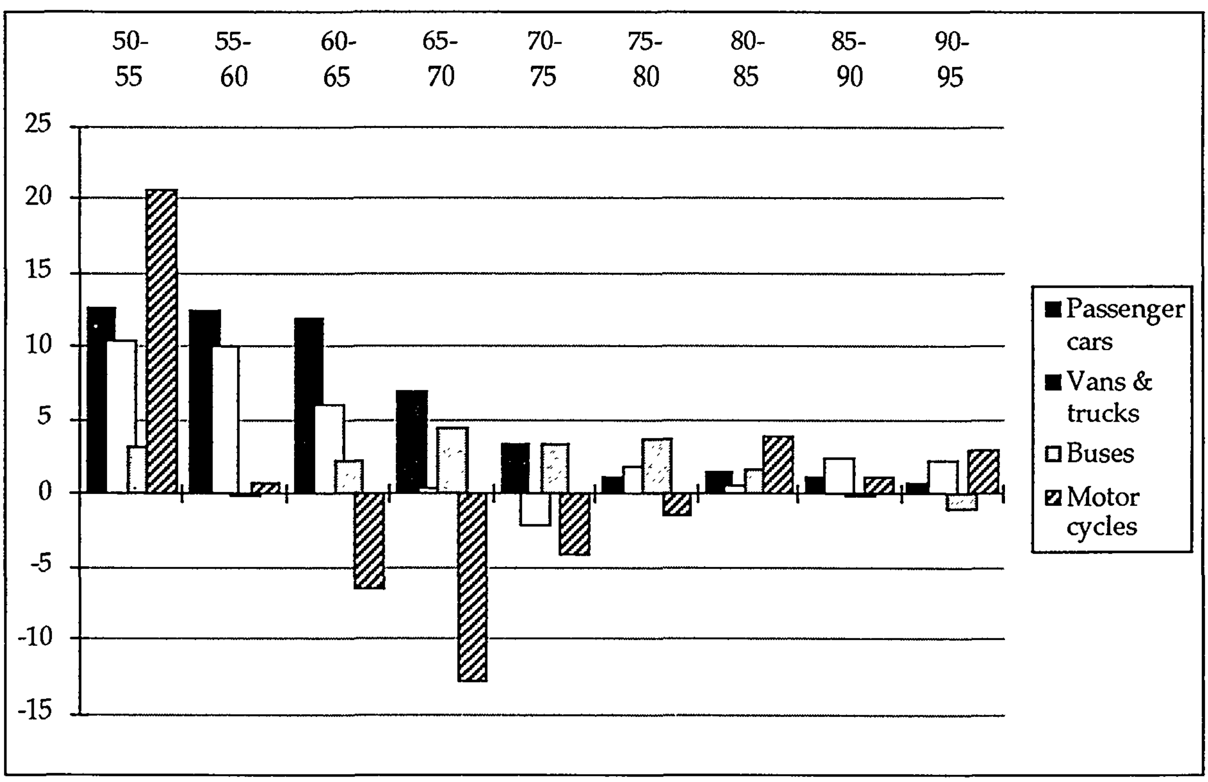

Figure 6.2. Growth in vehicle densities in Denmark in the form of annual averages over 5 year periods (see Figure 6.1).

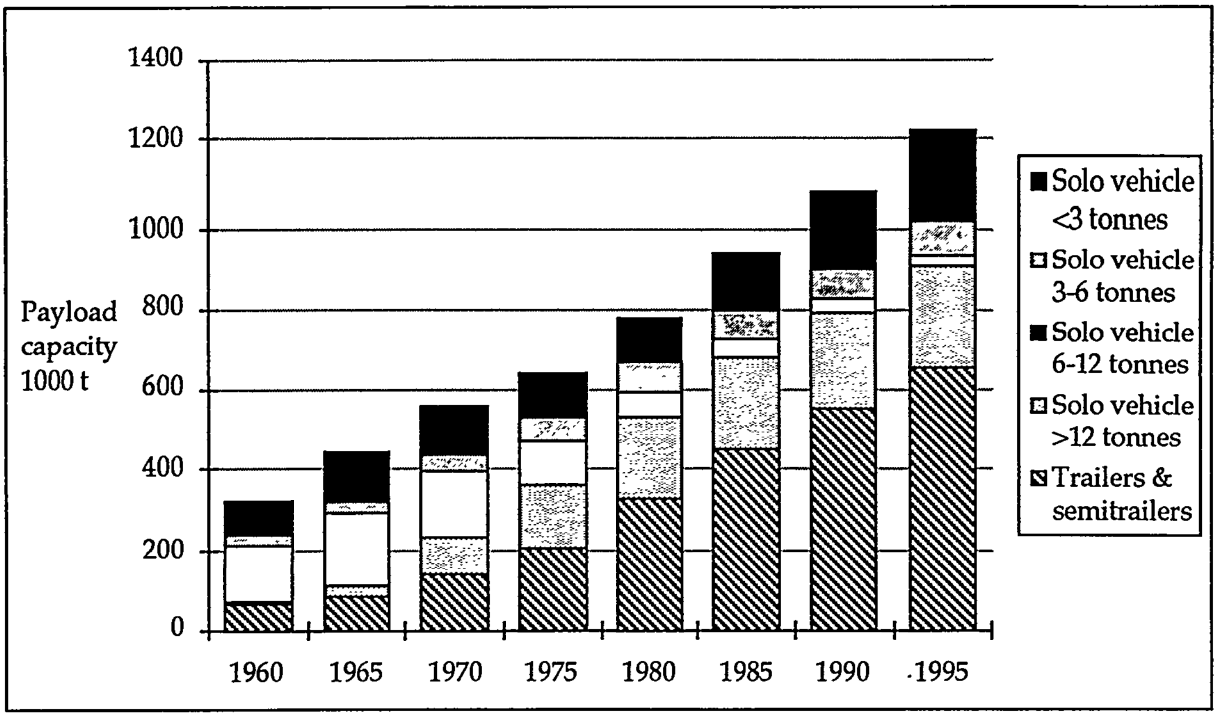

Figure 6.3. Development of the total payload capacity of vans and trucks in Denmark, and its distribution on gross vehicle weight intervals and vehicle types (solo vehicles and trailers and semitrailers).

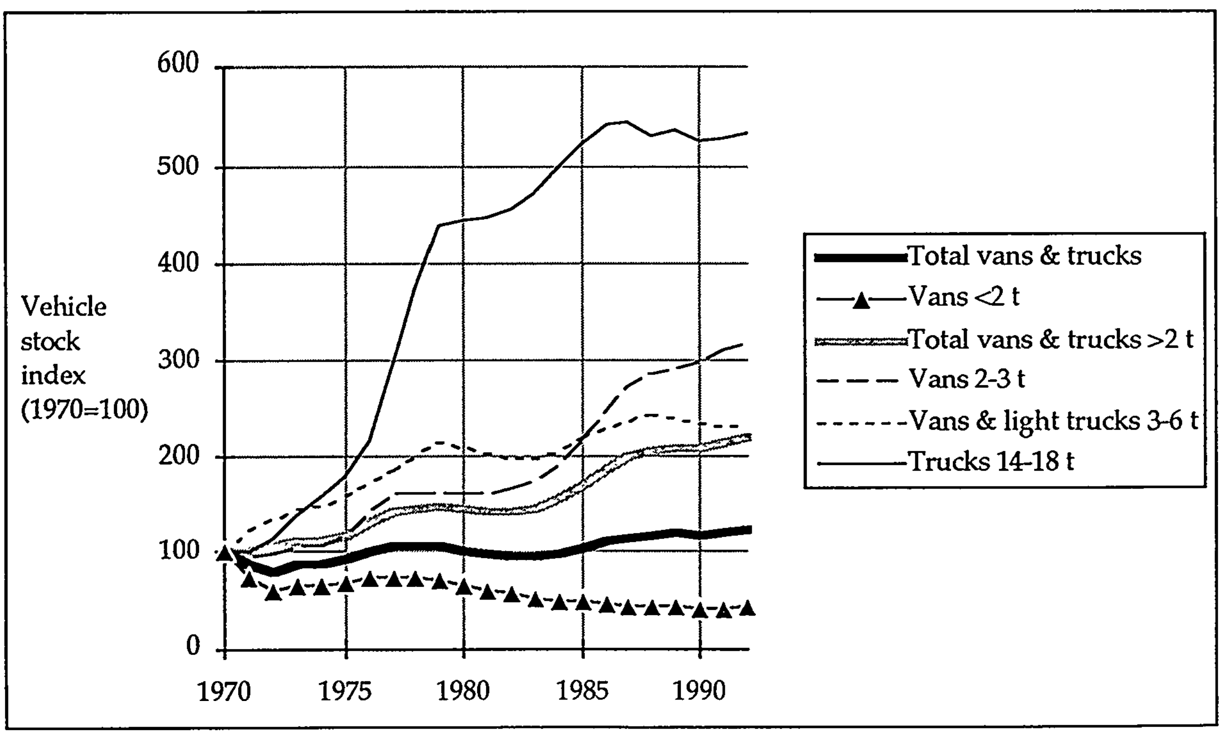

Figure 6.4. Development of freight vehicle stock in Denmark, as index with 1970=100. The graph shows the development of the stock as a whole, of vehicles heavier than 2 tonnes of gross vehicle weight, and of selected freight vehicle categories (Automobil-Importørernes Sammenslutning 1995).

By numbers, the bus stock has been on the increase during most of the period until around 1980, and, in addition, the average bus grew in capacity during the same period, so that the total bus capacity increased 4 times between 1960 and 1980. During the last 10-15 years, there has been a moderate decline of the total bus capacity.

Vehicles registered for freight transport, vans and trucks, increased rapidly by numbers until around 1965, with average annual growth rates around 5-10%. Since then the expansion has been much more moderate, even with periods of decline. When looking at the payload capacity, however, there has been a strong growth during the whole of the post-war period, as can be seen from Figures 6.3 and 6.4. In part, this is due to the introduction of larger vehicles (greater payload capacity), particularly in conjunction with the expansion between 1965 and 1980 of 12-20 tonnes delivery trucks[48] at the expense of lighter delivery trucks. More importantly, however, there has been a strong growth of the significance of trailers and semi-trailers, accounting for more than half of the payload capacity in 1994, as compared to 20% in 1960.

The post-war period has been characterised by the following significant trends in vehicle design, focusing on factors relating to the fuel economy and emissions (Vibe-Petersen 1993; Automobil-Importørernes Sammenslutning 1995; Friis-Hansen & Antvorskov 1995; Jørgensen 1995f; Groenewegen & Potter 1996; Jørgensen 1996a):

- The average curb weight of passenger cars declined until the mid-sixties, mainly due to increased sale of very small cars, but since then it is has been increasing slowly, from 850 kg in 1965 to the present average of 925 kg. This conceals two opposing development trends, namely on the one hand that lighter constructions and lighter materials are being applied in vehicles and on the other hand that vehicles have gained weight due to safety and comfort demands and provision of auxiliaries. There has been a steady decline in the fraction of small cars (<800 kg) from almost half of the stock in 1970 to just over one quarter today, and instead medium-sized passenger cars (e.g. VW Golf) and, more recently, large cars have won larger shares (see Figure 6.5). The trend towards heavier passenger cars has been reinforced during the last couple of years.
- The aerodynamics of passenger cars have improved dramatically, while other vehicle types have experienced more moderate improvements. At the same time, the average speeds have increased for most vehicles.
- Vehicles in general and passenger cars in particular, have been equipped with much more powerful engines, seen in relation to the vehicle weight - i.e. the weight to power ratio[49] (kg/kW) of the vehicles is reduced. As a result, most engines operate at low loads, reducing their efficiency considerably. The trend continues, especially among the smallest passenger car models and vans, both of which are approaching medium-sized passenger cars with respect to weight to power ratio, reflecting the focus on acceleration capabilities (especially overtaking) even in this category[50].

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48 *See Section 6.2.for further explanation.*

49 *The ratio between vehicle curb weight and maximum output of the engine.*

50 *Wolfgang Sachs explains the increasing engine power as the "second motorisation wave", in response to the automobile starting to become a universal commodity (Sachs*

(the note continues)

- While gasoline engines were dominating in most vehicle categories, except the heaviest trucks, around 1960, there has since been a significant development towards a greater share of diesel engines, especially among vans, light duty vehicles and medium duty trucks. Today, only motorcycles, passenger cars and the lightest vans have a majority of gasoline driven vehicles.
- The thermal efficiency of gasoline engines have been improved considerably for given driving patterns (but the more powerful engines pull in the opposite direction).

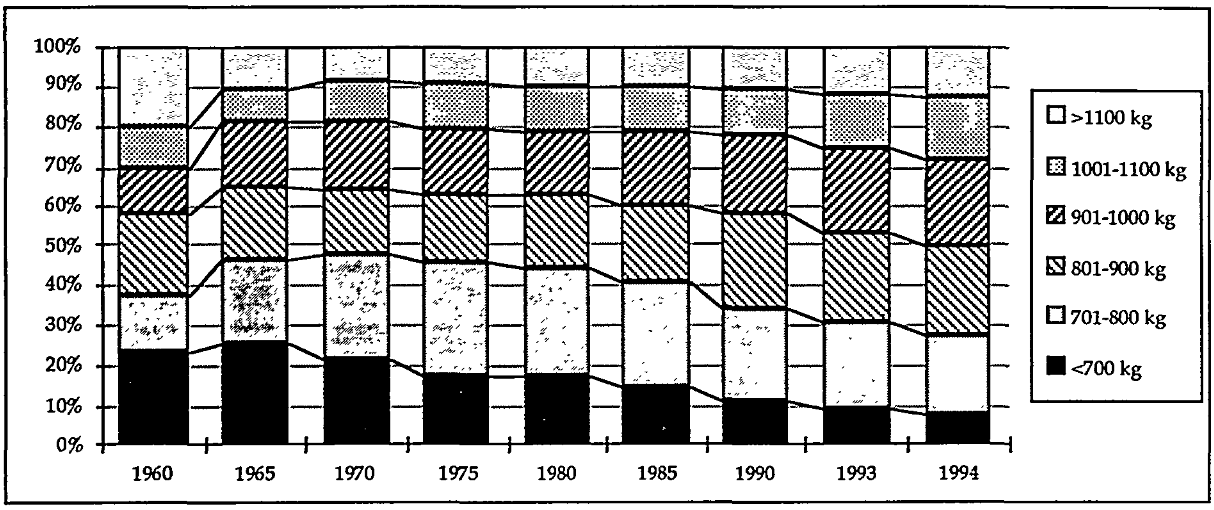

Figure 6.5. Development of the Danish passenger car stock on curb weight intervals (Automobil-Importørernes Sammenslutning 1995).

- In the 1960s, gasoline engines were typically operated on a rich fuel/air mixture, resulting in high CO and HC emissions and relatively low NOx emissions, while since the 1970s they have typically been operated at stochiometric mixture formation, which lead to a reduction of CO and HC emissions at the expense of higher NOx emissions. From around 1990 onwards three-way catalytic converters have, in effect, been mandatory in new passenger cars.
- The lead content in gasoline has been reduced dramatic, and the development can be expected to continue until the total gasoline consumption is "lead free".
- Diesel engines, too, have been improved substantially in different ways, even if the benefit has to some extent been offset by the impact of more powerful engines.
- There has been a shift to cleaner diesel with reduced sulphur content.

1984). The spreading of high-powered engines to small cars can be linked on the one side to the phasing out of the class of distinctly low-powered and low-standard minis (e.g. Citroën 2CV) and on the other hand the development of the new class of "high-class minis", initiated in the early 1980s with the introduction of the Peugeot 205. See Section 2.2.

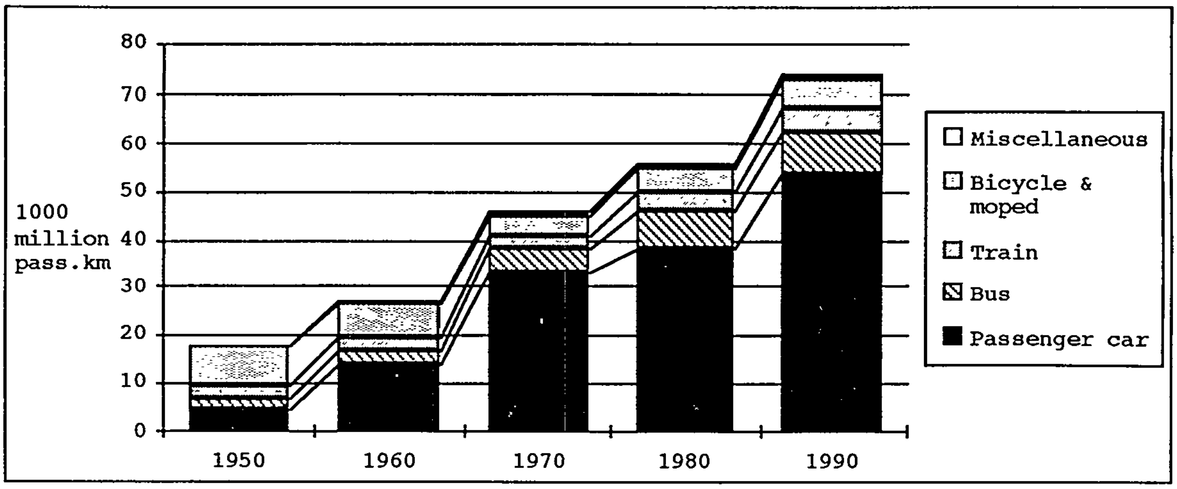

Figure 6.6. Development of passenger transport demand on transport modes from 1950 to the present. Based on data from (Lund 1975; Vejdirektoratet 1994). Bicycling in the years 1950, 1960 and 1970 is based on own estimates.

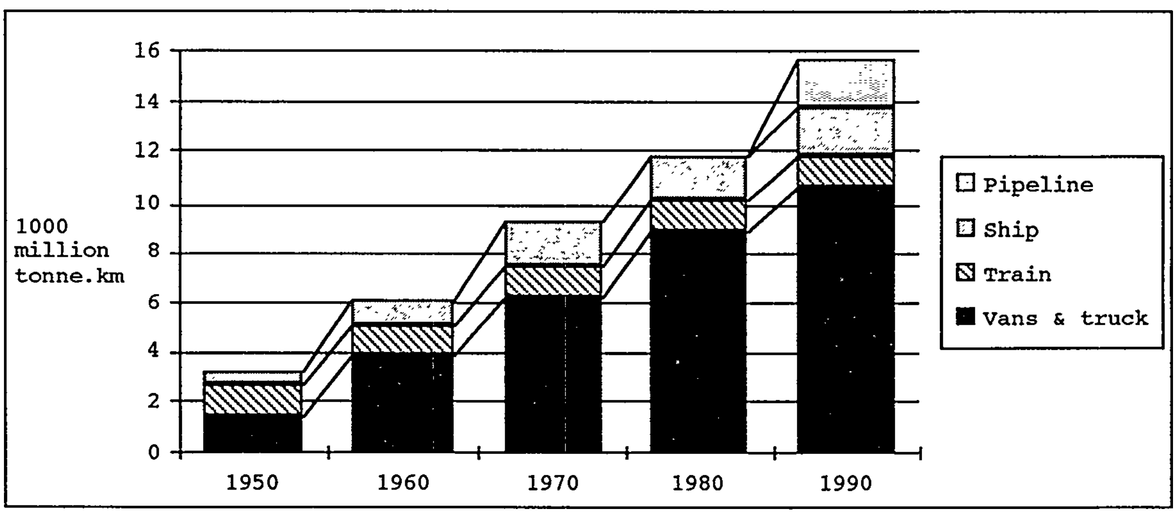

Figure 6.7. Development of freight transport demand on modes from 1950 to the present. Based on data from (Knudsen 1975; Vejdirektoratet 1994). The year 1960 is based on own estimate.

Figures 6.6 and 6.7 illustrate the development in passenger and freight transport during the post-war period. Both have increased about 4-5 times (of which some 20% can be attributed to population growth). In each case, individual, motorised traffic has taken most of the growth, especially in passenger transport, with passenger car driving being about 13 times higher today than in 1950 and driving in vans and trucks nearly 8 times higher. In freight transportation, there has been a substantial growth in both sea transport by ship and pipeline transport[51].

6.2 Vehicle Stock and Transport Patterns

Table 6.1 contains a survey of passenger transport and the distribution of transport modes in Denmark in 1993 (Ministry of Transport 1995)

	1000 vehicles	% gasoline	Driving mill. km	Transport mill. p-km
Passenger cars	1614	95	30500	55600
Motorcycles, scooters	49	100	305	380
Mopeds	109	100	400	400
Individual motorised transport, total	1772	96	31200	56400
Busses	8	1	470	7500
Trains (domestic)	-	-	-	1200
Air (domestic)	1060	100	10	500
Cycles	-	-	5100	5100
Passenger transport, total	-	-		70700

Table 6.1. Survey illustrating passenger transport in Denmark in 1993, showing vehicle stock, gasoline fraction (by stock), driving (vehicle-km) and transport demand (passenger-km) (Jørgensen 1996c). Passenger cars include taxis, hire cars etc. The gasoline fractions of the passenger car categories are own estimates.

The passenger car density in Denmark is lower than that of most other countries at a similar economic development stage, and also Danish passenger cars, generally, are relatively small, mainly due to the almost total absence of large cars. These characteristics probably reflect the high, value-added registration tax levels in Denmark, making car buying in general, and acquisition of large passenger cars in particular, very expensive. The main exceptions from this rule are taxis and vehicles registered for freight (due to lower taxation levels)[52] and, to some extent, vehicles from the former East-Bloc (due to lower production prices).

Tables 6.2 and 6.3 give an overview of road vehicles registered for freight transport. These vehicles can be divided into the following three main categories:

- Light goods vehicles (LGV): vans and light duty trucks with a gross vehicle weight of less than 6 tonnes;

51 *Pipeline transport was introduced in Denmark in the1980s as a consequence of the start of utilisation of oil resources in the North Sea.*

52 *Section 6.5 investigates the issue of light duty freight vehicles in further details.*

- Medium goods vehicles (MGV): delivery trucks with two or three axles and with a gross vehicle weight between 6 and 24 tonnes;
- Heavy goods vehicles (HGV): trucks with a gross vehicle weight of more than 24 tonnes, mostly in the form of truck & trailers or tractor & semitrailer.

This classification[53] is based on both the characteristics of the vehicle models on the market and on the application of the vehicles. There is a relatively sharp distinction, with respect to both aspects, between the LGVs on the one side and the two other categories on the other. In fact, the two are even covered by different vehicle manufacturers. On the basis of this observation there is a line of demarcation at 6 tonnes of gross vehicle weight. Other borders used for division between light duty vehicles and medium/heavy duty vehicles are 3 tonnes and 3.5 tonnes of gross vehicle weight, the latter of which is particular relevant, as this is the upper limit for a vehicle that can be driven on a normal driving licence. Also 3-3.5 tonnes is the range above which light duty trucks (as opposed to vans) become common.

Even though these vehicles are registered for freight transport a considerable percentage are used for passenger transport or mixed transport purposes. This applies in particular to LGVs, as described in Section 6.5.

	1000 vehicles	% gasoline	Driving mill. km	Transport mill. t-km
Light goods vehicles, <2 t	55.6	78	1150	30
Light goods vehicles, 2-3 t	158.3	26	3500	295
Light goods vehicles, 3-3.5 t	41.9	9	1240	105
Light goods vehicles, 3.5-6 t	5.1	3	200	70
LGVs, total	260.9	34	6090	500
Medium goods vehicles, 6-12 t	7.3	3	145	210
Medium goods vehicles, 12-14 t	5.1	0	115	270
Medium goods vehicles, 14-18 t	7.0	0	245	755
Medium goods vehicles, 18-24 t	7.0	0	245	140
MGVs, total	26.4	1	750	2650
Heavy goods vehicles, >24 t	14.1	0	625	6760
Vans & trucks, total	301.4	30	7465	9900

Table 6.2. Survey of freight transport by road in Denmark in 1993: vehicle stock, gasoline fraction (by stock), driving (vehicle-km) and transport demand (ton-km) (Jørgensen 1996c).

53 *Certain vehicles do not fall into those three categories, e.g. vans with a gross vehicles weight of more than 6 tonnes, but these account for a very small proportion of the total vehicle stock.*

	Payload capacity per gvw %	kg per kW	$c_W \cdot A$ per tonne payload capacity	$c_W \cdot A$ per tonne curb weight
Delivery van (<2 tonnes)	25-35	14-22	1.5-2.5	0.8-1.0
Van (2-3.5 tonnes)	35-45	22-35	0.9-1.5	0.7-0.8
Light duty truck, soft top (3-3.5 t)	30-35	35-40	0.9-1.4	0.5-0.6
Light duty truck, hard top (3-3.5 t)	25-35	35-45	0.8-1.5	0.4-0.5
Medium Goods Vehicle (2-axle, 15-17 t)	53-58	50-60	0.2-0.25	0.3-0.35
Medium Goods Vehicle (3-axle, 22-24 t)	57-62	55-65	0.15-0.18	0.25-0.30
Heavy Goods Vehicle (40-45 t)	65-70	30-50	0.05-0.15	0.15-0.25

Table 6.3. Survey of key characteristics of freight vehicles: payload capacity per gross vehicle weight (%); curb weight to engine power; apparent frontal area (cWxA) per tonne payload capacity (m2/tonne); and apparent frontal area per tonne curb weight (m2/tonne). Based on (Jørgensen 1995f; Jørgensen 1996a).

6.3 Development of Specific Fuel Consumption and Emissions

Figure 6.8 illustrates the estimated development of the specific fuel consumption of Danish passenger cars and Light Goods Vehicles with less than 3.5 tonnes of gross vehicle weight (stock averages)[54]. Between 1972 and 1992 the specific fuel consumption of all the vehicles considered is improved by about 20%, mainly due to a substantial improvement of the fuel economy of LGVs - for which the average specific fuel consumption has been almost cut by half - whereas the specific fuel consumption of passenger cars have remained roughly constant. The major part of the improvement of LGVs probably can be explained by the switch from gasoline to diesel engines in this category. Since around 1988 the average specific fuel consumption of the stock has remained constant.

54 *It should be emphasised that the estimates are connected with considerable uncertainty due to the quality of the data. The most reliable results are the total values, whereas the attempt to separate out passenger cars and Light Goods Vehicles is more uncertain. It is argued in (Jørgensen 1996e) that in all likelyhood the reductions in fuel consumption are moderately over-estimated due to a systematic error in the data used for the estimate (Fenhann & Kilde 1994).*

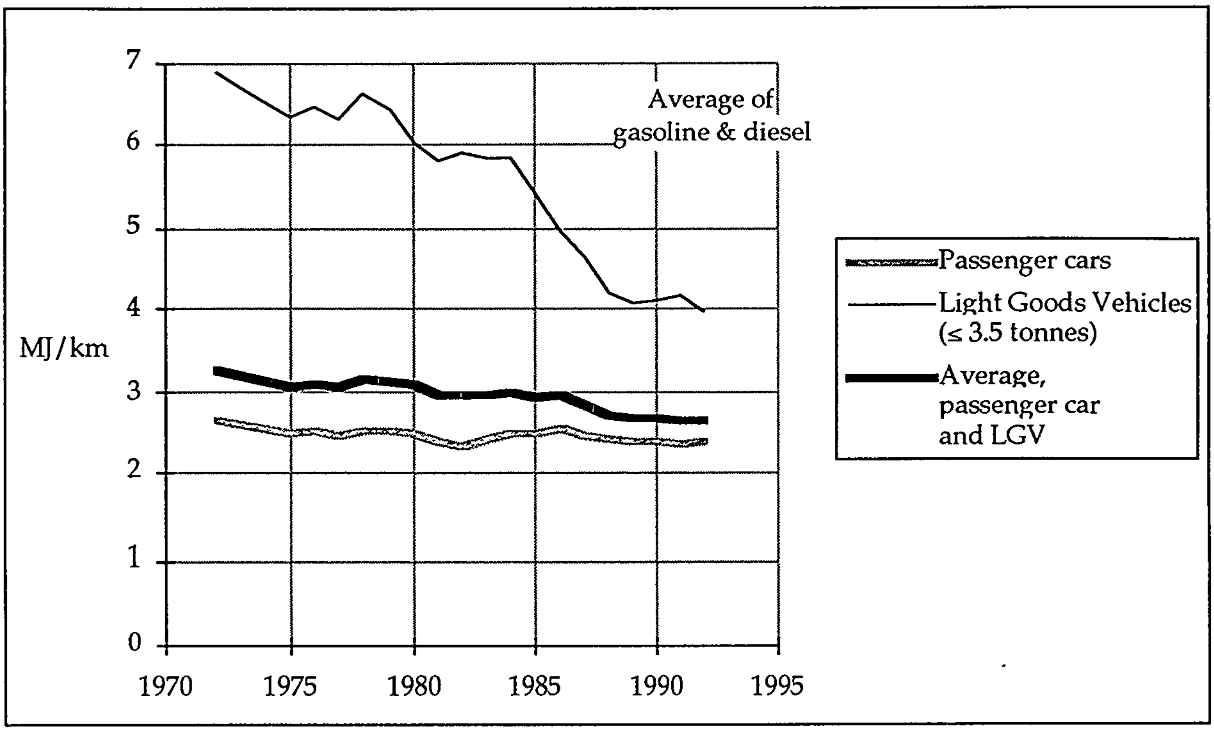

Figure 6.8. Estimated development of the specific fuel consumption of passenger cars and Light Goods Vehicles with a gross vehicle weight of less than 3.5 tonne (Jørgensen 1996e).

Summing up: vehicle technological development has shown progress in certain areas, where these have been obtainable without restricting traffic. Fuel economy and CO2 emissions have had technical progress, but this has been balanced by increased demands for comfort, safety, performance etc.

6.4 Transport Sector Fuel Consumption and Emissions

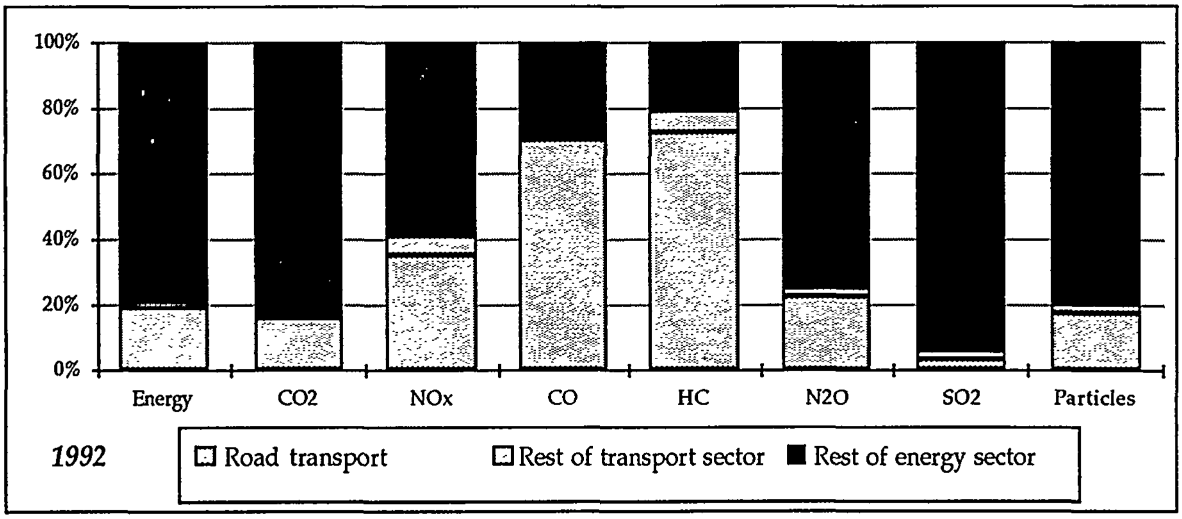

Figure 6.9. Distribution of fuel consumption and emissions of CO2, NOx, CO, HC, N2O, SO2 and particle mass according to use: road transport, the remaining transport sector (national transport only) and remaining energy sector in Denmark in 1992 (Haaland 1992; Fenhann & Kilde 1994; Ministry of Transport 1994a).

Figure 6.9 provides an overview of the role of the transport sector with respect to fuel consumption and emissions.

Tables 6.4 to 6.12 provides an overview of the distribution of fuel consumption and emissions on different vehicle categories. The inventory is based on existing statistical data and calculations carried out by the author[55]. Naturally, an inventory as detailed as this should be treated with great caution.

55 *Further documentation in (Jørgensen 1996c).*

Fuel consumption,	Diesel PJ	Gasoline PJ	Total PJ	SFC MJ/km	MJ/pkm MJ/tkm
Small passenger cars	0.1	15.8	15.9	2.3	1.35
Medium-sized passenger cars	0.8	42.4	43.2	2.6	1.55
Large passenger cars	5.6	8.9	14.7	3.0	1.75
Passenger cars, total	6.6	67.0	73.8	2.6	1.55
Buses	5.6	0.1	5.7	10.5	1.20
Motorised passenger transport, road	12.2	67.1	79.5	13.1	2.8
Light goods vehicles, <2 t	1.0	3.0	4.0	3.5	140
Light goods vehicles, 2-3 t	10.3	5.2	15.6	4.3	72
Light goods vehicles, 3-3.5 t	5.0	0.7	5.8	4.6	30
Light goods vehicles, 3.5-6 t	1.3	0.0	1.3	6.7	13
LGVs ≤6 tonnes, total	17.6	8.9	26.7	4.3	54
Medium goods vehicles, 6-12 t	1.0	0.0	1.1	7.5	5.2
Medium goods vehicles, 12-14 t	1.2	0.0	1.2	10.5	4.5
Medium goods vehicles, 14-18 t	3.0	0.0	3.0	12.0	3.9
Medium goods vehicles, 18-24 t	4.2	0.0	4.2	17.0	2.9
MGVs, total	9.4	0.0	9.4	12.5	3.5
Heavy goods vehicles, >24 t	13.2	0.0	13.2	21.0	1.9
Vans and trucks, total	40.2	8.9	49.3	6.5	4.6
- of which LGVs <6 t, %	44	99.5	54		
- of which MGVs, %	23	0.5	19		
Nat. freight transport, total	50.3	8.9	59.2	-	4.3
- of which vans and trucks, %	80	100	83		
Motorised road transport, total	52.4	77.0	128.8	-	-
- of which passenger transport	23	88	62		
Nat. transport, total	74.2	76.1	155.3	-	-
- of which passenger cars, %					
- of which vans & trucks, %	54	12	32		
- of which grocery distribution, %	-	-	12		

Table 6.4. Inventory of fuel consumption of Danish national transport in 1992 (Haaland 1992; Ministry of Transport 1994a; Energy Agency 1995; Jørgensen 1995a; Jørgensen 1996c). Only direct consumption is included, but the bottom line shows the estimated percentages which should be added to account for losses during refining and distribution of the fuel. The far right column shows specific consumption per passenger-km (passenger cars and buses) or per tonne-km (vans and trucks), based on average capacity utilisation factors. The fuel consumption totals include small contributions from LPG, and diesel includes all kinds of oil used for transport. For definition of LGVs, MGVs and HGVs see Section 6.2.

CO_2	1000 t/a	%	gram per km	gram per pkm or per tkm
Small passenger cars	1160	22	170	100
Medium-sized passenger cars	3160	59	190	110
Large passenger cars	1080	20	220	130
Passenger cars, total	5390	100	190	110
Buses	420	-	780	89
Motorised passenger transport, road	5810	-	210	110
Light goods vehicles, <2 tonnes	290	15	258	10300
Light goods vehicles, 2-3 tonnes	1150	59	312	5200
Light goods vehicles, 3-3.5 tonnes	430	22	338	2180
Light goods vehicles, 3.5-6 tonnes	100	5	493	900
LGVs ≤6 tonnes, total	1960	100	319	3990
Medium goods vehicles, 6-12 t	80	11	554	380
Medium goods vehicles, 12-14 t	90	13	777	330
Medium goods vehicles, 14-18 t	220	31	888	285
Medium goods vehicles, 18-24 t	310	44	1258	215
MGVs, total	700	100	928	260
Heavy goods vehicles, >24 t	980	-	1550	145
Vans & trucks, total	3640	-	476	340
- of which LGVs, %	54			
- of which MGVs, %	19			
Nat. freight transport, total	4450	-	-	325
- of which vans and trucks, %	82			
Motorised road transport, total	9450			
- of which passenger transport	62			
National transport, total	11400			
- of which passenger cars, %	47			
- of which vans and trucks, %	32			
- of which grocery distribution, %	12			

Table 6.5. Inventory of the emissions of carbon dioxide (CO_2) of Danish national transport in 1992 (Haaland 1992; Fenhann & Kilde 1994; Ministry of Transport 1994a; Jørgensen 1995a; Jørgensen 1996c). Only emissions linked to the direct fuel consumption is included, but the bottom line shows the estimated percentage which should be added to account for losses during refining and distribution of the fuel. The far right column shows specific emissions per passenger-km (passenger cars and buses) or per tonne-km (vans and trucks), based on average capacity utilisation factors. For definition of LGVs, MGVs and HGVs see Section 6.2.

NOx	1000 t/a	%	gram per km	gram per pkm or per tkm
Small passenger cars	15.1	26	2.20	1.30
Medium-sized passenger cars	35.5	61	2.15	1.25
Large passenger cars	7.4	13	1.55	0,90
Passenger cars, total	58.0	100	2.05	1.20
Buses	4.9	-	9.10	1.05
Motorised passenger transport, road	62.9	-	2.20	1.20
Light goods vehicles, <2 tonnes	2.2	20	1.95	78
Light goods vehicles, 2-3 tonnes	6.3	57	1.70	28
Light goods vehicles, 3-3.5 tonnes	2.1	19	1.65	11
Light goods vehicles, 3.5-6 tonnes	0.6	5	3.05	6.2
LGVs, <6 tonnes, total	11.1	100	1.80	23
Medium goods vehicles, 6-12 t	0.8	11	5.8	3.8
Medium goods vehicles, 12-14 t	1.0	13	8.5	3.7
Medium goods vehicles, 14-18 t	2.6	35	10.7	3.4
Medium goods vehicles, 18-24 t	3.1	41	12.5	2.2
MGVs, total	7.5	100	10.0	2.8
Heavy goods vehicles, >24 t	10.7	-	17.0	1.6
Vans and trucks, total	29.3	-	3.8	3.0
- of which LGVs, %	38			
- of which MDVs, %	26			
Nat. freight transport, total	30.8	-	-	
- of which vans and trucks, %	95			
Motorised road transport, total	92.2			
- of which passenger transport	68			
National transport, total	107.4			
- of which passenger cars, %	54			
- of which vans and trucks, %	27			
- of which grocery distribution, %	13			

Table 6.6. Inventory of the emissions of nitrogen oxides (NOx) of Danish national transport in 1992 (Haaland 1992; Fenhann & Kilde 1994; Ministry of Transport 1994a; Jørgensen 1995a; Jørgensen 1996c). Only emissions linked to the direct fuel consumption is included, but the bottom line shows the estimated percentage which should be added to account for losses during refining and distribution of the fuel. The far right column shows specific emissions per passenger-km (passenger cars and buses) or per tonne-km (vans and trucks), based on average capacity utilisation factors. For definition of LGVs, MGVs and HGVs see Section 6.2.

CH4	1000 t/a	%	gram per km	gram per pkm or per tkm
Small passenger cars	0.35	27	0.05	0.03
Medium-sized passenger cars	0.80	62	0.05	0.03
Large passenger cars	0.15	12	0.03	0.02
Passenger cars, total	1.30	100	0.05	0.03
Buses	0.04	-	0.06	0.006
Motorised passenger transport, road	1.33	-	0.05	0.03
Light goods vehicles, <2 tonnes	0.06	30	0.06	2.40
Light goods vehicles, 2-3 tonnes	0.12	58	0.03	0.50
Light goods vehicles, 3-3.5 tonnes	0.02	10	0.02	0.13
Light goods vehicles, 3.5-6 tonnes	0.00	1	0.01	0.02
LGVs ≤6 tonnes, total	0.21	100	0.03	0.38
Medium goods vehicles, 6-12 t	0.01	12	0.05	0.03
Medium goods vehicles, 12-14 t	0.01	13	0.07	0.03
Medium goods vehicles, 14-18 t	0.02	32	0.08	0.04
Medium goods vehicles, 18-24 t	0.03	43	0.11	0.02
MGVs, total	0.06	100	0.08	0.02
Heavy goods vehicles, >24 t	0.08	-	0.13	0.01
Vans and trucks, total	0.35	-	0.05	0.04
- of which LGVs, %	59			
- of which MGVs, %	17			
Nat. freight transport, total	0.36	-	-	
- of which vans and trucks, %	98			
Motorised road transport, total	1.68			
- of which passenger transport	81			
National transport, total	2.45			
- of which passenger cars, %	53			
- of which vans and trucks, %	14			
- of which grocery distribution, %	14			

Table 6.7. Inventory of the emissions of methane (CH_4) of Danish national transport in 1992 (Haaland 1992; Fenhann & Kilde 1994; Jørgensen 1995a; Jørgensen 1996c). Only emissions linked to the direct fuel consumption is included, but the bottom line shows the estimated percentage which should be added to account for losses during refining and distribution of the fuel. The far right column shows specific emissions per passenger-km (passenger cars and buses) or per tonne-km (vans and trucks), based on average capacity utilisation factors. For definition of LGVs, MGVs and HGVs see Section 6.2.

NMHC	1000 t/a	%	gram per km	gram per pkm or per tkm
Small passenger cars	20.9	27	3.0	1.75
Medium-sized passenger cars	48.8	62	3.0	1.75
Large passenger cars	8.5	11	1.75	1.00
Passenger cars, total	78.2	100	2.8	1.65
Buses	1.1	-	2.1	0.25
Motorised passenger transport, road	79.3	-	2.75	1.55
Light goods vehicles, <2 tonnes	3.5	29	3.1	124
Light goods vehicles, 2-3 tonnes	7.1	58	1.9	32
Light goods vehicles, 3-3.5 tonnes	1.4	11	1.1	7.1
Light goods vehicles, 3.5-6 tonnes	0.2	2	1.0	2
LGVs <6 t, total	12.2	100	1.9	24
Medium goods vehicles, 6-12 t	0.3	13	1.7	1.2
Medium goods vehicles, 12-14 t	0.2	12	2.1	0.9
Medium goods vehicles, 14-18 t	0.6	32	2.4	0.8
Medium goods vehicles, 18-24 t	0.8	44	3.4	0.6
MGVs, total	1.9	100	2.3	0.6
Heavy goods vehicles, >24 t	2.6	-	4.2	0.4
Vans and trucks, total	16.7	-	1.7	1.2
- of which LGVs, %	73			
- of which MGVs, %	11			
Nat. freight transport, total	16.9	-	-	
- of which vans and trucks, %	99			
Motorised road transport, total	96.0			
- of which passenger transport	83			
National transport, total	104.2			
- of which passenger cars, %	76			
- of which vans and trucks, %	16			
- of which grocery distribution, %	14			

Table 6.8. Inventory of the emissions of non-methane (NMHC) of Danish national transport in 1992 (Haaland 1992; Fenhann & Kilde 1994; Jørgensen 1995a; Jørgensen 1996c). Only emissions linked to the direct fuel consumption is included, but the bottom line shows the estimated percentage which should be added to account for losses during refining and distribution of the fuel. The far right column shows specific emissions per passenger-km (passenger cars and buses) or per tonne-km (vans and trucks), based on average capacity utilisation factors. For definition of LGVs, MGVs and HGVs see Section 6.2.

CO	1000 t/a	%	gram per km	gram per pkm or per tkm
Small passenger cars	123.3	27	17.9	10.5
Medium-sized passenger cars	288.0	63	17.5	10.3
Large passenger cars	48.7	11	10.1	5.9
Passenger cars, total	460.0	100	16.3	9.6
Buses	6.0	-	11.1	1.3
Motorised passenger transport, road	466.0	-	16.2	8.9
Light goods vehicles, <2 tonnes	15.5	25	13.8	550
Light goods vehicles, 2-3 tonnes	38.1	63	10.3	170
Light goods vehicles, 3-3.5 tonnes	6.5	11	5.1	33
Light goods vehicles, 3.5-6 tonnes	0.9	1	4.6	9
LGVs ≤6 tonnes, total	60.9	100	9.7	120
Medium goods vehicles, 6-12 t	1.4	13	9.5	6.6
Medium goods vehicles, 12-14 t	1.4	13	12.0	5.1
Medium goods vehicles, 14-18 t	3.5	34	14.0	4.5
Medium goods vehicles, 18-24 t	4.2	40	17.0	2.9
MGVs, total	10.4	100	13.8	3.9
Heavy goods vehicles, >24 t	15.7	-	25.0	2.3
Vans and trucks, total	87.0	-	11.4	8.1
- of which LGVs, %	70			
- of which MGVs, %	12			
Nat. freight transport, total	87.5	-	-	
- of which van and trucks, %	99			
Motorised road transport, total	553.0			
- of which passenger transport	83			
National transport, total	567.9			
- of which passenger cars, %	81			
- of which vans and trucks, %	15			
- of which grocery distribution, %	12			

Table 6.9. Inventory of the emissions of carbon monoxide (CO) of Danish national transport in 1992 (Haaland 1992; Fenhann & Kilde 1994; Ministry of Transport 1994a; Jørgensen 1995a; Jørgensen 1996c). Only emissions linked to the direct fuel consumption is included, but the bottom line shows the estimated percentage which should be added to account for losses during refining and distribution of the fuel. The far right column shows specific emissions per passenger-km (passenger cars and buses) or per tonne-km (vans and trucks), based on average capacity utilisation factors. For definition of LGVs, MGVs and HGVs see Section 6.2.

SO_2	1000 t/a	%	gram per km	gram per pkm or per tkm
Small passenger cars	0.35	18	0.05	0.03
Medium-sized passenger cars	0.95	48	0.06	0.04
Large passenger cars	0.70	35	0.15	0.09
Passenger cars, total	2.00	100	0.07	0.04
Buses	0.55	-	0.95	0.11
Motorised passenger transport, road	2.55	-	0.09	0.05
Light goods vehicles, <2 tonnes	0.15	8	0.14	5.6
Light goods vehicles, 2-3 tonnes	1.08	59	0.29	4.8
Light goods vehicles, 3-3.5 tonnes	0.49	27	0.39	2.5
Light goods vehicles, 3.5-6 tonnes	0.12	7	0.61	1.2
LGVs<6 tonnes, total	1.84	100	0.29	3.6
Medium goods vehicles, 6-12 t	0.10	11	0.69	0.48
Medium goods vehicles, 12-14 t	0.11	12	0.99	0.42
Medium goods vehicles, 14-18 t	0.28	32	1.13	0.36
Medium goods vehicles, 18-24 t	0.40	45	1.60	0.37
MGVs, total	0.89	100	1.18	0.33
Heavy goods vehicles, >24 t	1.24	-	1.98	0.18
Vans and trucks, total	3.97	-	0.52	0.37
- of which LGVs, %	46			
- of which MGVs, %	22			
Nat. freight transport, total	4.90	-	-	
- of which vans and trucks, %	81			
Motorised road transport, total	6.52			
- of which passenger transport	39			
National transport, total	9.70			
- of which passenger cars, %	21			
- of which vans and trucks, %	41			

Table 6.10. Inventory of the emissions of sulphur dioxide (SO_2) of Danish national transport in 1992 (Fenhann & Kilde 1994; Ministry of Transport 1994a; Jørgensen 1996c). Only emissions linked to the direct fuel consumption is included, but the bottom line shows the estimated percentage which should be added to account for losses during refining and distribution of the fuel. The far right column shows specific emissions per passenger-km (passenger cars and buses) or per tonne-km (vans and trucks), based on average capacity utilisation factors. For definition of LGVs, MGVs and HGVs see Section 6.2.

Particle mass (PM)	1000 t/a	%	gram per km	gram per pkm or per tkm
Small passenger cars	0.15	13	0.02	0.01
Medium-sized passenger cars	0.42	36	0.03	0.02
Large passenger cars	0.57	50	0.12	0.07
Passenger cars, total	1.15	100	0.04	0.02
Buses	0.46	-	0.85	0.10
Motorised passenger transport, road	1.61	=	0.06	0.03
Light goods vehicles, <2 tonnes	0.11	8	0.10	4.0
Light goods vehicles, 2-3 tonnes	0.88	61	0.24	4.0
Light goods vehicles, 3-3.5 tonnes	0.38	26	0.30	1.9
Light goods vehicles, 3.5-6 tonnes	0.08	5	0.39	0.8
LGVs ≤6 tonnes, total	1.45	100	0.23	2.9
Medium goods vehicles, 6-12 t	0.10	13	0.68	0.47
Medium goods vehicles, 12-14 t	0.10	13	0.85	0.36
Medium goods vehicles, 14-18 t	0.26	35	1.05	0.34
Medium goods vehicles, 18-24 t	0.30	39	1.20	0.21
MGVs, total	0.75	100	1.00	0.28
Heavy goods vehicles, >24 t	0.94	-	1.50	0.14
Vans and trucks, total	3.15	=	0.41	0.30
- of which LGVs, %	45	-	-	
- of which MGVs, %	24			
Nat. freight transport, total	3.45	=	=	
- of which vans and trucks, %	9			
Motorised road transport, total	4.75			
- of which passenger transport	34			
National transport, total	5.35			
- of which passenger cars, %	21			
- of which vans and trucks, %	59			
- of which grocery distribution, %	15			

Table 6.11. Inventory of the emissions of particle mass (PM) of Danish national transport in 1992 (Ministry of Transport 1994a; Jørgensen 1995a; Jørgensen 1996c). Only emissions linked to the direct fuel consumption is included, but the bottom line shows the estimated percentage which should be added to account for losses during refining and distribution of the fuel. The far right column shows specific emissions per passenger-km (passenger cars and buses) or per tonne-km (vans and trucks), based on average capacity utilisation factors. For definition of LGVs, MGVs and HGVs see Section 6.2.

N_2O	tonnes/a	%	mg per km	mg per pkm or per tkm
Small passenger cars	210	27	30	18
Medium-sized passenger cars	480	61	29	17
Large passenger cars	100	13	21	12
Passenger cars, total	790	100	28	16
Buses	45	-	84	10
Motorised passenger transport, road	835	-	29	15
Light goods vehicles, <2 tonnes	26	19	23	900
Light goods vehicles, 2-3 tonnes	84	58	24	410
Light goods vehicles, 3-3.5 tonnes	26	19	23	145
Light goods vehicles, 3.5-6 tonnes	6	4	30	85
LGVs ≤6 tonnes, total	144	100	24	290
Medium goods vehicles, 6-12 t	9	11	64	44
Medium goods vehicles, 12-14 t	9	11	80	34
Medium goods vehicles, 14-18 t	27	33	110	35
Medium goods vehicles, 18-24 t	37	45	150	26
MGVs, total	82	100	110	31
Heavy goods vehicles, >24 t	157	-	250	25
Vans and trucks, total	385	-	51	39
- of which LGVs, %	38	-	-	
- of which MGVs, %	21			
Nat. freight transport, total	390	-	-	
- of which vans and trucks, %	99			
Motorised road transport, total	1220			
- of which passenger transport	68			
National transport, total	1275			
- of which passenger cars, %	65			
- of which vans and trucks, %	31			

Table 6.12. Inventory of the emissions of nitrous oxide (N_2O) of Danish national transport in 1992 (Haaland 1992; Fenhann & Kilde 1994; Jørgensen 1996c). Only emissions linked to the direct fuel consumption is included, but the bottom line shows the estimated percentage which should be added to account for losses during refining and distribution of the fuel. The far right column shows specific emissions per passenger-km (passenger cars and buses) or per tonne-km (vans and trucks), based on average capacity utilisation factors. For definition of LGVs, MGVs and HGVs see Section 6.2.

Finally, Figure 6.10 sums up the analysis of the fuel consumption and emissions of road transport in Denmark.

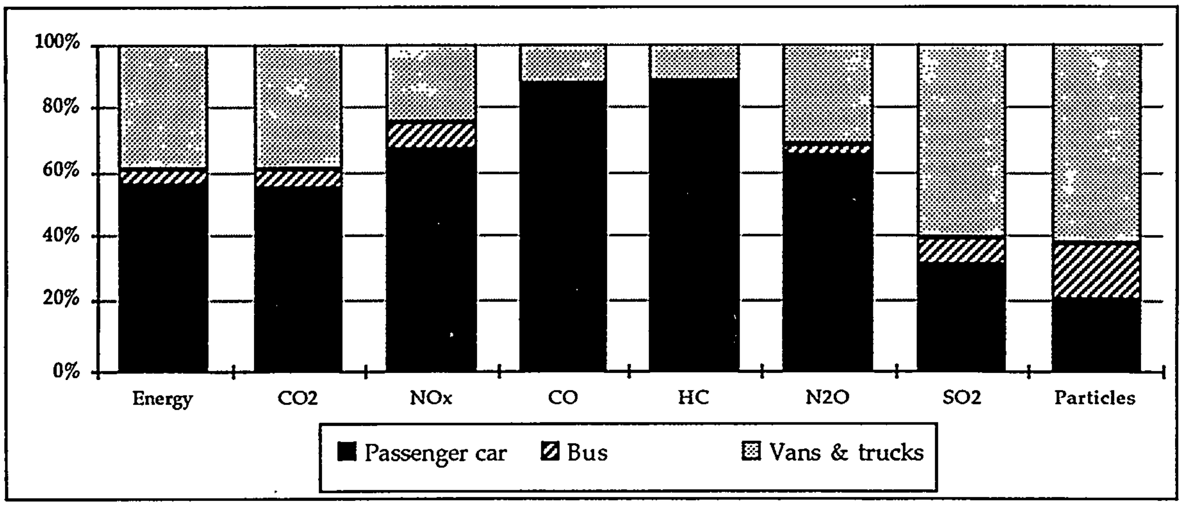

Figure 6.10. Distribution of fuel consumption and emissions of road transport in Denmark in 1992 according to transportation means: Passenger cars, busses and freight vehicles (vans and trucks) (Haaland 1992; Fenhann & Kilde 1994; Jørgensen 1996c).

6.5 Light Goods Vehicles

Light Good Vehicles constitute a particularly serious problem with regard to fuel consumption and emissions (Ministry of Transport 1990; Ministry of Transport 1994a; Jørgensen 1994a; Jørgensen 1995f; Jørgensen 1996i; Jørgensen 1996j). In this context, the light goods vehicle category (LGVs) is defined as covering all road vehicles registered for freight transport with a gross vehicle weight of less than 6 tonnes.

The category can be subdivided into the following (quite different) main types:

- delivery vans, based on passenger car models (about 20% of LGV stock, predominantly less than 2 tonnes of gross vehicle weight);
- normal vans, with self-supporting body and no chassis; about 2/3 of the LGV stock, particularly in the 2-3.5 tonnes range
- light duty truck, chassis-based construction; about 15% of the LGV stock, mostly in the 3-6 tonnes range; either open or with soft or hard top

Based on maximum gross vehicle weight the LGV category falls into the following main intervals:

- less than 2 tonnes of gross vehicle weight - mainly delivery vans based on passenger car models
- 2-3 tonnes - mainly vans
- 3-3.5 tonnes - a combination of vans and light duty trucks
- 3.5-6 tonnes - mainly light duty trucks.

Overall the stock of light duty freight vehicles has grown by about one quarter since 1970, roughly the same increase as that of the total stock of freight vehicles. The 2-3 tonnes range has shown particularly strong growth over the last 20-25 years, with an approximate doubling of both number of vehicles, driving (vehicle-kilometres) and transport demand (t-km) since 1980, and more than a trebling of the vehicle stock since 1970. There was particularly strong periods of growth in the mid-1970s and in the mid-1980s, but the growth has been virtually uninterrupted during the period. The 3-3.5 tonnes range has had a similar growth, albeit on a slightly less dramatical scale, with a 250% growth in the number of vehicles since 1970. Also there has been sign of stagnation for this category, though recent changes in the taxation schemes for freight vehicles are likely to lead to a reinforcement of this weight range.

The growth of 2-3.5 tonnes vans by and large has happened at the expense of the delivery van category, which has been reduced by almost 60% since 1970.

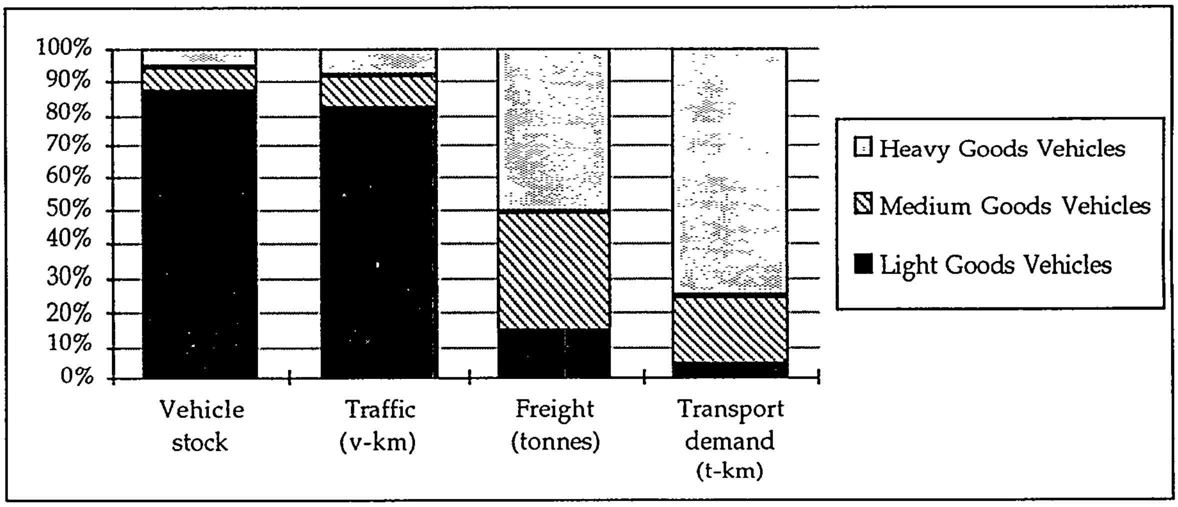

Figure 6.11. Distribution of vehicle stock , annual driving, annually transported load (tonnes) and annual freight transport demand (tonne-km) on categories of road vehicles for freight transport (Jørgensen 1995g; Jørgensen 1996j). Based on data from 1992.

Figure 6.11 illustrates the role of the LGVs in the overall transport pattern of road vehicles. In 1992, they accounted for 87% of the stock of road freight vehicles and for 82% of their annual driving, but they only covered about 15% of the transported freight (in tonnes) and 4% of the freight transport demand (in tonne-km) by road, see Figure 6.11. In other words, these vehicles typically have moderate daily driving demands, short journeys (reflecting that they are primarily applied in urban driving) and small payloads. These small vehicles not only carry very small payloads in absolute terms but their capacity utilisation in relative terms is very poor: about 5-7% based on weight (Danmarks Statistik 1993b; Jørgensen 1996a). In comparison, the capacity utilisation of heavier trucks is on average much higher, though in many cases more driving is needed to fill up the heavier vehicle.

Even though LGVs are registered for freight transport (at substantially reduced registration tax rates) they are to a great extent used for other applications. Less than a third of their annual driving is freight transport proper, according to a study carried out in 1992 by Denmark's Central Statistical Office (Danmarks Statistik 1993b), while 44% is various forms of service driving and the remaining 25% passenger transport as such. Indeed the so-called MPVs (Multi-Purpose-Vehicles), mainly developed for passenger transport, are sold almost entirely as vans (i.e. registered as freight vehicles) in Denmark, even though they are primarily used for passenger transport. This way the buyer may save up to 200-250.000 Danish Kroner, equivalent to a reduction by about 50-60%, the only limitation to the utilisation of the van being that passengers are only allowed on the front seat (Jørgensen 1996a).

Whether applied for freight or passenger transport purposes, however, LGVs generally have very poor energy and environmental performance. This is aggravated by their typical utilisation patterns - low capacity utilisation, application in urban driving patterns - but even when the impact of this is eliminated the specific fuel consumption per tonne-km[56] is still 4-5 times that of the total stock of vans and trucks. In relation to passenger transport the specific fuel consumption per passenger-kilometre is about twice the average of passenger cars. In each capacity, they carry small loads, typically 50-100 kg when used for freight transport and 1-2 passengers when used for passenger transport.

On average light freight vehicles' specific fuel consumption is 54 MJ per tonne-km[57], but within the category there is a strong inverse correlation between gross vehicle weight and specific fuel consumption, with the heaviest category using less than one tenth of the fuel per tonne-kilometre than the lightest vehicles do. In part, this is because the vehicles are more efficient and partly because they have better capacity utilisation.

These results are based on the assumption that all the vehicles are used for freight transport. If only the vehicles used for freight transport proper are taken into consideration the average specific fuel consumption would be about 1/3 to 1/4 of the figure given for LGVs in Table 6.4 - that is, around 15 MJ/tkm.

Concluding, LGVs constitute a key problem in the Danish transport sector, and the problem is of increasing significance. It has two main aspects:

- LGVs are applied as passenger cars to save registration tax. Sometimes this is due to vehicles in freight or service transport applications also being used for passenger transport to avoid having to buy an extra vehicle, but in many cases LGVs are used only as passenger cars.
- LGVs are applied in local distribution of goods, small parcels etc. or used for service driving and the like, that is for tasks for which we do not today have better technologies (except bicycles).

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56 *Based on payload capacity.*

57 *Based on actual payloads.*

7 Environmental Impacts of Grocery Distribution

On the background of the study of the grocery sector on the one hand (Chapter 4 and 5) and the vehicle fuel consumption and emissions on the other (Chapter 6), this chapter presents the findings of the analysis of the energy and environmental impacts of grocery distribution. Section 7.1 contains an evaluation of the present transport demand as well as the historical development from 1960 to the present, while the energy and environmental impacts are covered in Section 7.2.

The results are based on (Jørgensen 1995a).

7.1 The Present and Historical Transport Demand in the Grocery Sector

In the following, the historical development of the transport demand in conjunction with grocery distribution is reviewed. Figures 7.1 and 7.2 show the development from 1960 to 1993 of the transport demand of the consumer system (passenger transport) and of the wholesale system (freight transport). In each case, the distribution on transportation means is shown.

In the consumer system the transport demand has grown 3.8 times from 1960 to 1993, while car driving has increased about 6.7 times. From 1980 to 1993, the consumer system transport demand increased by just under 50%, while car driving almost doubled during the same period. Thus, the growth in the total transport demand for grocery shopping is continuing, albeit at a slightly lower rate, and the car is continuing to increase its share.

The increase of the transport demand is almost entirely due to longer average trip lengths, while the number of shopping trips have remained roughly constant, at least since 1980. This, however, contradicts the common perception that the shopping pattern have developed from one with many, short trips to one with longer, but fewer, trips. This picture of a well-planned shopping pattern with 1-2 visits to the grocery shop is not borne out by the statistics.

The growth has not been quite as strong in the wholesale system, but even here it has been quite remarkable. From 1960 to 1993, the wholesale transport demand (in tonne-km) has been calculated to have tripled, while the driving of vans and trucks in conjunction with grocery distribution have increased 2.3 times. From 1980 to 1993 the transport demand in the wholesale system has increased by just under 40%, while the driving in vans and trucks have increased by about 65%. Thus, taking the period from 1960 to 1993 as a whole, the growth of the driving has been weaker than the transport demand growth, but this conceals that there has been a shift to heavier trucks. The driving of heavy trucks (with a gross vehicle weight of more than 24 tonnes) in connection with grocery distribution has been calculated to have increased more than 10 times.

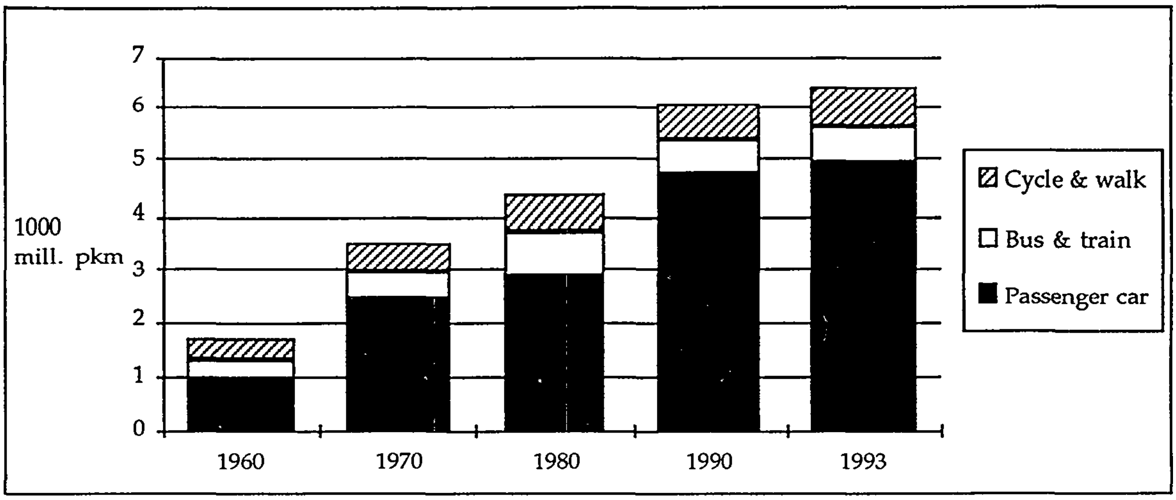

Figure 7.1. Development of the calculated transport demand (passenger-km) in conjunction with the consumer system of the grocery sector (Jørgensen 1995a).

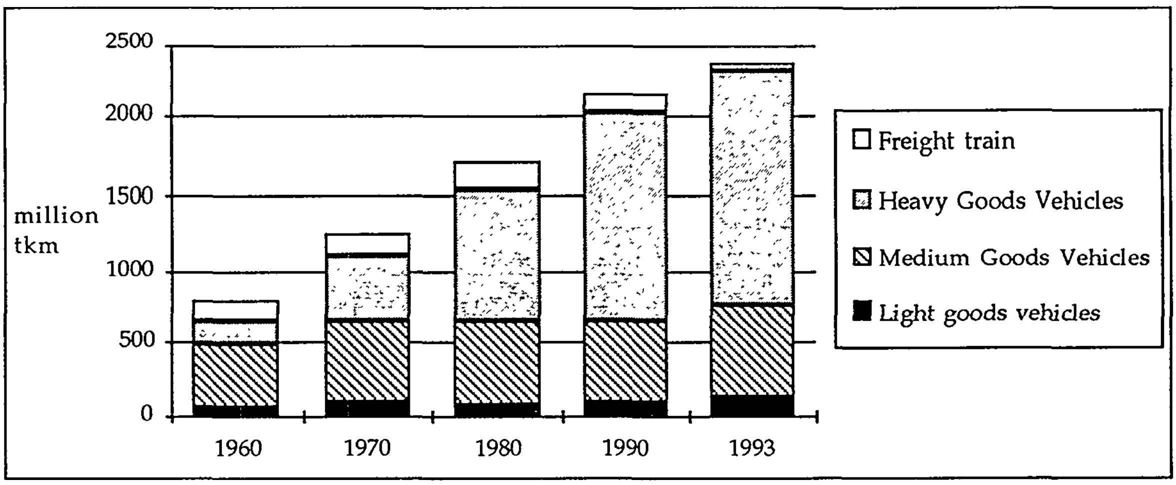

Figure 7.2. Development of the calculated transport demand (tonne-km) in conjunction with grocery distribution in the wholesale system, including its distribution according to light goods vehicles (≤ 6 tonnes of gross vehicle weight), medium goods vehicles (6-24 tonnes) and heavy goods vehicles (> 24 tonnes) (Jørgensen 1995a).

Motor vehicles - passenger cars, vans and trucks - have gained a dominating role in both consumer and wholesale systems, with more than 3/4 of the transport demand in the consumer system and 97% of the transport demand in the wholesale system - as compared to 55% and 81% respectively in 1960.

Figure 7.3 shows the calculated historical fuel consumption for grocery distribution, with the split on shopping and wholesale transport. From 1960 to 1993, the total fuel consumption for grocery distribution has increased 2.5 times, according to the calculations. There has been a particularly strong growth in the consumer system (4.4 times), which has increased its share of the grocery fuel consumption from 30% in 1960 to just over 50% in 1993 - but there has been an increase in the wholesale side also (2 times). Hence, the assumption frequently made that the increase in the consumer system is balanced out - at least in part - by greater efficiency on the wholesale side is not borne out in practice, as both sides show a substantial increase in fuel consumption.

According to the analysis grocery distribution accounts for about 12% of the total transport sector fuel consumption (Ministry of Transport 1994a; Jørgensen 1995a).

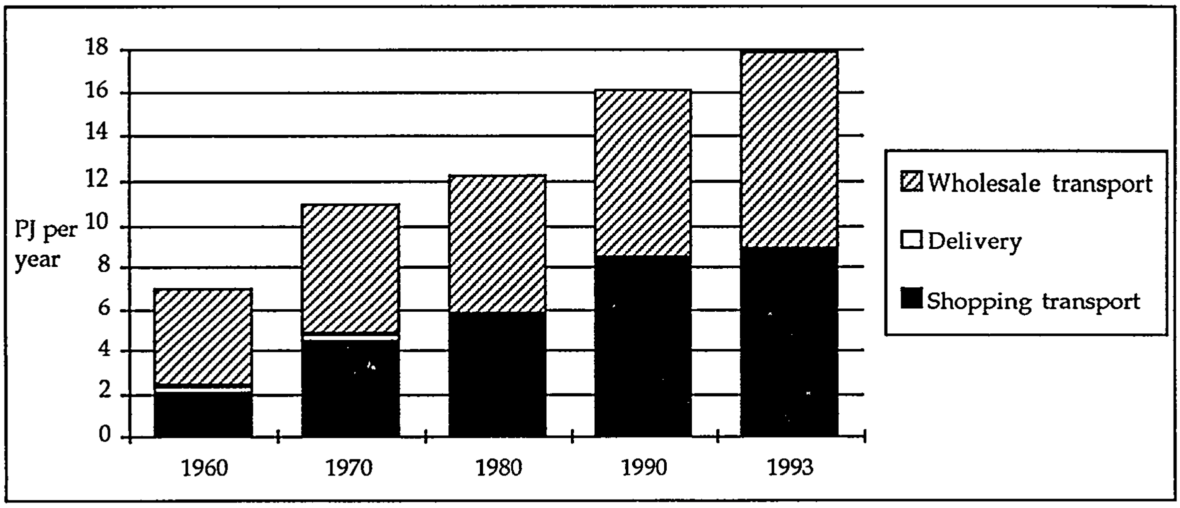

Figure 7.3. The calculated development of fuel consumption for grocery distribution, including the distribution of shopping, delivery services (from shop to home) and wholesale transport (Jørgensen 1995a).

Figure 7.4, showing the indexed development of the fuel consumption and emissions of grocery distribution, illustrates the point that all of the energy and environmental impacts investigated show a substantial increase.

CO2, being nearly proportional to the fuel consumption (given that the fuel is either gasoline or diesel), has followed virtually the same development, having increased more than 2.5 times from 1960 to 1993. NOx has shown even stronger growth - 3.5 times higher in 1993 than in 1960 - though it should be taken into account that the NOx-emission level of 1960 was relatively low. At that time, most vehicles, except the heaviest trucks, were gasoline driven, with engines operated with a rich fuel/air mixture, resulting in low NOx-emissions and high emissions of carbon monoxide (CO) and hydrocarbons (HC). Today, most gasoline driven vehicles have stochiometric combustion, which have the opposite effect (high NOx-emissions and lower emissions of CO and HC). So far three-way catalytic converters have only had limited impact.

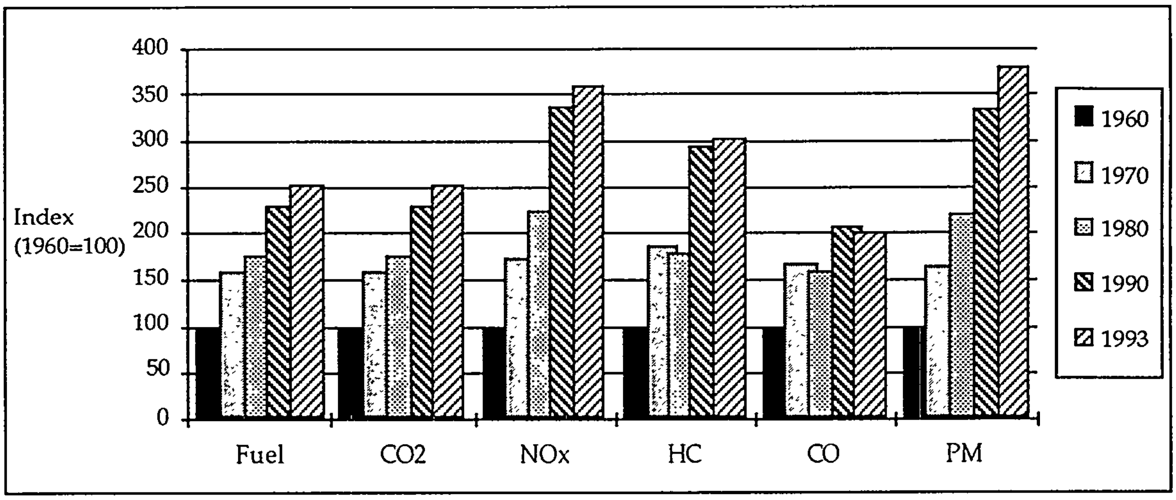

Figure 7.4. Historical development of fuel consumption and emissions in conjunction with grocery distribution (wholesale and consumer systems). Index in relation to the level of 1960 (Jørgensen 1995a). The emissions are: carbon dioxide (CO2); nitrogen oxides (NOx); total hydrocarbons (HC); carbon monoxide (CO); and particle mass (PM).

Thus the emissions of CO and HC were relatively high in 1960, and at the same time the shift from gasoline to diesel vehicles in the wholesale transport has further reduced these emissions. On the other hand, the relative growth of the consumer system has pulled in the opposite direction, since this side is dominated by gasoline vehicles. The HC-emissions from grocery distribution have tripled during the period, while CO-emissions have doubled.

Finally, the emissions of particle mass have shown the strongest growth of all the emissions analysed here, having increased 3.8 times from 1960 to 1993. These emissions are almost entirely linked to diesel vehicles. Therefore, the shift to diesel vehicles in the wholesale transport has reinforced the growth, while the relative growth of the consumer system - with a smaller diesel percentage - has reduced it. While the above has illustrated the total traffic, energy and environmental effects of grocery distribution, the following graph illustrates its fuel and emission intensity, i.e. its costs - in broad terms - in relation to its benefits, i.e. the outcome of the grocery distribution[58]. The costs included are the transport demand, the fuel consumption and the emissions, while the benefit outcome of the operation is measured as groceries (by weight[59]) distributed to the consumers. It should be remembered that the outcome

58 *The intensity is the inverse efficiency, and therefore a higher ratio reflects a poor efficiency.*

59 *Almost the same results would have emerged had the benefits been measured in economic terms (in fixed prices).*

can be measured in different terms, such as monetary value in fixed prices[60]. Moreover, there may be other aspects of the outcome than simply measuring the quantity - e.g. the freedom of choice between a large assortment.

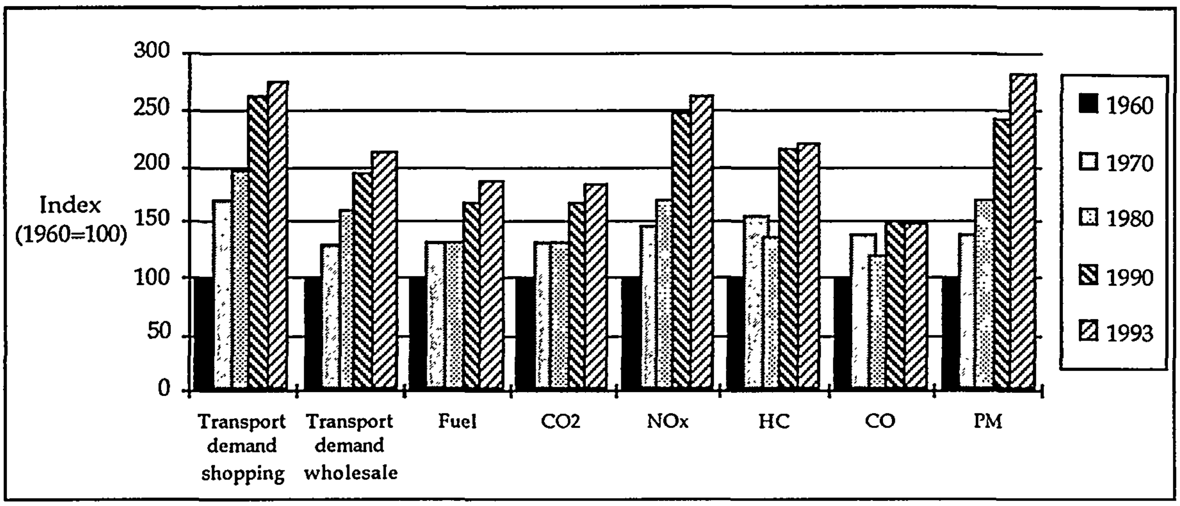

Figure 7.5. The fuel and emission intensity of the grocery distribution seen in relation to the weight of the distributed commodities, shown as indexes with 1960=100 (Jørgensen 1995a).

Figure 7.5 shows the indexed fuel and emission intensities in relation to the 1960 level. The indexes for all aspects investigated, with the exception of CO, are 200 or higher in 1993, that is, equivalent of at least a halving of the efficiency. For CO the technical improvement of gasoline driven vehicles has modified the growth, especially during the 1960s and the 1970s. For emissions of NOx and particle mass the indexes in 1993 are 260 and 280 respectively, equivalent of a deterioration of the efficiency by 60-65% during the period from 1960 to 1993. As regards the transport demand the index in 1993 is around 250 in the consumer system and 200 in the wholesale system.

As shown by Figure 7.6 only a minor fraction of the growth in transport demand, fuel consumption and emissions may be attributed to higher grocery consumption. The remaining increases indicates a deterioration of the efficiency of the grocery distribution system, which generally - with the exception of CO - are the major contributions. Figure 7.7 illustrates - using the fuel consumption as example - the historical development of the grocery distribution, in the form of a quantity index illustrating the growth in grocery consumption[61] (by weight) and an index of the grocery distribution system intensity. Grocery consumption grew during the first part of the period, but has remained roughly constant during the last 15-20 years. The intensity index increased (that is, the efficiency deteriorated) during the 1960s and from the 1980s onwards,

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60 *In which case the results would hardly differ, since the price in real terms have only changed insignificantly over the whole of the period.*

61 *Including the effects of both population growth and the development of the per capita grocery consumption.*

whereas it remained roughly constant during the 1970s, in the wake of the oil crisis. The overall effect is that the fuel consumption has increased during the entire period[62].

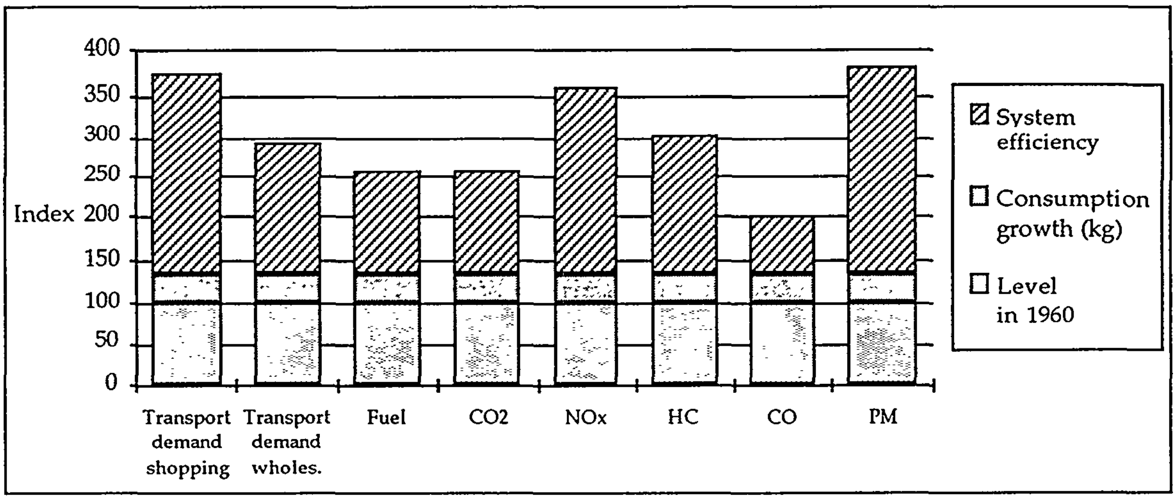

Figure 7.6. Comparison of the costs (transport demand, fuel consumption and emissions) of grocery distribution, comparing the levels in 1993 with those of 1960 (Jørgensen 1995a), showing the distribution between growth attributed to higher consumption of groceries and to poorer efficiency of the grocery distribution system (Jørgensen 1995a).

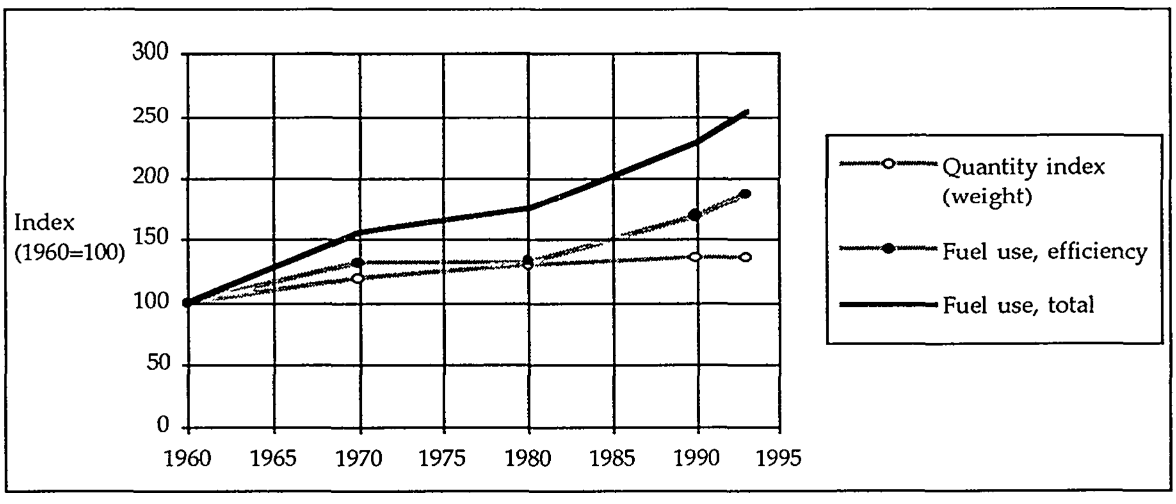

Figure 7.7. The development of the quantity index for grocery consumption (kg), system fuel intensity (fuel consumption per kg groceries) and the total fuel consumption for grocery distribution (Jørgensen 1995a).

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62 *At least for the years illustrated - the analysis does not say anything about the development between these years.*

8 Reduction of Fuel Consumption and Emissions by Means of Technical Improvements of Vehicles

In this chapter, the scope for technical improvements of the energy and environmental characteristics of vehicles are assessed. The main energy and environmental effects included in the analysis are:

- energy efficiency and fossil fuel use;
- reductions of carbon dioxide (CO2) emissions (a function of the fuel efficiency and the fuel used);
- reductions of the emissions of nitrogen oxides (NOx), hydrocarbons (HC), carbon monoxide (CO), sulphur dioxide (SO2), nitrous oxides (N2O) and particle mass (PM), as a function of the fuel used, the combustion process and exhaust gas treatment.

The main emphasis is on energy efficiency and CO2.

There are many other aspects to environmental improvements and other negative impacts to take into consideration, but these are not included in this analysis. Even when limiting the scope to the above aspects, the improvements have to be determined as a compromise between conflicting demands and considerations.

Most studies of energy efficiency potentials are based on stringent criteria as regards the standards that should be met by the vehicle regarding performance, safety, comfort, payload and seating capacity, interior volume etc. - without questioning the appropriateness of these standards.

There are, however, substantial potentials for environmental improvements of vehicles through altered standards. Indeed, such measures, further described in Section 8.2, probably represent the most viable improvement options in the short term. Moreover, there is nothing to substantiate the precisely the present form of the vehicle should be the ultimate target for the development process.

On this background, a less rigid definition is applied in this report.

The environmental impacts are assessed on the basis of fuel cycle considerations, taking into consideration the whole chain from from primary energy source to end use. Generally, the study does not consider life cycle analyses of the technologies applied[63].

The main focus is on vehicles that are relevant to grocery distribution (passenger cars, light goods vehicles, medium goods vehicles, heavy goods vehicles). In particular, passenger cars,

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63 *That is, analysis of the manufacturing, operation and discarding of the technologies.*

light goods vehicles and heavy goods vehicles have been selected for more detailed analyses. Most studies focus on passenger cars, whereas investigations of improvement potentials for freight vehicles are more rare.

8.1 Strategies for Technical Improvements

The fuel cycle efficiency[64] is the product of the energy system efficiency and the vehicle efficiency - of which the former cover the supply of the fuel or electricity to the vehicle, while the latter determines how efficient the vehicle utilise the electricity or fuel.

The Energy System

The energy system efficiency covers the part of the fuel cycle from energy resource to the individual vehicle, including extraction, conversion and distribution. In energy terms, it can be based on the total energy use (including renewable energy) or it can be confined to the fossil fuel consumption. Theoretically, the utilisation efficiency of renewable energy is less important than that of fossil fuels due to the much greater resources available.

In practice, however, the renewable sources are limited by other considerations than the total energy flows - notably the land requirements for the conversion - and therefore the efficiency of the utilisation cannot be ignored in this case. Table 8.1 illustrates typical losses of different energy systems in the form of primary energy requirements and CO2-emissions to provide 1 kWh fuel or electricity at the vehicle.

	Primary energy kWh/kWh	CO2 emissions g/kWh
Gasoline	1.18	310
Diesel	1.09	290
Electricity, coal (waste heat utilised)	1.25	425
Electricity, coal (waste heat not utilised)	2.50	865
Electricity, natural gas (waste heat utilised)	1.25	250
Electricity, natural gas (waste heat not utilised)	2.50	510

Table 8.1. Primary energy consumption and CO2-emissions per kWh fuel or electricity delivered at the vehicle in different energy systems (Jørgensen 1996e; Jørgensen & Nielsen 1997; Horstmann & Jørgensen 1997). Based on average in-use technology in the power supply system and including transmission losses.

64 *As explained in Section 3.2 "efficiency" is used as a generic term for the ratio between benefits and costs, in which not only energy consumption but also emissions can be included on the cost side.*

The energy system efficiency is influenced by the calculation principles applied. Mostly, it is not possible to assign certain fuel consumption and emissions of energy systems to certain end uses, due to the integrated fashion in which most energy systems operate. There are two important issues in this connection:

- the difference between average and marginal operating conditions - in principle marginal conditions should be applied, but it is frequently problematic establishing the marginal conditions;
- the assignment of fuel use and emissions in systems delivering more than one service, such as cogeneration systems supplying both heating and power.

The latter issue is particularly significant in conjunction with utilisation of electricity from the grid, in which case it has to be established to what extent the power is generated with utilisation of the waste heat. This is necessary for the assignment of the fuel consumption. In other words, it has to be determined whether power from cogeneration is available in the marginal operating situation. But even if this is available, the advantage of the joint production may be assigned (by definition) to the heating side. Indeed, this has been common practice since the 1970s, presuming that the principal objective is the power generation[65], whereas the heat is perceived as a waste product. In recent years, however, this principle has increasingly been questioned, as a number of combined heat and power plants have clearly been aimed at the heating market. In Table 8.1, as in the following, the impact of this issue has been illustrated by including both extremes in the calculations.

Similar considerations apply in conjunction with gasoline and diesel supply systems since the refineries operate as integrated processes with a number of products and by-products.

Vehicle Efficiency

As regards the vehicle efficiency, this can be split into a demand side and the onboard[66] supply system (see Figure 8.1):

- the demand side - or the vehicle load - includes the tractive forces linked to the vehicle motion (air resistance, braking and grading) and the power demand for onboard assessories.
- the onboard supply system (the drive system) - converting the energy and transmitting it to the driving wheels - includes the drive train (motor/engine, transmission), the onboard energy storage, onboard power generation and the exhaust gas treatment (if applicable).

When the tractive forces of the vehicle (in Newton) is known, the power requirement (in Watt) to move the vehicle can be found by multiplying with the vehicle velocity (m/sec) and dividing with the drive system efficiency. The total power demand can be found by adding the power demand for accessories divided by the onboard power supply efficiency.

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65 *In fact, this presumption is implied in the use of the term "waste heat".*

66 *The term "onboard" is used to distinguish it from the stationary energy system.*

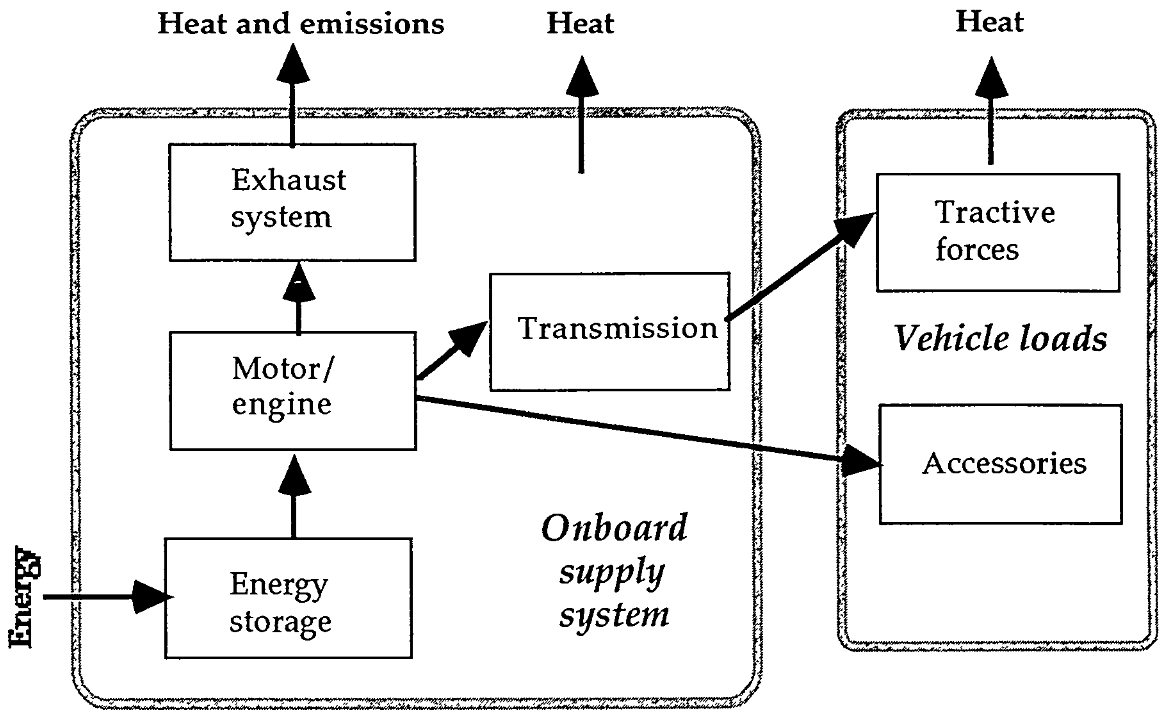

Figure 8.1. Simplified vehicle model illustrating the main factors determining the fuel consumption and emissions of a vehicle. The arrows show the energy flows

The demand side. The vehicle load is made up of tractive forces and power demand for on-board accessory loads. The tractive forces are the resistances to be overcome in connection with the vehicle motion: acceleration resistance, air resistance (air drag), rolling resistance (road drag) and grading resistance. Of these air and rolling resistances lead to irreversible losses to air and ground, whereas the acceleration leads to motion of the vehicle. The acceleration work is only lost in conjunction with the deceleration (braking) of the vehicle. In principle, braking energy can be recovered (except for the deceleration due to air and rolling resistances), but in vehicles driven by internal combustion engines (ICE-vehicles) this require special systems, and even in electrical vehicles only part of the braking energy can be recovered, in practice. Grading losses can be both positive and negative (downhill motion), and therefore they are, in principle, reversible, provided the vehicle return to the same level as that of the starting point, and provided it is capable of utilising the downhill force in the given driving pattern.

The key dividing line as far as tractive forces are concerned is between the weight-related resistances (acceleration, rolling, grading) on the one hand and the air resistance, which is related to the vehicle size and form but not to the weight, on the other. The latter is the only tractive force related to the vehicle velocity and, being proportional to the square of the speed, it rapidly increases in significance with increasing speed. At low vehicle speeds and in urban driving patterns the weight-related resistances are predominant, typically accounting for 70-80% of the total external vehicle resistances, whereas its share falls to 20-30% at highway speeds (DeLuchi et al 1988; Jørgensen 1996b). The key characteristic of the vehicle with regard to aerodynamics is the apparent frontal area[67] which has undergone substantial improvements during most of the automobile's history (mostly to enable higher speeds).

The significance of weight and vehicle form can be indicated by means of the ratio between the apparent frontal area and the vehicle weight (Jørgensen 1996b):

- passenger cars: 0,5-1,0 m2/tonne (declining for increasing vehicle size)
- delivery vans (<2 tonnes of gross vehicle weight): 0,8-1 m2/tonne
- medium-sized vans (2-3,5 tonnes): 0,5-0,7 m2/tonne
- large vans (4-6 tonnes): 0,3-0,35 m2/tonne
- light duty trucks (3-6 tonnes): 0,4-0,6 m2/tonne
- delivery trucks (14-24 tonnes): 0,25-0,35 m2/tonne
- heavy duty trucks (35-45 tonnes): 0,15-0,25 m2/tonne

From this, it can be seen that weight plays a greater role for heavier vehicles for a given driving pattern.

Table 8.2 on next page shows calculated power demands - from the engine shaft - to overcome the different tractive forces in three different vehicles, each of which is typical of its category.

It can be seen that the contribution from air resistance grows rapidly with increasing velocity, which means that the engine power available for acceleration declines with increasing velocities. Moreover, a given acceleration demands higher engine power at high velocities[68], and therefore overtaking at high speeds is probably the most power demanding operation of vehicles. Indeed, it is probably only at high speeds that differences in motorisation (i.e. engine power in relation to weight) would be felt in practice[69].

The van has roughly the same engine power as the passenger car, despite being considerably heavier and having much greater air drag, and consequently its acceleration capability is much lower, especially at high speeds[70]. For the heavy-duty truck, weight is relatively

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67 *The apparant frontal area is the product of drag coefficient, c_W, and frontal area. It is common practice to use the drag coefficient as measure but this can be misleading because improvements of the drag coefficient can be achieved by increasing the frontal area. For instance, the Toyota Previa freqently has been termed an aerodynamical vehicle because of its (relatively) low c_W-factor, but when taking its large frontal area into account its apparent frontal area is about 30-40% above a typical passenger car.*

68 *The power demand is equal to the product of acceleration resistance and velocity.*

69 *Even though the differences in engine power lead to variations with regard to the time needed to accelerate from zero to a given velocity, these differences are of little significance in practical driving patterns.*

70 *The light goods vehicles are moving closer towards passenger cars with respect to engine power per weight.*

more important than for lighter vehicles, and therefore rolling resistance is the dominating contribution even at high speeds.

kW from engine shaft	Passenger car	Van & light-duty vehicle	Truck heavy-duty
20 km/h (constant)			
Air drag	0.1	0.2	0.5
Rolling resistance	0.6	1.1	24
Maximum acceleration, m/sec2	10	5.5	1.1
50 km/h (constant)			
Air drag	1.3	2.4	7.5
Rolling resistance	1.5	2.7	59
Maximum acceleration, m/sec2	4	2.1	0.4
100 km/h (constant)			
Air drag	10	19	61
Rolling resistance	3.1	5.5	119
Maximum acceleration, m/sec2	1.6	0.7	0.1

Table 8.2. Approximate engine power (kW) needed to overcome air and rolling resistance in different vehicles at different constant velocities, and the maximum acceleration (m/s2) allowed given typical installed engine power. The three vehicles are: medium-sized passenger car; 3.5 tonnes van; and a 42 tonnes heavy-duty truck. Calculations by the author.

The accessory loads - lights, pumps, power braking, power steering etc. - result in increasing onboard power demand (DeCicco & Ross 1993; Moore & Lovins 1995; Friis Hansen & Antvorskov 1995). In ICE-driven vehicles space heating can be covered by surplus heat from the engine, whereas air conditioning requires extra power[71]. In electrical vehicles, due to the smaller losses of electrical motors, the quantities of surplus heat are smaller and provided at lower temperatures, and therefore it is normally necessary to either use electricity for space heating (in which case the heating deteriorates the vehicle range during winter) or to install a gasoline fired heater. Theoretically, the quantities of surplus heat available in electric vehicles are sufficient to cover the space heating demand, but in practice they are available at relatively low temperatures. Moreover, the insulation standard of ICE driven vehicles has been neglected in the past due to the abundance of surplus heat.

Onboard supply system. The drive system efficiency is the product of the onboard handling efficiencies, notably the energy storage efficiency, the motor/engine efficiency and the transmission efficiency. In conjunction with use of power generated onboard, the efficiency of this must be included.

71 *Today, nearly all vehicles in the USA and Japan and many other countries are provided with air conditioning, but the provision of this utility is envisaged to spread to most of the world, included countries with a cooler climate, such as Northern Europe.*

In most vehicles, the engine/motor accounts for the major part of the losses. Since the early decades of this century, nearly all drive systems in vehicles have been based on internal combustion engines (ICE). Traditionally, the gasoline engine has been dominating in road vehicles except in the heaviest trucks and busses, but from the 1960s onwards there has been a shift towards diesel engines in lighter busses, trucks and vans. Even in passenger cars, the diesel share has increased, though still remaining a small percentage (around 5% of the vehicles and 10% of the annual driving).

There is considerable debate about the pros and cons of gasoline and diesel. The diesel engine is more fuel efficient and cleaner with respect to CO, HC and NOx-emissions. But the introduction of three-way catalytic converters has improved the gasoline engines substantially in these respects, and in particular leaves the diesel engine trailing with regard to NOx-emissions. In addition, the diesel engine has major problems with emissions of particle mass. The diesel engine is a heavier and more expensive engine type.

Alternative fuels may be applied either as fuel switch in conventional engines or by a shift of drive system to one based on electrical drive. As regards the former option, a distinction between those fuel or fuel additives that can be used in an existing engine without further changes and those requiring engine adjustments or even engine change. This factor plays a role in determining the possible pace of the changes.

In gasoline or diesel driven vehicles, the losses linked to the onboard energy storage is small in energy terms[72], and therefore the onboard storage losses are excluded from most analyses. However, for certain alternative drives (notably electrical and hydrogen) the onboard storage losses, including the filling losses, may reduce the vehicle efficiency by as much as one third.

Most vehicles have onboard power generation facilities, though mainly used for power demands of accessories. In the future, onboard power generation by means of engine/generator-units could also be applied for tractive purposes in hybrid vehicles or - in the longer term - fuel cell driven vehicles.

On this background, the <u>total power required as an input to the vehicle</u> can be written as follows

$$P_{tot} = F_{trac} \cdot V / \eta_{drive} + P_{acc} / \eta_{power} + P_{idle}$$

$$F_{trac} = F_{air} + F_{acc} + F_{roll} + F_{grade}$$

$$= F_{weight} + F_{air}$$

$$F_{weight} = F_{acc} + F_{roll} + F_{grade}$$

$$F_{air} = 0.5 \cdot q \cdot V^2 \cdot F \cdot cw$$

72 *The evaporative losses of hydrocarbons are a significant problem in conjunction with gasoline vehicles, though.*

$F_{acc} = m \cdot a$

$F_{roll} = \mu_R \cdot m \cdot g$

$F_{grade} = m \cdot g \cdot \sin ß$

$\pi_{drive} = \pi_{stor} \cdot \pi_{motor} \cdot \pi_{trans}$

$\pi_{power} = \pi_{motor} \cdot \pi_{gen}$

where

P_{tot}	=	total power demand	[W]
F_{trac}	=	total tractive forces	[N]
F_{acc}	=	acceleration losses	[N]
F_{air}	=	air drag	[N]
F_{roll}	=	rolling losses	[N]
F_{grade}	=	grading losses	[N]
F_{weight}	=	tractive forces related to vehicle weight	[N]
V	=	vehicle velocity	[m/sec]
P_{acc}	=	power demand for accessories	[W]
P_{idle}	=	power demand for idling	[W]
q	=	density of atmospheric air	[kg/m^3]
F	=	frontal area of vehicle	[m^2]
c_W	=	drag factor	
m	=	vehicle mass	[kg]
a	=	vehicle acceleration	[m/sec^2]
μ_R	=	rolling resistance coefficient	
g	=	gravity	[m/sec^2]
ß	=	grading angle	[rad]
π_{drive}	=	drive system efficiency	
π_{stor}	=	onboard storage efficiency	
π_{motor}	=	motor/engine efficiency	

π_{trans} = transmission efficiency

π_{power} = efficiency of onboard power generation

π_{gen} = efficiency of the generator

As can be seen from this formula, different improvement measures in most cases only impact a fraction of the total power requirement. Later in this chapter, this fraction is indicated by means of the sensitivity factor, which is a function of both the vehicle and the driving patterns.

Improvement Strategies

Because 80-85% of the energy content of the fuel input is lost in the drive system, particularly in the engine, the greater part of the attention in the past has been directed towards the improvement of the onboard supply system, while the vehicle loads have been somewhat neglected. At the same time, the technical progress on both counts so far has been largely offset by higher standards with respect to performance, comfort and safety[73].

Given the need for substantial improvements to meet the environmental targets, there are two important questions in connection with the technological development for energy and environmental improvements:

- whether it follows a gradual development, based on incremental refinements on existing designs, systems and components, or aim at application of technological breakthroughs?
- whether it is based on the presumption that the vehicle meet (at least) the same standards concerning performance, safety, comfort etc. as the existing vehicles, or could - and should - a lowering of the demands be a part of the strategy?

The former of these issues - incremental development versus breakthrough technologies - is particularly important due to the demand for substantial technical improvements to meet the environmental targets. The technological development within the automobile industry is characterised by conservatism, based on concern about market acceptability and about the capital invested in expensive tooling. In addition, there are other - frequently conflicting - demands to car development than fuel economy and emissions, and these are usually given higher priority by both car manufacturers and buyers.

As a result, the traditional technological development to promote clean cars have been limited to incremental improvements on well-known designs and components. However, incremental refinements does not necessarily lead to the best overall solution, even if the optimal decision is made in each marginal choice (Hvelplund 1980).

The issue of environmental improvements through lowering of standards - or adaptation to the demand - is dealt with in Section 8.2.

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73 *See Chapter 6.*

Leapfrog Design or Incrementalism?

Amory Lovins and co-workers at the Rocky Mountain Institute (RMI) in Colorado, USA provide a perspective quite different from the traditional approach. They attack what they call "the conventional wisdom framing the US car-efficiency debate", namely that "the doubling of new-car efficiency during 1973-86 had virtually depleted the 'low-hanging fruit' - opportunities for fuel economy consistent with affordability, safety and performance" (Lovins 1995a). In other words, conventional wisdom assumes further improvement to be extremely expensive or/and to reduce performance, comfort and safety standards.

Conversely, Lovins argues that "the next doubling of car-efficiency will be easier than the first was" and would not be in conflict with other vehicle design objectives (Lovins 1995a). This presumes, however, that the conventional strategy based on incremental refinement of existing models is discarded and replaced by so-called "leapfrog technologies" based on a totally redesigned vehicle. This, according to Lovins, will lead to the development of the "hypercar", distinguished by the decoupling of the fuel economy and emissions from the vehicle characteristics - such as size, weight, costs, performance, crashworthiness and comfort levels. Thus, a leapfrog in fuel economy may be achieved without compromising other demands from consumers and others, and hence there is no need to market the vehicle[74]. Lovins does not envisage the hypercar as a long-term option but as an ongoing development that will bring the hypercar to the market in a very short time. He has labelled it an "emerging revolution" envisaging the breakthrough to be within a few years (Lovins 1995). In the most recent publications, it is projected that the first hypercar could start appearing within about four years and that they could be commercially available in the "first few years of the next decade" (Rocky Mountain Institute 1997).

According to Lovins the hypercar strategy can be seen as a response to the following features of the classical approach to fuel efficiency improvements (Lovins 1995a), namely that

- it focuses on components rather than systems;
- it explores incremental rather than radical changes to those components;
- it "thinks from the engine toward the wheels", i.e. follows the flow of the energy rather than taking the demand side (the vehicle load) as starting point;
- it focuses on the improvement of the drive systems (engine, transmission) rather than the vehicle load.

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74 *E.g.: "Most big changes in modern cars were driven either by government mandate, subsidy, or taxation motivated by externalities, or by random....fluctuations in oil price. However, the more fundamental shift to hypercars can instead be driven by customer's desire for superior cars and manufacturers quest for competitive advantage. Customers will buy hypercars because they're better car, not because they save fuel--just as people now buy compact discs instead of vinyl records." (Lovins 1996). And "the issue seems less whether it will happen than who will do it and whether it will done thoughfully (Lovins et al 1993). In addition, Lovins argue that increasing fuel taxation levels in transportation would be both unnecessary and without significant impact because of the coming of the hypercar, which will lower the specific fuel consumption to a very low level (Lovins & Lovins 1995).*

Lovins stresses that the potentials for fuel economy improvements through incremental refinements are by no means exhausted, but could increase the present fuel efficiency of American automobiles by a factor 3-4. But the hypercar strategy could boost the efficiency 5-10 times if based on components commercially available today, and 10-20 times based on technologies still in the laboratory[75]. This would be based on a vehicle design combining two main features: first, the reduction of the vehicle load to an absolute minimum - by means of an ultra light and extremely aerodynamical car with special low-rolling resistance tyres and efficient accessories - and secondly the application of an extremely efficient propulsion system (hybrid electric). The "leapfrog" nature of this approach is related to the fact that, unlike conventional vehicle design, it is not confined to refining existing designs. In contrast, the vehicle industry is restricted by its inertia, limiting its scope to designs that can be realised within the normal industry framework. In this respect, the focus on incremental refinements mirrors the fact that the automotive industry can only absorb minor changes to the given development direction[76]. Moreover, Lovins distinguishes the hypercar from most alternative fuel strategies in that it is not satisfied with replacing the propulsion system in an otherwise conventional vehicle.

Besides the RMI, others inside and outside the USA have pursued similar strategies, albeit with different degrees of radicalism. Notably, the Partnership for a New Generation of Vehicles (PNGV), launched as Lovins' hypercar concept in 1993, is a joint initiative between the American car industry and government aiming to improve the average fuel economy of new vehicles 3 times while meeting the same design criteria as a typical new passenger car in the American market[77]. The PNGV has been criticised by Lovins for being too modest, establishing a target which can be achieved by incremental improvements alone, thus enabling the designers and manufacturers to avoid carrying through necessary changes in the industry (Lovins 1995a).

In Lovins' understanding, the overall aim of the leapfrog design is not just to meet certain energy and environmental targets but also to promote a technological revolution in vehicle design. In other words, he emphasises the technological revolution as a value in itself in characterising hypercar designs. Given the automotive industry conservatism, Lovins does not envisage the hypercar being developed within the present automotive industry but rather by new industries (analogue to the development in the computer field). Indeed, the introduction of the hypercar is seen as being closely linked to an industrial transformation, substituting a new design-oriented industry for the old capital-intensive automotive industry. At present, car manufacturing is characterised by expensive tools, long product cycles, and strong emphasis on rapid assembly of parts shipped in from most of the world. In contrast, the projected hypercar industry would have, according to Lovins, cheap tooling and slower but fewer manufacturing operations. This would allow product differentiation and manufacture-to-order to a much greater extent than today. The RMI is involved in the development of a joint-venture

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75 *Later, Lovins et al have moderated these targets somewhat towards the lower end of these ranges (Moore 1996; Rocky Mountain Institute 1997).*

76 *According to Lovins et al, the overall objective of the automotive industry could be defined as the working up of steel, rather than manufacturing certain vehicles (Lovins et al 1993).*

77 *In Section 8.7, the technical contents of these approaches are treated in more details.*

aiming to promote the development, in practice, of such a vehicle. According to Lovins "by mid-1994, the hypercar concept had engaged the commercial effort of approximately twenty entities with impressive capabilities, including auto makers, large electronics and aerospace companies, and world-class venture capitalists" (Lovins 1995a). These activities, however, are surrounded by secretiveness, making a proper evaluation nearly impossible. As part of this work a proprietary report on the technological opportunities has been produced by the RMI (Lovins et al 1995a).

The PNGV also aims at a transformation of the automotive industry but, unlike Lovins, the PNGV does not focus solely on the leapfrog[78] aspect, which is only ranked as the third of its three main goals (PNGV 1995a). The two other main goals focus on the automobile industry (aiming to significantly improve national competitiveness in US manufacturing) and on the short-term (incremental) improvements of conventional vehicles (implementation of commercially viable innovations). These two goals aim to provide the foundation for meeting the third goal, which is considered to be very ambitious in technological terms. According to the time schedule a production prototype should be ready by the year 2004, but there are no production schedule. Generally, no financial or regulatory commitments have been made regarding the longer-term implementation of the PNGV strategy[79].

In this report, the focus is on the need for a leapfrog in fuel economy and emission levels, while technological development is not seen as an end in itself. Therefore, a slightly different terminology is adopted. The concept "breakthrough design" is used to designate a slightly different development from that envisaged in Lovins' hypercar concept. The distinguishing features of the breakthrough design are, first, that it is working towards set environmental targets defined by the carrying capacity of the environment and, secondly, that it aims at improving the vehicle as a whole rather than focusing on certain components or systems. In contrast, an incrementalist strategy takes the refinements as the starting point, trying to reach as far as possible within the given constraints. Thus, a breakthrough design is based on the demands imposed by environmental considerations, whereas an incrementalist strategy is defined on the basis of technical realism[80]. The PNGV in its platform draws an analogy to the Apollo space programme that brought man on the moon, since man would hardly have been brought anywhere near the target based solely on technical realism (PNGV 1995a).

Alternative fuels are somewhere in between the incrementalist and the leapfrog approach. Some forms are clearly within the boundaries of incrementalism (e.g. bio-fuels added to gaso-

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78 *The term is not used by the PNGV papers.*

79 *According to (Sperling 1995) the automobil manufacturers involvement in the PNGV should be seen in context with the threat of the Californian "Zero Emission Vehicle" mandate (the ZEV mandate) spreading beyond California, in other words, as a part of the automotive industry's activities to undermine this mandate. The ZEV mandate aims to advance electric vehicles (and similar vehicles) as a means for improving the air quality of California (see Section 8.5).*

80 *The tightening of the Danish emission standards for passenger cars in 1989/90, in a way, represents a leapfrog approach, since it cuts through the arguments of the automobile industry that it would not be possible, realistically, to meet the targets. Neverthelesss, the targets were adapted to the technical possibilities and confined to problems that could be solved with minor technical changes.*

line engines in small percentages) whereas others are clearly crossing this boundary without being breakthrough designs. This report mainly considers the latter type which is treated as a category on its own, characterised by the term "advanced drive systems".

Technology Levels

The technical level of the vehicle stock is determined by two factors: first, the technological development of vehicles and traffic systems and, secondly, the penetration of the improvements into the market. The latter factor, in turn, depends on the time lag before market introduction and on the take-up rate among vehicle buyers. Thus, there is a time delay in conjunction with the impact of the improvement, partly because the take-up of the improvements is less than 100%, or it takes some time to reach 100% penetration of the sale, and partly because of the time it takes to replace the stock. New vehicles generally have a higher annual mileage than older, though, and thus the penetration will normally be faster on a mileage-basis than its share of the vehicle stock indicates.

In the following, the impact of technological development on fuel consumption and CO2-emissions has been illustrated by means of different technical levels[81]:

- The Reference Level (REF) is based on the present vehicle stock average, i.e. in the year 1995 (cf. Section 6.3).
- Average Sold Technology Level (AST) represents the average of today's sale of vehicles, thus illustrating the level that the vehicle stock average (REF) is approaching if the present development continues. In many cases, but not always, this level will be better than the Reference Level, reflecting ongoing technical improvements and tougher standards.
- Best Sold Technology Level (BST) is based on the best technology currently available in the marketplace in Denmark. Hence, BST illustrates the maximum improvement potential if the Danish consumers (i.e. car buyers) selects the best of the existing technologies (in the marketplace), illustrating the maximum improvement potential that may be influenced directly by Danish regulatory instruments.
- The Developed Technology Level (DEV) represents technologies that are close to commercialisation and do not face engineering constraints. There are, however, certain uncertainties linked to them due to limited experiences with large-scale production (manufacturing risks) and with the marketing of the improvements (commercial risks).
- The Efficient Technology Level (EFF) is based on improvements in advanced stages of development, albeit needing a certain technical development before being available for production - which is typically realistic within about 10-15 years. This level covers (in Amory Lovins' terminology) incremental developments only, and alternative fuels are excluded from the perspective.
- The Present Alternative Fuel Vehicle Level (AFV1) represents the most efficient alternative fuel technology currently on the market today. As far as the remaining vehicle -

81 *Defined, among others, on the basis of the following sources: Jørgensen 1991; Lovins et al 1993; Nadis & MacKenzie 1993; DeCicco & Ross 1993, Jørgensen 1996b.*

apart from the drive system - is concerned, the AFV1-vehicles are similar to the BST level.

- The Advanced Alternative Fuel Vehicle Level (AFV2) is similar to the AFV1 level in the beginning but gradually includes more advanced alternative fuel technologies - electric, hybrid electric and hydrogen propulsion - that can be commercialised within the same time horizon as the EFF level (10-15 years). Apart from these drive system improvements, the vehicles are assumed to be improved according to the targets of the EFF level.
- The Advanced Vehicle Level (ADV) presumes the introduction of breakthrough technologies, albeit based on near-term drive trains (hybrid electrics). Because of this, many uncertainties are linked to this technological development, not least the risks of unforeseen problems and the required changes in the consumer demand. Therefore, their penetration of the car sales figures is presumed to be extended over a longer period than the preceding levels. Fuels in the ADV level are presumed to be confined to the conventional options, gasoline and diesel.
- The Hypercar Level (HYP), which is equivalent to Level ADV, except that longer-term drive trains, based on fuel cells, are applied.

In summary, the REF, AST and BST levels are based on the existing market options (i.e. do not presume further technical improvements, new designs or marketing of new options), whereas EFF are based on incremental improvements of existing designs. Finally, the AFV, ADV and HYP levels presume a break with the present vehicle development. The improvement potentials, generally, increase with increased levels, and at the same time the technical and commercial risks increases.

In three of the Technology Levels - AFV1, AFV2 and HYP - a shift to fuels based on electricity is included, which means that the CO2-emissions depend on the fuel mix. For each of these three levels, two versions of the power supply are investigated, namely a continuation of the present fuel supply (mainly coal) and a shift to natural gas and renewable energy in accordance with Energy 21. Furthermore, the effects of a 100% shift to renewable energy is analysed.

In each case, it has been presumed that the necessary regulatory instruments have been introduced. Generally, the penetration rates are based on optimistic assumptions.

8.2 Down-sizing, Reduced Standards and Driving Behaviour

As mentioned in Section 8.1, a key issue concerns the required standards with regard to performance, comfort, safety etc. that should be met by the environmentally improved vehicles. Most studies of the potentials for environmental design improvements presume that the vehicle should meet (at least) the same standards with regard to performance, comfort, safety etc. as today's vehicles, and generally base assessments of improvement potentials on the same usage patterns as the present. At the same time, however, there are considerable potentials for further improvements through adaptation of the vehicle standards and changed usage patterns - and, conversely, increased standards and changed driving patterns can undermine the improvements obtained through design. In the following, three examples of this are outlined - "down-sizing", increase of weight to power ratio and changes in the driving patterns.

The scope for "down-sizing", i.e. the choice of a smaller vehicle to carry out a particular task, is based on the fact that the capacity utilisation of most vehicles is poor. For instance, the utilisation of passenger cars in Denmark has been estimated to be 1.7 persons on average and 1.3 persons in rush hour traffic, and in 55% of the annual driving there is only 1 person onboard (Ministry of Transport 1993b). Light Goods Vehicles, on average utilise 5-10% of their pay-load capacity, and in Danish busses in regular traffic there is on average 10 passengers on-board, excluding the driver (Ministry of Transport 1995), corresponding to a effective utilisation of about 20-25% of the seating capacity and about 10-15% of the total capacity (seats and standing capacity). This reflects the fact that vehicles are designed for peak load, perhaps even with a reserve capacity[82], which only occurs in a small part of the time.

Here, down-sizing is based on the seating or payload capacity of the vehicle, adapting this to the demand. In addition, the interior volume can be reduced for a given capacity, thus improving the weight characteristics and aerodynamics of the vehicle.

Increasing the vehicle weight to engine power ratio - reducing the acceleration capability of the vehicle - is particularly important in today's ICE-bases vehicles, because it improves the operational conditions of the engine, and hence its efficiency. For decades, this ratio has been decreasing in new vehicles to achieve better performance, and the improvements of the engine efficiency achieved through technical development have been more or less undermined by the poorer operating conditions (Vibe-Petersen 1993).

The changing driving patterns - especially, the higher speeds - influence the fuel consumption and emissions in two ways. Directly, through the impact on vehicle loads and drive system efficiency, and indirectly through its impact on the technological development. Demand for higher speeds, acceleration, overtaking capabilities etc. lead to a strong emphasis on engine power. There are different trends concerning the development of the driving patterns:

- increasing congestion resulting in more stop-go driving;
- a general trend towards longer journeys, especially in the commuter traffic[83];
- higher vehicle densities mean that walking and cycling are being substituted by automobiles (and in some countries by motorised two-wheelers). Thus, these take a greater percentage of the short journeys.

8.3 Technologies on the Market

The potentials for improved fuel economy merely through the customer's choice when acquiring a car can be assessed by comparing the most fuel efficient model with the average passenger car in the Danish market. The reduction of the fuel consumption is in the range of 10-25%, which is due partly to the smaller weight and dimensions of the vehicle and partly to the fact that smaller vehicles, generally, have higher weight to power ratios (Jørgensen 1996b). Without down-sizing the improvement potential is limited (Winther & Møller 1996). On

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82 *For Light Goods Vehicles, however, the low capacity utilisation also reflects that there are incentives in the taxation schemes to buy too large vehicles. See Section 6.5.*

83 *This applies particularly to Denmark.*

both accounts, however, the difference between the average of the vehicle stock and the smallest models is diminishing, as the latter more and more are approaching the average of the vehicle market.

However, even small passenger cars have a seating capacity for 4-5 persons, including the driver. Since there are rarely more than 1-2 persons in the vehicle further improvements could be achieved by a shift to smaller vehicles, for instance 1-2 seated cars or scooters (albeit not at the same level of comfort). These vehicles could lead to a reduction of the fuel consumption by 50-75%, and moreover they would be particularly beneficial in congested urban areas.

	Sensitivity	AST	BST
		% improvement in relation to REF	
Passenger cars			
Weight	0.75/0.20	-5	25
Air resistance	0.20/0.75	10	20
Rolling resistance	0.20/0.05	0	10
Accessories	0.05/0.05	-10	15
Transmission	0.95/0.95	0	5
Engine, same engine type	1.0/1.0	0	10
Engine, incl. shift of engine type	1.0/1.0	-	20
Onboard generator	0.05/0.05	0	0
Total	-	*-5*	*25*
Light Goods Vehicles			
Weight	0.75/0.20	-10	10
Air resistance	0.20/0.75	10	25
Rolling resistance	0.20/0.05	0	10
Accessories	0.05/0.05	-10	10
Transmission	0.95/0.95	0	5
Engine	1.0/1.0	0	5
Onboard generator	0.05/0.05	0	0
Total	-	*-10*	*15*
Heavy Goods Vehicles			
Weight	0.85/0.35	5	10
Air resistance	0.10/0.60	5	10
Rolling resistance	0.30/0.15	0	5
Accessories	0.05/0.05	-10	10
Transmission	0.95/0.95	0	5
Engine	1.0/1.0	0	5
Onboard generator	0.05/0.05	0	0
Total	-	*5*	*10*

Table 8.3. Estimated fuel efficiency improvement potentials for passenger cars, light goods vehicles and heavy goods vehicles in conjunction with existing market choices (Friis Hansen & Antvorskov 1995; Jørgensen 1995f; Jørgensen 1996b). The sensitivity figures indicate the estimated impact of each remedy on overall fuel efficiency in urban driving patterns and by 90 km/h. For each of the Technology Levels AST and BST (see Section 8.1), percentages are given for the estimated potential for improvement compared to the REF level (the present stock average). A negative figure indicates a negative impact on fuel efficiency (AST only). The improvement potentials for each element is not necessarily referring to the same vehicle, and therefore the total improvement potentials given for each vehicle type are generally less than the sum of each element.

Table 8.3 compares the fuel efficiency characteristics of the vehicle sale with the average of the vehicle stock (REF). The vehicle sale is characterised by means of the average fuel efficiency standard (AST) and the best available technology (BST). For passenger cars and light goods vehicles, AST is generally slightly more efficient than the present stock average mainly because of the backlog of older vehicles in the stock. For heavy goods vehicles, the new vehicles are generally more fuel efficient than the stock average, due to improvements over the last 10-15 years.

Overall, these vehicles' impact on fuel consumption, air quality, congestion etc. depends on the way in which they replace existing traffic. If introduced on the market as a cheap option, without further changes, most likely they will not only replace car traffic but also public transport and cycling. A Danish study of the effects of introducing the Danish 1-seated electrical vehicle "Mini City-el" (nicknamed the "Ellert") illustrates this problem: about 40% of the people driving this vehicle are transferred from public transport, 25% from cycling and 25% from conventional automobiles (Nissen et al 1990). Roughly, the positive effect of substituting automobiles with the electrical vehicle is balanced out by the negative effect of cycling being replaced by electrical vehicle driving.

8.4 Incremental Improvements

In the Technological Levels based on incremental improvements, down-sizing is not included as a possible means. This explains why the DEV and EFF levels are relatively close to the BST level in which down-sizing is included. In some cases, the improvement potential in conjunction with the DEV level is even lower than that of the BST level.

The potentials for fuel economy improvement in conjunction with these two levels are determined on the basis of various studies (Sachs et al 1989; Ross et al 1991; Piëch 1992; DeCicco & Ross 1993; Friis Hansen & Antvorskov 1993; Nadis & McKenzie 1993; Ross 1994; Jørgensen 1995f; Jørgensen 1996b). Furthermore, the EFF level potentials can be illustrated by means of the "3-litre auto" initiative within the German automotive industry[84], aiming at the development of a passenger car with a fuel economy of 3 litre/100 km or better. This corresponds to a 2.5 times improvement of the fuel economy, or a reduction of the specific fuel consumption by 60%. In this range, a number of prototype vehicles can be found - for instance, the Volvo LCP and the Renault Vesta - as well as the Greenpeace conversion of a Renault Twingo to a car capable of running more than 30 km/litre.

The potentials for improvements, when the scope is limited to incremental improvements, is summarised in Table 8.4. Vehicle weight can be reduced by means of leaner constructions and lighter materials, notably aluminium and fibre glass materials. Examples of construction changes in the past which have made the vehicle lighter are the self-supporting body and the shift from rear to front wheel drive, but the gains from these and other measures have been more than offset by weight increases due to higher safety and comfort standards.

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84 *Launched by the VW group (Piëch 1992), but General Motors (that is, German Opel).is carrying out analyses of the concept as well, and is probably closer to practical results than VW.*

	Sensitivity	DEV	EFF
		% improvement in relation to REF	
Passenger cars			
Weight	0.75/0.20	25	40
Air resistance	0.20/0.75	25	25
Rolling resistance	0.20/0.05	25	35
Accessories	0.05/0.05	20	25
Transmission	0.95/0.95	10	10
Engine, same engine-type	1.0/1.0	25	35
Engine, shift of engine-type	1.0/1.0	35	45
Onboard generator	0.05/0.05	15	25
Total	-	*30*	*60*
Light Goods Vehicles			
Weight	0.75/0.20	25	30
Air resistance	0.20/0.75	30	40
Rolling resistance	0.20/0.05	25	35
Accessories	0.05/0.05	15	20
Transmission	0.95/0.95	10	10
Engine, same engine-type	1.0/1.0	15	20
Engine, incl. shift of engine-type	1.0/1.0	15	25
Onboard generator	0.05/0.05	15	25
Total	-	*25*	*50*
Heavy Goods Vehicles			
Weight	0.85/0.35	10	15
Air resistance	0.10/0.60	10	30
Rolling resistance	0.30/0.15	20	35
Accessories	0.05/0.05	10	15
Transmission	0.95/0.95	10	20
Engine	1.0/1.0	10	10
Onboard generator	0.05/0.05	15	25
Total	-	*15*	*25*

Table 8.4. Estimated fuel efficiency improvement potentials for passenger cars, light goods vehicles and heavy goods vehicles in conjunction with incremental improvements using the present vehicle stock as reference level (Sachs et al 1989; Ross et al 1991; Piëch 1992; DeCicco & Ross 1993; Friis Hansen & Antvorskov 1993; Nadis & McKenzie 1993; Ross 1994; Jørgensen 1995f; Jørgensen 1996b). The sensitivity figures indicate the estimated impact of each remedy on overall fuel efficiency in urban driving patterns and by 90 km/h. For each of the Technology Levels DEV and EFF (see Section 8.1), percentages are given for the estimated potential for improvement compared to the REF Level (the present stock average). The improvement potentials presume adaptation of the engine to the reduced load, and they are not additive.

The weight saving potentials depend on the extent to which different vehicle elements are included in the process. An incrementalist approach would avoid changing the basic structure of the vehicle, restricting the changes to items such as the body, interior etc. Further, the impact of given weight reductions on the fuel consumption depends on the driving pattern and the overall design of the vehicle. For instance, in heavy-duty vehicles the curb weight of the vehicle, generally, constitutes a smaller percentage of the gross vehicle weight[85].

The aerodynamics have been improving constantly during the last several decades, but at the same time the speeds have increased. In the future, further improvements can be expected, but again the impact on the fuel economy depends on the speed. In urban driving patterns, the air resistance play a relatively minor role.

Rolling resistances are affected by weight reductions but can be further reduced through the choice of tyres. Even today, there are considerable improvement potentials by selecting the most fuel-efficient tyres on the market, but other considerations influence the choice of tyres (safety, comfort, costs).

Accessories account for a small but rapidly increasing part of the vehicle losses. There are two main factors to consider to reduce these losses, namely to reduce the demand for accessories and to provide these as efficiently as possible. The former can be the result of accepted lowering of standards or it can follow from other changes of the vehicle. For instance, substantial weight reductions can reduce the demand for power steering. As regards the efficiency of the accessories, the large number of electric motors performing a variety of tasks are particularly important (e.g. power steering, ventilation and opening of windows).

In a typical vehicle, the transmission losses are in the range of 10-15% leaving relatively limited scope for further improvements. In addition to reducing the transmission losses as such, proper design of the transmission can ensure that the engine can be operated as efficiently as possible.

The efficiency of the loaded engine can be improved by technical development but at least as importantly through adaptation of the operational point of the engine - in particular through avoiding over-capacity. In the past, heavy duty diesel engines have had the greatest improvements whereas there is still a considerable scope for further improvements of gasoline engines and light duty diesel engines even in the incremental improvements scenario. In addition, idling losses are crucial for the engine's overall performance, especially in urban driving patterns. Remedies to stop the engine when idling may be an option even as incremental improvement.

As can be seen from Table 8.4, the total improvement potentials are highest for passenger cars and lowest for heavy duty trucks, partly because the latter have been subjected to more efficiency improvements in the past and partly because the payload reduces the direct impact of remedial measures on the fuel economy.

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85 *The payload capacity's share of the gross vehicle weight increases with increasing vehicle size, and moreover a greater part of the capacity is generally utilised.*

8.5 Alternative Energy Carriers and Renewable Energy

Today, the principal energy carrier in transport is oil, as virtually all of the fuels in the Danish transport sector are oil-derived products (gasoline, diesel and LPG)[86]. Most vehicles are driven by internal combustion engines (ICE), in the form of either spark-ignition engines (SI engines) or compressed-ignition engines (CI engines or diesel engines).

The main advantages of gasoline and diesel are good combustion properties and, in particular, the fact that they are easily storable with high energy density by mass and volume. Hence, it is possible to achieve a long driving range without having to carry a heavy and bulky on-board storage. The main disadvantages of these two fuels are their limited supply and their emissions of CO2 as well as other emission problems. In addition, gasoline have posed considerable handling problems, being, among other things, volatile, explosive and highly inflammable[87]. These problems, however, have to a great extent been overcome, and today gasoline is considered a relatively safe fuel, though the radiation of heat from gasoline fires is a serious problem.

Rationales Behind Alternative Fuels

In general, "alternative fuels" are defined as all other fuels (and other forms of energy supply) than gasoline or diesel - including electricity, hydrogen, bio-fuels, natural gas and liquefied petroleum gas (LPG). There is a variety of different reasons for applying these fuels:

1. Improvement of the local environment, in particular in urban areas, through reduction of the emissions of NOx, HC, CO and particle mass, and through the option of applying vehicles with less noise. This perspective addresses concentration problems rather than the overall environmental impacts, focusing mostly on areas of heavy traffic (notably urban areas);
2. Improvement of the security of energy supply, through reduction of the dependence on (imported) oil-derived fuels. From this point of view, the main objective is to include a greater range of different energy sources in the supply[88].
3. The opportunity to apply new, and more appropriate, drive trains than the present, predominantly ICE based, drive systems. The latter are not well-suited for the typical driving patterns in the most common applications, characterised by idling, stop/go-driving and varying (most low) loads. Electrical propulsion provides an opportunity to circumvent many of those problems, since electrical motors are switched off at standstill, offer good braking regeneration facilities and are less sensitive to operation at low loads. Moreover, electrical vehicles, potentially, make less noise.
4. Improvement of the overall environmental impact, for instance, by exploiting the option of introducing cleaner fuels or utilising technologies with better system efficiency (linked

86 *The only notable exception is trains driven by electricity, produced on the basis of coal and a small contribution from renewables.*

87 *Indeed, Otto, the inventor of the SI engine, decided not to use gasoline for it for safety reasons, opting instead for towngas.*

88 *Both different fuels and different suppliers of these fuels.*

to item 3). In this case, it is not considered sufficient to move the pollution to central sources, as pollution in the whole of the fuel cycle are included.

5. Using alternative fuels as an energy carrier for renewable energy sources. This reason is closely linked to item 4, but adding the objective of reducing the utilisation of fossil fuels to the environmental benefits. Here also, the whole fuel cycle should be included in the assessment,

Most of today's efforts to promote alternative fuels can be divided into two main categories: those directed towards concentration problems (mainly environmental) and those aimed at more globally oriented problems (resource depletion, regional and global environmental problems, security of supply). These two approaches do not necessarily point to the same solutions.

Many lobby groups are promoting a particular fuel or propulsion system, but from an energy and environmental point of view alternative fuels should be seen as a means, not as a goal in itself. Hence, the assessment should be based on its contribution to the environmental improvements. Such assessments cannot provide simple answers given in advance, since they depend on the circumstances, notably how the alternative fuel is generated and distributed and how efficient the vehicle exploits the energy.

Renewable Energy in the Transport Sector

Renewable energy sources are a means for reducing the fossil fuel consumption and CO2 emissions of transport. They are probably necessary to achieve a long-term solution to the problem of creating sustainability in the transportation sector. This applies in particular if the present growth trends are allowed to continue, but even with curbed transport growth it will be difficult to establish substantial reductions in CO2 emissions without a shift to renewable energy sources.

On a global scale the influx of energy from the sun is around several thousand times greater than the present total energy consumption for human purposes, and even in the OECD countries, with the highest energy demand, the solar energy influx is roughly 800 times higher than the present demand (Scheer 1993). Hence, even with poor utilisation, and even with a substantial growth in total energy demand, the physical energy resources will still be well above the demand.

In practice, however, the resources are constrained, since the limiting factor is not the total resources, but the construction and operation of the technologies needed to convert the solar energy into useful energy: wind or solar power plants, cultivated fields, dams for hydropower plants etc. Thus, there are social costs linked to the utilisation of renewable energy in the form of environmental impacts (air quality, visual pollution, noise etc.) and requirements for energy, materials, land, labour[89], investments etc. In particular the land areas required, which can be considerable, constitute a serious problem of many renewable energy sources. To a certain extent, the utilisation of areas for renewable energy can be combined with other utili-

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89 *The labour requirement - perceived as job opportunities - is frequently seen as an advantage, but fundamentally this is linked to the present problems of distributing the work.*

sations - e.g. solar heating panels integrated with roof constructions or forests being used at the same time for biomass growing and recreational purposes - but generally this reduces the problem rather than solving it.

Altogether, this means that there are good reasons for utilising renewable energy sources as efficiently as possible. The significance of the system efficiency - i.e. the conversion of the energy content of the solar influx to the driving force, including the losses due to added storage weight etc. - is that it determines the efficiency in the utilisation of land, and hence translates into the land needed to cover the demand.

From an efficiency point of view, the major difference is between biomass-based paths, in which case the solar energy is converted by means of photosynthesis, and paths avoiding the biomass-step. Normally, the biomass-based paths include a secondary conversion of the biomass to bio-fuels (alcohols, vegetable oils), biogas or hydrogen, or to electricity by means of conventional power stations or fuel cells. In a longer term, direct conversion of solar energy to hydrogen through photolysis may be an option (Jørgensen 1994c).

The remaining paths are all based on electricity as an energy carrier, whether used directly onboard electric vehicles or as an intermediate step in the production of hydrogen. The electricity may be generated by means of photo voltaics, wind turbines, hydropower, wave power etc.

The system efficiency is determined by the following factors:

- the conversion of solar energy to useful fuels or energy carriers;
- the conversion of the fuel or energy carrier to mechanical energy onboard the vehicle;
- the mechanical energy needed to move the vehicle, influenced, among other things, by the weight of the vehicle, which in turn is influenced by the onboard technologies required by the given fuel or energy carrier (onboard energy storage, energy conversion devices etc.).

Table 8.5 summarises the comparison of the system efficiencies of different energy conversion paths. The system efficiency has been calculated, taking into consideration the losses in each conversion step from solar energy to driving wheels[90]. Based on this, the land requirements to cover transport energy demands have been calculated: for the operation of an average passenger car (17.000 km/a) and for the present transport energy demand in Denmark (155 PJ/a). The table does not reflect whether these areas can be used for other purposes simultaneously with the energy generation. Even so, it does reflect the constraints placed on general planning by the land use requirements.

90 *Including the losses in conjunction with the production and distribution of fuels and electricity, the utilisation of the fuels and electricity onboard the vehicle, and the effect of added weight due to onboard storage, fuel cells etc., but excluding energy demands for production of technology.*

	land to cover avg. pass. car m2	land to cover transp. sector energy km2
Electric vehicles based on....		
Photovoltaic power	20-50	75-200
Wind farms (land based)	70-250	250-900
Wind farms (sea based)	50-170	175-600
Individual wind mills	15-70	50-260
Power from biomass power stations (without CHP)	1500-2300	5500-8300
Power from biomass power stations (with CHP)	750-1100	2800-4100
Hydrogen ICE based on...		
Photovoltaic power	80-450	300-1700
Wind farms (land based)	300-1800	1100-6700
Wind farms (sea based)	200-1200	750-4500
Individual wind mills	50-540	190-2000
Biomass gasification	3300-17000	12000-64000
Hydrogen fuel cell based on...		
Photovoltaic power	30-200	125-750
Wind farms (land based)	125-800	450-3000
Wind farms (sea based)	80-550	300-2000
Individual wind mills	20-240	80-900
Biomass gasification	1300-7200	4700-27000
Bio fuels used in		
Internal combustion engines	3000-11000	11000-41000
Fuel Cells	1200-5200	4400-19000

Table 8.5. The two columns show the land needed to cover the demand of a medium-sized passenger car (left column) and the total Danish transport energy demand (right column). For hydrogen and systems based on internal combustion engines (ICE) and fuel cells (FC) are included. EV stands for electrical vehicles. Power generation based on biomass is shown with and without utilisation of the heat generated for district heating ("with CHP" and "no CHP", respectively). The intervals given reflect the range between present state-of-the-art (lower value) and the improvements envisaged on the market in the course of 10-20 years (upper value). Source: (Jørgensen & Nielsen 1997).

Table 8.5 is based on the following assumptions (Jørgensen & Nielsen 1997):

- conversion of solar energy to power: 10-15% (photovoltaics); 2-5% (wind parks, land based); 3-7% (wind parks, sea based); 8-25% (individual windmills);
- conversion of solar energy to biomass: 0,4-0,6% (150-200 GJ/hectare)
- conversion of biomass to bio-fuels: 60-70% (presuming by-products are utilised)
- conversion of biomass to hydrogen: 60-75%
- conversion of electricity to hydrogen (electrolysis): 80-95%

- distribution losses for electricity: 8%
- distribution and handling losses for hydrogen, including compression energy, excluding liquefaction energy for liquid hydrogen: 8-15% (gaseous hydrogen); 15-25% (liquid hydrogen);
- liquefaction losses (hydrogen): 30-40%
- ICE drive train efficiency, including transmission: 15-22%
- electric motor efficiency, incl. transmission: 70-80% (present state); 85-91% (advanced motor);
- battery efficiency, including charging losses, excluding weight penalty: 70-80% (present); 75-85% (advanced);
- efficiency of onboard hydrogen storage, excluding weight penalty: 85-95% (gaseous hydrogen); 75-90% (liquid hydrogen)
- weight penalty (per cent to be added to specific electricity consumption): 25-30% (present electric vehicles); 10-15% (advanced electric vehicles); 15-25% (hydrogen ICE vehicles with compressed gas tanks); 5% (liquid hydrogen vehicles); 15-35% (hydrogen fuel cell vehicles);
- onboard fuel cell efficiency (electricity): 40-50%
- regeneration of braking energy: 20% for electric vehicles (including fuel cells);

On the basis of the results in Table 8.5, the following general conclusions can be drawn, focusing mainly on the issue of energy conversion efficiency:

- electrical vehicles, generally, have the best conversion efficiencies, followed by hydrogen, and again bio-fuels is the least efficient option - but if longer vehicle ranges are demanded this will deteriorate the efficiency of the electrical options (at least at the present technological level);
- if the drive system is based on fuel cells, the efficiency of hydrogen comes close to electrical vehicles, especially if combined with demands to vehicle range
- among the renewable energy sources considered, photo voltaics and wind mills are the most efficient options - but photo voltaics have important drawbacks (costs, development stage, seasonal variations);

Biomass, as a general rule, has very poor conversion efficiency. This is because the step of converting solar energy to biomass via photosynthesis deteriorates the overall system efficiency considerably. The photosynthesis process typically only converts around 0,5-1% to biomass energy, although the practical maximum of the photosynthesis efficiency for land plants is in the range of 6-7% (Sørensen 1979).

On the other hand, bio-fuels do not require heavy and/or bulky onboard storage, but this usually is not sufficient to offset the poor fuel cycle efficiency. The application of fuel cell based drive trains improve the vehicle efficiency considerably, but even so, fuels based on biomass fall a long way behind the other options.

The direct conversion of solar energy into mechanical or electrical energy operates at much higher efficiencies, and even though electrical propulsion normally requires heavier onboard storages (see below), the overall systems efficiency is many times higher than that of fuel cycles based on biomass. Even hydrogen, normally having an extra conversion step, is vastly superior (provided it is not based on gasification of biomass) to biomass-based fuels.

In the energy system, the bio-fuels have the advantage of being suited to storage over longer periods, e.g. seasonal storage, whereas storage of electricity based on photo voltaics or wind energy is expensive, and therefore limited in quantity (short covering periods). Photo voltaic electricity, moreover, has unfortunate seasonal variations which would result in problems for vehicles based exclusively on this energy source. Bio-fuels can play a role as a remedy for reducing the negative impact of these shortcomings, but at the same time biomass must be seen as a limited resource, that can only serve as a sustainable energy source in limited quantities.

Comparing the different biomass-based paths, significantly higher efficiencies can be obtained by means of electric vehicles based on electricity from biomass-fired power plants as opposed to utilising it as bio-fuels. This applies in particular if the electricity is generated in the form of combined heat and power. In addition, the former option allows greater flexibility with respect to fuel input.

In addition to the systems efficiencies, showing the overall utilisation of the total energy input, it would be of interest to compare the fossil fuel input needed in conjunction with each conversion path. As regard the fuel cycle, the most significant fossil fuel input is related to the generation of bio-fuels, for which the fossil fuel typically represents about 10-25% of the total energy content of the bio-fuel, though it can be greater than this (Ecotraffic 1992).

Therefore, the main focus in the following is on electrical, hybrid electric and hydrogen propulsion, since these are seen as offering the most far-reaching potentials for utilising renewable energy. There may be a more limited role for biomass-based fuels in the shorter term, and, possibly, as a means for utilising biomass residuals, such as manure.

Electrical Propulsion

Mostly, electrical propulsion is being promoted to improve local air quality and increase security of fuel supply. For instance, the objective of the Californian ZEV-mandate[91] is to improve the very poor air quality, especially in the area around Los Angeles. ZEVs in effect are electrical vehicles based on the present technology, though other types (e.g. based on fuel cells) may be added. Therefore, the ZEV-mandate, in effect, works as a promotional tool for electrical propulsion, which is a vital factor in the world development of electrical vehicles - despite the fact that the pollution problems of California are not necessarily representative of other parts of the world. For instance, fuel economy and global environmental problems probably play a more significant role in Denmark than poor urban air quality. In conjunction with the urban air quality, particle mass emissions from diesel engines probably plays a more

91 *I.e. Zero-Emission-Vehicles. Initially, the ZEV-mandate required that by 1998 2% of the passenger cars sold in California by the 7 largest car manufactorers (the so-called Big Seven) should be ZEV's, increasing to 10% by the year 2003. In the beginning of 1996, the mandate was modified in the light of concern about the prospects of having advanced batteries developed by 1998. The target for 2003 was retained, while the mandates before that year were abandoned.*

important role, as opposed to the hydrocarbons/ozone problems dominating the Californian urban environment.

However, electrical vehicles may also lead to improvements of the overall energy and environmental effects, depending on two principal factors, namely the vehicle efficiency - in terms of the specific electricity consumption of the vehicle, measured in kWh/km off the socket - and the losses and pollution in conjunction with power generation and supply. The vehicle efficiency, in turn, depends on the one side on the external resistances of the vehicle, linked mainly to the vehicle weight, and on the other side the component efficiency onboard the vehicle (of charger, battery, motor, motor controller and transmission).

Thus, three links are vital in determining the overall efficiency of electrical vehicles:

- the on-board component efficiency (especially of the charger/battery, motor/control and transmission);
- the vehicle weight, influenced in particular by the weight of battery, but also by the motor weight;
- power generation and distribution.

In connection with the Californian ZEV-mandate, there is no explicit reference to overall energy efficiency, but there is a general incentive to improve the energy efficiency of electric vehicles because of the need to increase the vehicle range. However, the issue has been dealt with explicitly by the Swiss electrical vehicle programme, aiming to introduce so-called "light electrical vehicles" - LEM for "Leicht Elektro Mobile" - in Switzerland, covering 8% of the Swiss vehicle stock between the years 2010 and 2020 (Jørgensen & Nielsen 1997). LEM refers to vehicles complying with certain maximum values for the specific energy consumption. These limits are projected to be lowered in the coming years: for instance, the current limit for normal passenger cars is 0,20 kWh/km (electricity off the grid) envisaged to be progressively lowered to 0,15 kWh/km.

The limited vehicle range undoubtedly is the most important obstacle to a large-scale introduction of electrical vehicles. The range limitation provides a strong incentive to improve the vehicle efficiency in order to increase the range. At the same time attempts to surmount the range problem by increasing the battery can have unfortunate consequences for the specific electricity consumption of the vehicle, thereby undermining the gain in range. The lower the specific energy of the battery (Wh per kg battery weight) the stronger this link is, and, in practice, there is an upper limit to the achievable range for a given energy density of the battery. At the same time, this leads to an inherent conflict between range and vehicle efficiency, as illustrated by Figure 8.2 showing specific electricity consumption versus range for state-of-the-art and advanced batteries. Advanced batteries, however, relaxes this link, and so does increased vehicle efficiency.

Besides the energy density, the power density and efficiency are other vital characteristics of the battery. The crucial issue regarding the battery development concerns the prospect for a breakthrough in the foreseeable future. In a Californian battery review, the advanced batteries are envisaged to be marketed just after the change of the century - presuming (rather optimistically) a "100% success scenario" (Kalhammer et al 1995; Kalhammer 1996).

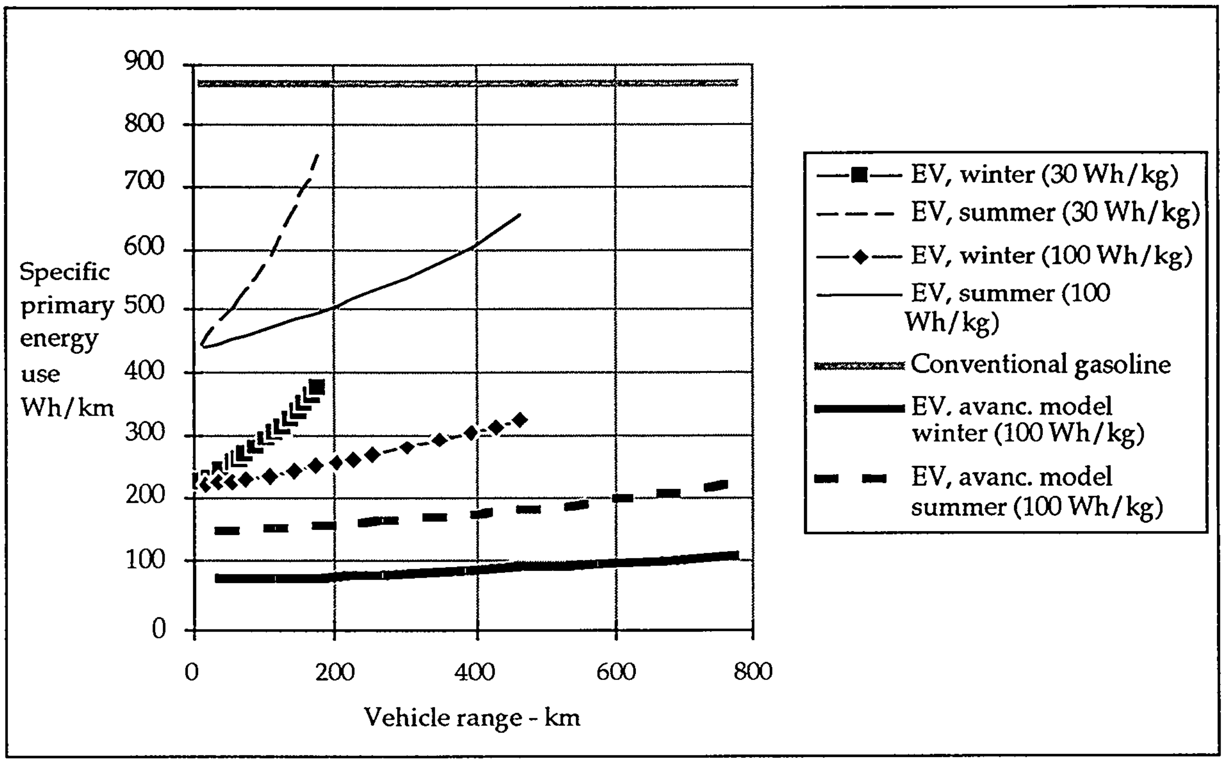

Figure 8.2. Specific primary energy consumption versus range for a electrically driven medium-sized passenger car (EV) with state-of-the-art and advanced batteries (Jørgensen 1996c). ECE urban driving pattern. The specific energy consumption of the EVs is shown with and without district heating (winter and summer). Advanced EV models have advanced drive trains in addition to the advanced batteries.

Regarding the choice between battery types for electric vehicles, the key issues concerning the future development can be summarised in the following questions (Deluchi et al 1989; Wang 1990; Wang & DeLuchi 1992; Kalhammar et al 1995; Kalhammar 1996; Nissen 1996):

- Will lead/acid-batteries remain the only option applied on a large scale, and how great are the potentials for improvement of this battery type?
- Will nickel-batteries - particularly nickel/metal hydride batteries (NiMH) - get a role as traction battery? Today, they are in widespread commercial use for consumer electronics, computers, cellular phones etc., but the question is whether they can be developed for electrical vehicles at competitive prices.
- Will high-temperature batteries, such as sodium/sulphur (NaS) and sodium/nickelchloride (NaNiCl), play a role? The have high energy densities and potentially low production costs, but also operational and safety problems, and they have the disadvantage of not having other markets, besides electrical vehicles, to support the development of a market.
- When will lithium batteries be available and what will their performance and costs be?

The vehicle performance (speed and acceleration) depends on the installed motor power seen in relation to vehicle weight. Due to the low specific power (kW per kg motor weight) of the conventional DC-motors, the predominant traction motor for many years, most electric vehicles have had limited power installed to keep down weight. This has laid the basis for the perceived image of electrical vehicles as slow, especially with regard to top speed and overtaking capabilities. DC-motors are in the process of being substituted by AC induction (asynchronous) motors, mainly due to improvement in power electronics. Beyond this, the future is uncertain: whether induction motors will be replaced by more advanced motor types and, if so, by what motors. Two candidates promise much better characteristics (weight, efficiency): AC permanent magnet synchronous motors (also known as DC brushless motors) and switched reluctance (SR) motors (Moore & Lovins 1995; Sperling 1995; Horstmann & Jørgensen 1997).

Figure 8.3 shows the calculated specific electricity consumption off the grid for different technological levels, illustrating the impact of more efficient and lighter vehicle components.

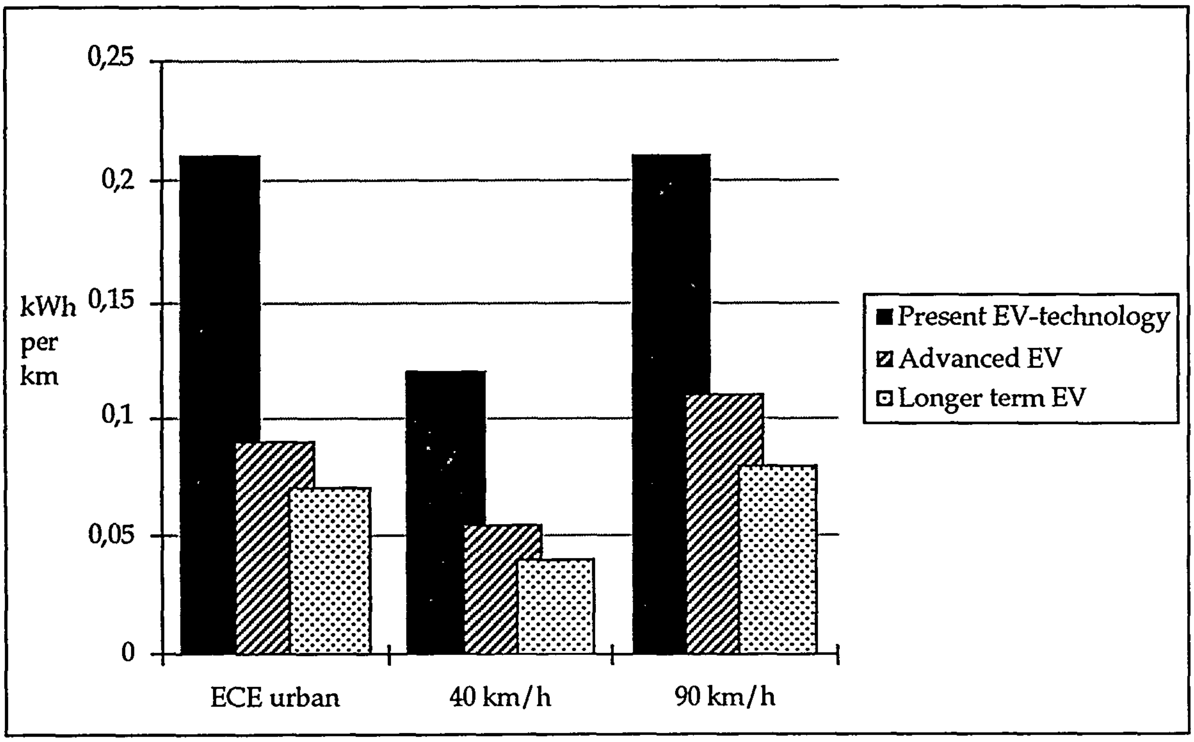

Figure 8.3. Calculated specific electricity consumption off the grid for electrically driven medium-sized passenger car, showing present technological state of EV, advanced EV (as of 2005-2010) and longer-term EV technology in which the impact of a lighter vehicle is included.

Figure 8.3 cannot be used for comparison between electric and gasoline propulsion, as the losses of power generation and distribution are not included. They are included in Figure 8.4, comparing the primary energy consumption of the same technology levels as shown in Figure 8.3 with that of gasoline driven versions of the same vehicle. The graph shows the electricity consumption off the power plant (black area), the power generation losses if the heat is used for district heating (hatched area) and the power generation losses if the heat is not used for heating purposes (dotted area). The specific primary energy consumption then is somewhere in the dotted area, depending on the utilisation of the heat from the power generation[92]. The equivalent gasoline vehicle is shown for two situations: the present average and a possible[93] future improvement of the same vehicle.

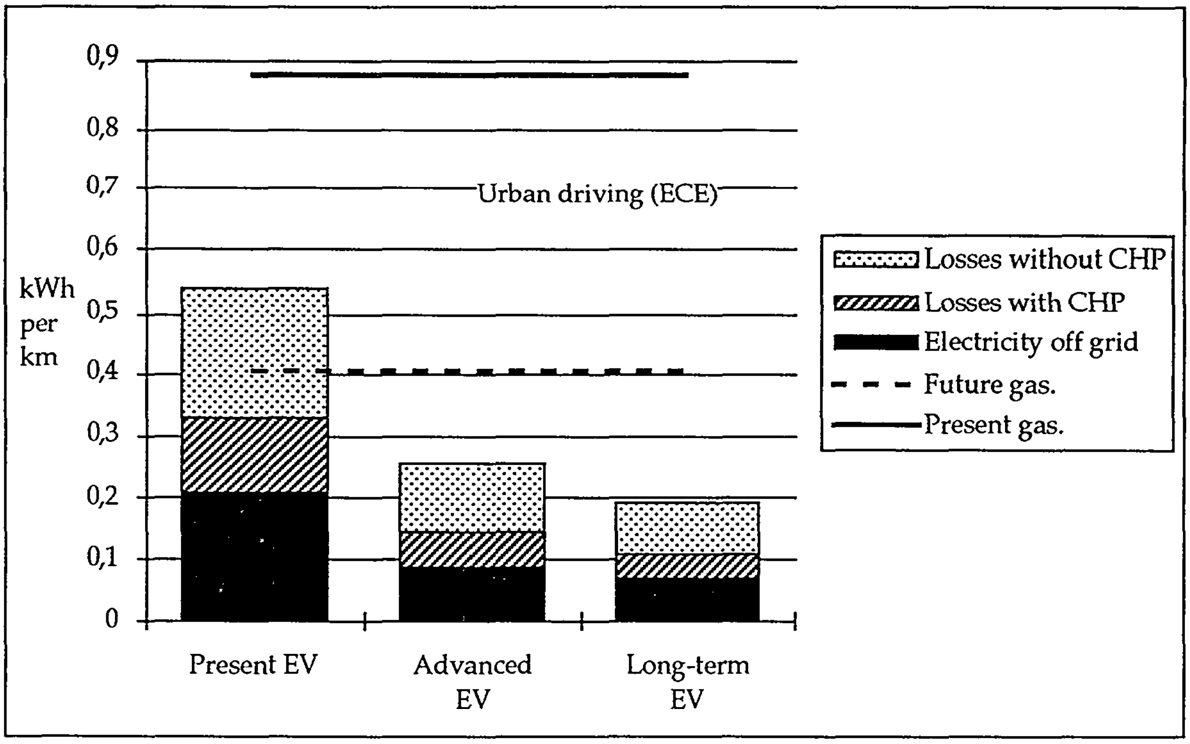

Figure 8.4. The primary energy consumption and in conjunction with an electrically driven medium-sized passenger car, compared to an equivalent gasoline-driven car. Three versions of the electric vehicle (see Figure 8.3) and two versions of the gasoline car. The electricity consumption is shown with and without utilisation of waste heat ("with CHP" and "without CHP").

In urban driving, the electric vehicle has a reduction of the primary energy consumption by more than one third, even without utilisation of waste heat. With maximum utilisation of the waste heat the energy consumption is reduced by two thirds. To achieve similar reductions in a conventional gasoline driven car it would have to have a fuel economy of 20-32 km/litre gasoline in urban driving. Future improvement may further increase the savings, but it is also possible that the gasoline vehicle is improved.

92 *And depending on the division of the cogeneration advantage between the electricity and the heating side.*

93 *But not necessarily "probable".*

Hybrid Electric Drive

Hybrid electric drive designates drive trains combining electrical motors and ICE, thereby enabling extension of the range provided by battery mode and/or reduction of battery weight. There are the following two configurations:

- series hybrid drive, in which only the electrical motor provide the traction, whereas the ICE is part of an onboard power generation unit (termed "auxiliary power unit", APU);
- parallel hybrid drive, in which both electrical motors and ICE are connected to the driving wheels.

Hybrid vehicles as a category covers a wide range of different concepts and design criteria (Burke 1992; Burke 1993; Sperling 1995; Moore & Lovins 1995). One extreme is, in effect, a conventional battery driven vehicle, designed to cover normal daily operation in battery mode, but with the option that the range can be extended by means of a small APU, designed mainly to serve as an "emergency tank" at very poor performance compared to a conventional vehicle. As the battery capacity is not compromised - or only to a limited extent - there is no reduction of battery weight to offset the weight of the APU, and therefore this has to be kept as small as possible. Mostly, this concept - termed "range-extended battery drive" - is configured as a series hybrid vehicle.

At the other extreme is a hybrid vehicle designed to operate, basically, as an ICE-driven vehicle, with very limited range in battery mode. However, the design with an APU supplying power for an electrical traction motor ensures better operating conditions for the ICE, using the (small) battery for load-levelling. This means that the ICE can operate at near-constant operating conditions close to its optimum, which significantly improves its efficiency and emissions. This concept - named "fuelled engine-electric" - mostly is based on series hybrid configuration.

In between the two, a concept called dual mode is a further development of the range-extended battery driven vehicle, in which the APU is designed to provide near-normal performance of the vehicle, even when the battery state of charge is zero. Battery weight cannot be reduced to any great extent, and due to the increased weight of the APU it is important to reduce the weight of the remaining drive train. In a parallel hybrid configuration, this can be done by reducing the installed power of the electrical motor (due to the option of operating the ICE and electrical motor in parallel), which results in this concept being mostly used for dual mode.

The electricity for hybrid vehicles may be based on electricity from stationary sources, typically off the public grid, or from on-board generation (the APU), with varying split between the two depending on the design.

The most obvious advantage of hybrid electric drive is the option to extend the range of battery driven vehicles, without adding unrealistically heavy batteries, but in certain respects the concept can also be used to improve the energy efficiency of the vehicle, based on today's technical level mainly by means of the fuelled engine-electric concept (Moore & Lovins 1995; Sperling 1995).

It is clear that a significant improvement can be achieved compared to conventional ICE-driven vehicles, because of the better operating conditions for the ICE. Whether an improvement can also be achieved in comparison with conventional battery driven vehicles depends on the technical development of the components (especially batteries) and of the requirements to range and performance of the vehicle. If a short range - less than about 50-70 km - is sufficient, then battery vehicles are probably hard to beat in so far as fuel efficiency is concerned, but if a longer vehicle range is required this worsens the energy efficiency of the battery driven vehicles, and hence, hybrid electric drive gains in comparison. In case advanced onboard storages are available, this extends the range below which the battery driven vehicle is superior.

Whether hybrid electrical drive has a future or not, depends on the requirements for range, the battery development and, not least, on the development of fuel cells (see below). If affordable and practical fuel cell systems are developed there probably will be no future for hybrids, but even in this case, it can serve as an intermediate solution, before fuel cells are developed, or, possibly, alongside these, if they turn out to be practical but relatively expensive.

Hydrogen

Hydrogen plays a more limited role in the alternative fuels picture, being still at the research, development and demonstration stage. It has, however, its strong proponents, to whom, in many cases, it signals not only a different fuel but also an alternative society - frequently named "hydrogen economy" (DeLuchi 1989; DeLuchi 1992; Cannon 1995; Jørgensen 1996d). It certainly has very considerable potentials, if its technical problems can be surmounted, and provided it is generated in a clean manner[94]. It is a clean burning fuel with few noxious combustion emissions, the major emission problem in conjunction with its combustion being NOx. Notably, its combustion does not result in CO2 emissions. To the overall assessment of hydrogen energy it is crucial to take the generation and distribution into account, since the emissions during hydrogen generation based on fossil fuels can be greater than from conventional fossil fuels applied in vehicles. Preferably, the hydrogen generation should be based on renewable energy (through electrolysis based on electricity from renewable energy sources or through biomass gasification).

The application of hydrogen in vehicles may take place either in ICE-driven vehicles, possibly in combination with another fuel such as gasoline, diesel or natural gas, or in drive trains based on fuel cells. The former option is by far the most common today, but fuel cells offer the most interesting perspective for hydrogen propulsion.

ICE-based hydrogen vehicles are similar to conventional gasoline and diesel driven vehicles, apart from the application of a very clean fuel. Therefore, they share the drawbacks of those, namely poor part load efficiency, idling losses and the lack of simple braking regeneration capabilities. The most suitable engine type is the spark ignition engine (the SI

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94 *The following publications by the author concern hydrogen energy: (Jørgensen 1993b; Jørgensen 1993c; Jørgensen 1994a; Jørgensen 1994c; Jørgensen 1995j; Jørgensen 1996d; Jørgensen 1996h; Jørgensen & Nielsen 1996).*

engine), either four-stroke or two-stroke, which may be designed as a dedicated hydrogen engine or as a bi-fuel engine, capable of operating on both hydrogen and gasoline[95] (either by switching between the two fuels or by fuel mixing between 0% and 100% hydrogen). In compression ignition engines (CI engines) - that is, diesel engines - 100% hydrogen is not a possibility, due to the high auto ignition temperature of hydrogen. Instead, it is necessary to mix the hydrogen with diesel, either varying the mixture according to the load or using the diesel as ignition fuel.

Even though hydrogen has many attractive characteristics with respect to combustion, the operation of a hydrogen fuelled SI-engine is not a simple task. Hence, much of the hydrogen energy research and development work has been directed towards this problem, focusing particularly on five major problem areas[96]: engine efficiency; engine output per stroke volume; NOx emissions; engine operation; engine design complexity.

The engine efficiency is generally slightly better than equivalent gasoline engines, but slightly worse than diesel engines. NOx-emissions, which are the only major emission problem from 100% hydrogen ICEs[97], can be equivalent to or higher than those of gasoline or diesel ICEs, but it is possible to reduce them to very low levels.

Similarly to electrical propulsion, the key problem for hydrogen propulsion is finding a suitable onboard storage technology. The options used most often are: compressed gas (CH2); liquid hydrogen (LH2); metalhydrides.

There is not one best storage option standing out in every respect, and the actual choice will be a balancing of different considerations. At the moment, the most interesting option probably is CH2 storage, combining relatively high energy density with acceptable fuel cycle efficiency. This storage type is undergoing a very rapid development with respect to energy density in connection with natural gas vehicles. LH2 storage offers high energy density and hence very good range compared to other alternative fuels, but its fuel cycle losses are unacceptably high. Metalhydrides, on the other hand, have good fuel cycle efficiency and good safety features, but they have not fulfilled the promises regarding energy density.

Besides these "big three" storage types, other options exist which may develop into interesting options. In particular, the storage in activated carbon in conjunction with CH2 storage has interesting perspectives.

A case study of the overall environmental impacts of the application of hydrogen in Danish light goods vehicles (LGVs, i.e. vans and light duty trucks of less than 6 tonnes of gross vehi-

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95 *Hydrogen can also be combined with other fuels, notably natural gas. In particular in the USA, much attention has been directed towards mixed hydrogen/natural gas engines (Jørgensen 1994c).*

96 *Based on (Jørgensen 1993b; Jørgensen 1994c; Jørgensen 1996d; Jørgensen & Nielsen 1996). Other important sources are (Das 1990; Das 1991; DeLuchi 1989; DeLuchi 1992; Peschka 1992;).*

97 *There are other emissions from hydrogen engines, especially HC and CO, which are linked to the lubricants and occur in very small quantities.*

cle weight) has been carried out by the author (Jørgensen 1994a; Jørgensen 1996h). LGVs are responsible for more than half of the fuel consumption of freight transportation, even though they only cover about 3-4% of the freight transport demand[98], and moreover they operate mainly in urban areas, contributing considerably to the deterioration of the urban environment. The latter characteristic at the same time makes them suited for hydrogen.

In the case study, hydrogen is assumed to be generated by means of electrolysis based on electricity from the Danish power grid. The study investigates different assumptions regarding vehicle technology (propulsion and onboard storage), penetration rates of the light duty vehicle market and power generation (renewable energy share). The study does not cover FC-based solutions, and the penetration rates considered vary between 15% and 100% of the light duty vehicle market (responsible for about 20% of the total transport sector fuel consumption in Denmark).

The study indicates the following environmental impacts (compared to the Danish transport sector as a whole):

- Primary energy use increases by between 6% and 105% and CO2 emissions by 8% to 145% if the present power generation fuel mix is used, whereas a reduction by up to approximately 20% may be achieved for both factors if the power generation is fully based on renewable energy[99].
- NOx emissions increase by up to around 30% based on the present power fuel mix and decrease by nearly 10% if the power generation is all renewable.
- HC and CO is reduced by up to about 10% regardless of the power generation. Both of these substances are predominantly linked to vehicles, whereas emissions of the power generation system are insignificant.
- SO2 emissions multiply by up to 7.5 times based on the present fuel mix, whereas a reduction by up to 17% may be achieved based on renewable power generation[100].
- Particle mass emissions increase by up to almost 40% based on present fuel mix, whereas a reduction by almost 30% may be achieved if the power is generated by renewables.

The following main conclusions are drawn on the basis of the study:

- hydrogen propulsion based on fossil fuels, generally, is not a good idea, except possibly during a transitional phase
- LH2 provides good ranges, but very poor fuel cycle efficiency.

In general, hydrogen provides a less efficient utilisation of electricity than electrical vehicles for short vehicle ranges (based on the present technology level). If longer ranges are required, however, hydrogen could be an interesting option. Clearly the most interesting long-

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98 *See Section 6.5.*

99 *Presuming that renewables have zero CO2-emissions and do not result in primary energy consumption.*

100 *The high growth factor should be seen in context with the fact that the SO2 emissions of the transport sector are very low.*

term perspective for hydrogen is the application in fuel cells, if these are developed into practical and affordable systems (see below).

Fuel Cells

The fuel cell technology, in many ways, is a key technology in the development of clean vehicles, providing an option for a very efficient power train and very low emission levels. The most suitable fuels may be either alcohols (especially methanol), hydrocarbons (natural gas, biogas) or pure hydrogen, of which hydrogen can be considered the ideal fuel, except for problems with storage and handling (as detailed above).

Today, fuel cells are still at a relatively early developmental stage, particularly for mobile applications. Even so, there are several examples of demonstration projects, and the list is growing. Of the different concepts, one - the Molten Carbonate Fuel Cell - is not suited for transport applications, while the remainder main types have been or could be used (DeLuchi 1991b; DeLuchi 1992; Williams 1992; Jørgensen & Nielsen 1997):

- The Phosphoric Acid Fuel Cell (PAFC) is the most advanced option, though applications are mainly in stationary purposes. The principal mobile application is in heavy duty vehicles.
- The Solid Polymer Fuel Cell (SPFC)[101] is probably the option with the greatest potentials for transport applications, especially in light duty vehicles.
- The Alkaline Fuel Cell (AFC) which was considered the most interesting option for mobile applications 5-10 years ago, but now has virtually disappeared from the demonstration projects
- The Solid Oxide Fuel Cell (SOFC) is still at a relatively early developmental stage, even for stationary applications, and it is uncertain whether it will be applied in transportation means.
- The Direct Methanol-Air Fuel Cell (DMAFC) is, in effect, an SPFC operated at slightly elevated temperatures, enabling it to use methanol directly.

Basically, the FC operation is based on supply of hydrogen and oxygen, and other fuels normally have to pass through a reformer to generate hydrogen. Onboard reforming, however, can be avoided if hydrogen is used as fuel, but this option, naturally, has various other problems (e.g. onboard storage and the risks in conjunction with handling of pure hydrogen and pure oxygen). The high-temperature SOFC (operating around 1000°C) can handle a number of fuels directly (have internal reforming) and the DMAFC can handle methanol directly.

The main development problems of fuel cells are:

- costs
- specific power per weight and volume
- ability to follow varying loads (especially for other fuels than hydrogen)

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101 *Also known as the Proton Exchange Membrane Fuel Cell.*

At the moment, the fuel cell technology is developing very rapidly, especially with regard to the specific power and costs (even though the latter is starting from an extremely high level). If this development continues, a large scale application of fuel cells may take place within 10-15 years. The question is whether it will based on hydrogen or some other fuel such as methanol, natural gas, gasoline etc.

Conclusions - Potentials of Alternative Fuels

Table 8.6 shows the estimated fuel efficiency improvements in Technology Levels AFV1 and AFV2 based on alternative. The technologies included are electric propulsion (passenger cars and Light Goods Vehicles) and hybrid electric propulsion (Heavy Goods Vehicles).

Electrical, hybrid electric and hydrogen propulsion provide more efficient utilisation paths for solar energy than bio fuels, and even substantial technological developments are not likely to change this. Generally, electric vehicles are more efficient than hydrogen, but to-day electrically driven vehicles are confined to relatively short ranges (up to 50-100 km) and also to some extent to limited power. If longer ranges are needed it will be advantageous to switch to hybrid electric or hydrogen, unless advanced electrical vehicles or fuel cell vehicles become available.

Fuel cells are a key technology in the development, in particular with regard to hydrogen's future role.

	Sensitivity	Level AFV1	Level AFV2
		% improvement in relation to REF	
Passenger cars			
Weight	0.75/0.20	-10	15
Air resistance	0.20/0.75	25	30
Rolling resistance	0.20/0.05	10	35
Accessories	0.05/0.05	15	25
Transmission	0.95/0.95	25	50
Motor	1.0/1.0	50	65
Storage	1.0/1.0	-25	-15
Onboard generator	0.05/0.05	0	25
Total	-	*50*	*75*
Light Goods Vehicles			
Weight	0.75/0.20	-20	10
Air resistance	0.20/0.75	30	45
Rolling resistance	0.20/0.05	10	35
Accessories	0.05/0.05	10	20
Transmission	0.95/0.95	25	50
Motor	1.0/1.0	50	60
Storage	1.0/1.0	-25	-15
Onboard generator	0.05/0.05	0	25
Total	-	*40*	*70*
Heavy Goods Vehicles			
Weight	0.85/0.35	-20	-10
Air resistance	0.10/0.60	10	30
Rolling resistance	0.30/0.15	5	35
Accessories	0.05/0.05	10	15
Transmission	0.95/0.95	25	50
Motor	1.0/1.0	35	50
Storage	1.0/1.0	-25	-15
Onboard generator	0.05/0.05	0	25
Total	-	*20*	*50*

Table 8.6. Estimated fuel efficiency improvement potentials for passenger cars, light goods vehicles and heavy goods vehicles in conjunction with shift to alternative fuels (Ross et al 1991; DeCicco & Ross 1993; Ross 1994; Friis Hansen & Antvorskov 1995; Jørgensen 1995f; Jørgensen 1996b). The sensitivity figures indicate the estimated impact of the remedy on overall fuel efficiency in urban driving patterns and by 90 km/h. For each of the Technology Levels AFV1 and AFV2 (see Section 8.1), percentages are given for the estimated potential for improvement compared to the REF Level. The improvement potentials for the motor include the additional losses linked to power generation as compared to supply of gasoline or diesel.

8.6 The Hypercar, PNGV and Other Breakthrough Designs

The designs covered in this section are collected under the common heading of "breakthrough technologies". These are defined as transport technologies aiming to meet an explicit fuel economy target, that is significantly higher than the present average, while maintaining - or even improving - all other qualities of the vehicle[102]. The objective can be said to be "achieving more with less" to quote Amory Lovins from the 1970s (Lovins 1976). In other words, this line of thinking is based on the assumption that it is possible to achieve substantial improvements of the energy efficiency and environmental impacts of automobiles without (necessarily) questioning the fundamental reasoning behind today's automotive society[103]. Naturally, it is possible to combine the breakthrough technologies with lowering of the standards in some areas - in other words, "achieving less with even less" - but, generally, this option is not considered by the technological strategies covered in the following[104].

In addition, it is a general characteristic of breakthrough technologies that they apply the improvement in the course of a short time period (as signalled even more by Amory Lovins' concept "leapfrog technologies").

The potential of the breakthrough technologies are analysed on the basis of two US strategies:

- The hypercar strategy of Rocky Mountain Institute (Amory B. Lovins et al), aiming to demonstrate the viability of a so-called "hypercar"[105], i.e. a passenger car with a fuel economy several times better than the present level (Lovins et al 1993; Lovins 1995; Lovins & Lovins 1995; Lovins et al 1995a; Lovins et al 1995b; Lovins et al 1995c; Moore & Lovins 1995; Lovins 1996; Mascarin et al 1996; Moore 1996; Rocky Mountains Institute 1997).
- The Partnership for a New Generation of Vehicles (PNGV), which is a co-operative effort between the American government and the automotive industry, initiated in 1993 and aiming at a tripling of the fuel economy of new passenger cars, without compromising the performance, comfort and safety of the car (DeCicco & deLaski 1995; Jost 1995: Moore & Lovins 1995; OTA 1995; Pandit 1995; PNGV 1995a; PNGV 1995b; Taylor 1996).

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102 *Thus, breakthrough technologies remind of Amory Lovins' concept "leapfrog technologies", but are not exactly the same. In Lovins' definition, leapfrog technologies must be based on different vehicle platforms (in effect, a composite vehicle equipped with an advanced hybrid electric drivetrain). In his approach, the aim is not just to achieve a certain fuel economy target but also to promote a technological and industrial transformation towards a relatively specific target. See Section 8.1 for a more detailed discussion of the background for these concepts.*

103 *Naturally, the hypercar approach may be combined with an acknowledgement of other reasons for questioning the advance of the automobile, e.g. traffic safety, the impact on urban development etc.*

104 *This issue is covered in Section 8.2.*

105 *Initially, the term "supercar" was used, but to avoid confusion with extremely powerful racing cars the term "hypercar" is now used.*

According to RMI's modelling, a hypercar with equivalent performance to conventional American passenger cars could have a specific consumption in the range of 2.5 litre gasoline equivalents per 100 kilometre (in mixed driving) in the short-term version, and probably 1.2 litre/100 km in the longer term. This represents a slight moderation of the initial targets: 1.6 litre/100 km in the short term and 0.8 litre/100 km in the longer term (Lovins et al 1993). At the 27th ISATA[106] conferences, 31st October - 4th November, 1994 in Aachen, Germany the concept was used as heading of one of ten parallel sessions, based on the following criteria: a fuel efficiency three times better than conventional designs, that is 2.3-2.9 litre/100 km for mid size passenger cars and 1.6-2.0 litre/km for a small passenger car, with zero emission capability in the city, and performance and safety standards equal to or better than conventional cars (Frank 1994).

The PNGV target is to develop, before the year 2004, a production prototype of a passenger car with a fuel economy 3 times better than the present American average, corresponding to 2.9 litre gasoline equivalent per 100 km (PNGV 1995a).

Both the RMI and the PNGV targets refer to a typical new US passenger car with a curb weight today around 1500 kg and ability to carry up to 6 persons and 475 litre of cargo, with emissions below the American Tier II levels[107] and with equivalent or superior performance with respect to safety, acceleration, gradability, ride and handling quality and noise, vibration and harshness control (PNGV 1995a; Moore & Lovins 1995). In addition, at least 80% of the vehicle by weight shall be recyclable

Since uncompromised range is another requirement, battery-powered electric vehicles are not considered by neither the RMI nor the PNGV strategy.

The PNGV Technology Strategy (PNGV 1995b) acknowledges that major advances must be made in three main fields to achieve the tripling of the fuel economy (shortened "3X"): the efficiency of the drive system, the mass of the vehicle and the implementation of efficient braking regeneration.

The achievements in each field determine the demands on the other fields, illustrated by three different paths that would all, according to PNGV modelling, lie within the "design space for achieving 3X":

- 40% thermal efficiency, 40% mass reduction, and 70% regenerative braking[108];
- 44% thermal efficiency, 30% mass reduction, and 70% regenerative braking;
- 51% thermal efficiency, 10% mass reduction, and 50% regenerative braking.

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106 *International Symposium on Automotive Technology and Automation, a European forum for automotive technology development, dating back to the early 1970s.*

107 *0.078 gram HC/km, 1.06 gram CO/km and 0.125 gram NOx/km - which is 2-4 times below the present Danish emission standards (Ministry of Transport 1993c; Moore & Lovins 1995).*

108 *I.e. 70% of the braking energy being recovered.*

The design space leads to certain innovation needs in the different fields. The thermal efficiency of the drive train is required to be in the range 40% to 55%, which is roughly 2-3 times the present average. This is beyond what is achievable with conventional ICE-based drives, and therefore new drive train technologies are required. The PNGV Technology Strategy mainly focuses on hybrid-electric and fuel cell drives. In this connection, there is a need for power storage devices, and therefore the PNGV strategy also addresses the development of flywheels and ultracapacitors.

In addition, there is a strong focus on lightweight materials and mass reducing design optimisation.

The PNGV approach is criticised by Amory Lovins and co-workers at the Rocky Mountain Institute for being too moderate, particularly with regard to the mass reductions potentials[109]. Instead, the RMI explores the viability of an "advanced ultralight hybrid" - that is, a vehicle combining radical reductions of vehicle loads (external driving loads and auxiliaries) with the application of advanced drive trains - aiming to exploit the synergy effect of the joint introduction. The RMI aims to meet or exceed the PNGV targets for vehicle standards, similarly focusing on a 6-seated passenger car.

In accordance with the principles outlined in Section 8.1, the design of the advanced ultralight hybrid starts from the wheels moving towards the engine. The basic problem of conventional vehicles is seen to be the fact that they are built mainly from steel, resulting in rather heavy vehicles. Even though a certain substitution of lighter materials, this happens at a component basis and is limited to changes that do not violate the existing designs. Due to the poor efficiency of the drive system the losses due to heavy weight, poor aerodynamics etc. are multiplied by a factor 5-7.

In addition, Lovins claims that the heavy vehicle weights of conventional automobiles are responsible for the great variations in engine load, and hence for the poor efficiencies of this engines. (Lovins 1995a). Therefore, it is assumed that lighter vehicles, such as the hypercar, would eliminate this problem. However, the under loading of the engines is linked to the ratio between peak and average loads, and not the difference between these in absolute terms. This will not change because of reductions in weight, air resistance etc. The same applies to his claim that lightweight hybrid electrics, unlike heavier hybrids, will reduce the engine performance map of the onboard engine/generator "to a point" (i.e. to insignificant variations). Again, it is the relative variations which are of interest, and they do not change with the vehicle weight (if the same design criteria are used).

The different degrees of radicalism are illustrated by four different targets, termed "Conservativa", "Gaia", "Ultima" and "Imagina" (Lovins 1995a):

- The Conservativa vehicle is deemed easily obtainable by Lovins. It has the following main features: curb weight 700 kg; frontal area 1.9 m2; c_W-factor 0.21; rolling resistance coefficient 0.008; power demand for accessories 20% lower than present American aver-

109 *Despite the criticism the PNGV target - 3 times better fuel economy than the present average of new vehicles - was applied as the criterion for hypercars in the ISATA hypercar meeting, chaired by Lovins (Frank 1994).*

age; average engine/transmission efficiency 26%. The calculated fuel economy: 2.4 litre per 100 km.

- The near-term Gaia vehicle based on technologies commercially available today has the following main features: curb weight 580 kg; frontal area 1.9 m2; c_W-factor 0.14; rolling resistance coefficient 0.007; power demand for accessories 50% lower than present American average; average engine/transmission efficiency 27%. The calculated fuel economy: 1.6 litre per 100 km.

- The advanced Ultima vehicle based on technologies that are envisaged to be developed into commercially available technologies in the near future. It has the following main features: curb weight 400 kg; frontal area 1.7 m2; c_W-factor 0.10; rolling resistance coefficient 0.006; power demand for accessories 70% lower than present American average; average engine/transmission efficiency 45%. The calculated fuel economy: 0.6 litre per 100 km.

- The long-term Imagina vehicle is a possible "early-next-century vehicle" based components at the edge of the technological development as we can see it today. It has the following main features: curb weight 400 kg; frontal area 1.5 m2; c_W-factor 0.087; rolling resistance coefficient 0.005; power demand for accessories 75% lower than present American average; average engine efficiency 54% (fuel cell/electric motor). Calculated fuel economy: 0.4 litre per 100 km.

Subsequently, RMI has further analysed a passenger car roughly based on the Conservativa vehicle (Moore & Lovins 1995). In addition to the 6 seat passenger car, a slightly smaller vehicle with seating capacity for 4-5 persons is studied (termed "further optimised scenario"). Since this vehicle is the closer option with respect to the typical Danish passenger car, the following focuses on this version. The improvements estimated by the Rocky Mountain Institute (Lovins 1995a; Moore & Lovins 1995) are as follows:

- Curb weight reduction to 520 kg, including a full fuel tank[110]. The key remedy to achieve this is the application of a composite (or aluminium) body, but in addition, the weight is reduced by careful design of each component
- Improved aerodynamics - by reducing the c_W-factor to 0.18, and by reducing the frontal area to 1.75 m2 (that is, a total reduction of the $c_W \cdot A$ product by 55% as compared to the average new American passenger car model)
- Reduction of the rolling resistance coefficient to 0.0066 (roughly a reduction by 50%)
- Reductions of the power demand for auxiliaries to 0.25 kW, including air conditioning of the cabin (a reduction by 75% compared to the average US passenger car[111])
- Installing of a series hybrid electric drive system with an average efficiency of 35%. The drive system is based on a Stirling engine for the onboard electricity generation.
- An ultracapacitor for load levelling - that is, a storage designed to level out power demand and supply but not to store energy for provision of vehicle range.

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110 *Termed "decoupling of mass and size" by Lovins - e.g. in (Lovins 1995a) - because the mass to size ratio is reduced considerably, though not anywhere near zero as a "decoupling" would imply.*

111 *A Danish car, without air conditioning, would have a lower reduction potential.*

Simulation results indicate an average specific fuel consumption of 1.7 litre/100 km in the American Federal Urban Driving Schedule (FUDS) and 1.9 litre/100 km in the Highway Fuel Economy Test Procedure.

	Sensitivity	Level ADV	Level HYP
		% improvement in relation to REF	
Passenger cars			
Weight	0.75/0.20	55	60
Air resistance	0.20/0.75	45	45
Rolling resistance	0.20/0.05	50	50
Accessories	0.05/0.05	60	60
Drive train	1.0/1.0	30	50
Storage	0.4/0.4	-10	-10
Total	-	*80*	*90*
Light Goods Vehicles			
Weight	0.75/0.20	50	55
Air resistance	0.20/0.75	40	40
Rolling resistance	0.20/0.05	50	50
Accessories	0.05/0.05	40	40
Drive train	1.0/1.0	25	45
Storage	0.4/0.4	-10	-10
Total	-	*70*	*80*
Heavy Goods Vehicles			
Weight	0.85/0.35	25	30
Air resistance	0.10/0.60	50	50
Rolling resistance	0.30/0.15	40	40
Accessories	0.05/0.05	30	30
Drive train	1.0/1.0	25	40
Storage	0.4/0.4	-10	-10
Total	-	*45*	*60*

Table 8.7. Estimated fuel efficiency improvement potentials for passenger cars, light goods vehicles and heavy goods vehicles in conjunction with leapfrog technologies (Moore & Lovins 1995; Jørgensen 1995f; Jørgensen 1996b; Moore 1996). The sensitivity figures indicate the estimated impact of the remedy on overall fuel efficiency in urban driving patterns and by 90 km/h. For each of the Technology Levels ADV and HYP (see Section 8.1), percentages are given for the estimated potential for improvement compared to the Reference Level (the present average).

These results indicate that a typical Danish passenger car based on short-term breakthrough technology could reduce the specific fuel consumption to 1.5 litre gasoline equivalent per 100 km. In the longer term, applying more advanced drive trains based on fuel cells, a specific fuel consumption of 0.7 litre/100 km is estimated to be achievable, based on RMI's modelling translated to Danish circumstances. These targets, corresponding to an increase in the fuel economy by a factor 5 and 10 respectively, are used to represent the ADV and HYP

Technological Levels (cf. Section 8.1). The main difference between the two is the drive system.

Table 8.7 shows the estimated improvements of fuel efficiency in conjunction with the Technology Levels ADV and HYP, based on breakthrough technologies.

It should be emphasised that these results by no means exhaust the theoretical improvement potentials, especially if the standards required are lowered. For example, vehicles participating in the various solar car challenges are capable of running several hundred kilometres per recharging.

8.7 Fuel and CO2-emission Impacts

In the following, the impacts on energy use and CO2-emissions of the different Technology Levels defined in Section 8.1 have been analysed. The analysis covers the next 40 years (1995 to 2035) and has been carried out by means of the dynamical model TECIMP. TECIMP models the penetration of the technical improvements first in the vehicle sale and then in the vehicle stock. In addition to the stock average based on the number of vehicles, it models the penetration on a mileage basis. Therefore, the model can analyse the influence of the fact that the newest vehicles generally have the highest annual mileage, which means that an evaluation based on stock figures will probably underestimate the impact on fuel and emissions.

The analysis focuses on passenger cars.

It is assumed that the following reduction patterns for fuel consumption and CO2-emissions can be achieved:

- the Best Sold Technology Level (BST): a reduction of the primary energy consumption and CO2-emissions of the improved vehicles by 25% - with the implementation starting within a year and reaching full penetration of the sale in another 5 years.
- the Developed Technology Level (DEV): reductions of the primary energy consumption and CO2-emissions of the improved vehicles by 40% - marketed by the year 2000 and reaching full penetration of the sale in another 5 years. Before this, the development follows the pattern of the BST level.
- the Efficient Technology Level (EFF): reductions of the primary energy consumption and CO2-emissions of the improved vehicles by 60% - with the improvements being introduced by the year 2005 reaching 100% penetration of sales figures in the course of another 3 years. Before this, the level develops along the same lines as the DEV level.
- the Present Alternative Fuel Vehicle Level (AFV1): a reduction of the primary energy consumption of the improved vehicles by 50% - introduced in the market within a year and reaching its maximum penetration (50% of the total car sale) in 10 years. The impact on the CO2-emissions are assessed on the basis of both the present power generation mix being retained and a shift to natural gas and renewable energy according to the projections of the energy plan, Energy 21 (as detailed below).
- the Advanced Alternative Fuel Vehicle Level (AFV2): long term reduction of the primary energy consumption of the improved vehicles by 75%. At first, the same development as in the AFV1 level, but with the technology being gradually improved leading to lower primary energy consumption and enabling higher penetration rates (due to longer

ranges between recharging). The improvements are assumed to have penetrated the vehicle sale by the year 2012. The impact on the CO2-emissions are assessed on the basis of both the present power generation mix being retained and a shift to natural gas and renewable energy according to Energy 21.

- the Advanced Vehicle Level (ADV): a reduction of the primary energy consumption and CO2-emissions of the improved vehicles by 80% - introduced by the year 2000 and building up to 100% penetration in the course of another 10 years. Before this, the same development is presumed as in the EFF level.
- the Hypercar Level (HYP): a reduction of the primary energy consumption of the improved vehicles by up to 90%. In the beginning, the same time-scale is followed as that of the ADV level, except that a gradual switch to fuel cell based drive trains is presumed to start in the year 2010, extending over a 5 years period and leading to a gradual improvement of the vehicle efficiency.

For the scenarios based on electricity from the power grid, two different developments with respect to the power generation technology have been investigated. First, it is assumed that the present technology and fuel mix as today is retained during the whole calculation period. This can be considered a pessimistic - and not very likely - projection. Secondly, a gradual shift to natural gas and renewable energy according to the projections of the energy plan, Energy 21 (Ministry of Environment and Energy 1996):

- a gradual shift to 100% natural gas by the year 2025;
- a gradual increase of the renewable electricity share from 3% to 55% by the year 2030.

In addition, the consequences for the land requirements of a 100% shift to renewable energy in the power supply are investigated.

The analysis is based on two economical projections from "Danmarks energifremtider" termed "high growth" and "low growth" (Ministry of Environment and Energy 1995). According to the high growth projection the vehicle stock increases by about 40% until the year 2005 and by 75% until the year 2030. The car density is expected to saturate around the year 2010 (at a level of 550 vehicles per 1000 inhabitants) and on top of this a decrease in the annual mileage per vehicle is expected after the year 2005. Hence, strong growth rates are projected during the first 15-20 years and beyond this a reduction of the total annual driving[112]. The "low growth" projection is based on a halving of the economical growth rates of the high growth scenario[113] and an anticipated saturation of the car density at 450 vehicles per 1000 inhabitants. The vehicle stock is anticipated to increase by one quarter by the year 2005 and by al-

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112 *The projection is based on continuing growth in both production output and private consumption during the whole period, which means that a decoupling of the vehicle stock and driving development from the economical development (and even from the development in private consumption). This is considered to be a very unlikely scenario but probably the least probable part of the projection is the anticipated persistant economical growth rather than the expected transport demand satuation (Jørgensen & Nørgård 1996).*

113 *Just like the high growth projection, persistant growth is expected in the low growth projection with the production output being increased by 50% and private consumption by two thirds.*

most half by the 2030, while the annual driving has a stronger growth (one third) until 2005 and a decline between 2005 and 2030. It should be noted that these two projections share a pattern of strong growth during the first couple of decades and saturation beyond the year 2010. Thus, they both have particular serious problems meeting the environmental targets of 2005 while the meeting of the longer term targets is to some extent being supported by the projected reduction of the transport demand[114].

Figures 8.5 to 8.11 show the calculated development of the primary energy consumption of each of the seven Technology Levels. The primary energy consumption includes the energy system losses from source to end-use. For technologies based on electricity it has been assumed that the waste heat is not utilised.

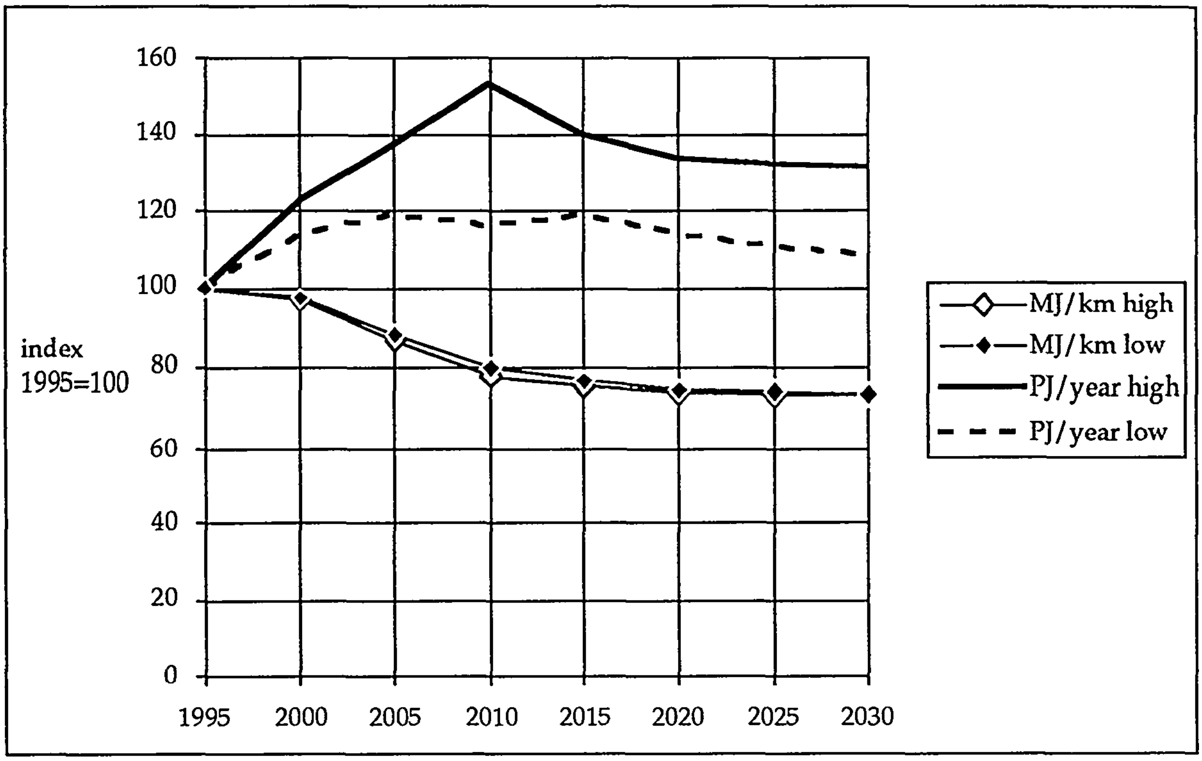

Figure 8.5. Projected development of average specific energy consumption and total primary energy consumption of the passenger car stock in conjunction with level BST, indexes shown with 5-years intervals (1995 = 100). Calculated for high and low economical growth rates. The specific energy consumption is averaged on the basis of driving.

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114 *The present governtal energy plan, Energy 21, published in 1996, is based on an economical projection between the two of "Danmarks Energifremtider" (Ministry of Environment and Energy 1996). During the first two decades, the growth rates are between the two projections described in the text, and beyond this the vehicle stock and annual mileage following the high growth projection - which means that the Energy 21 projection has a slightly more evenly spread growth.*

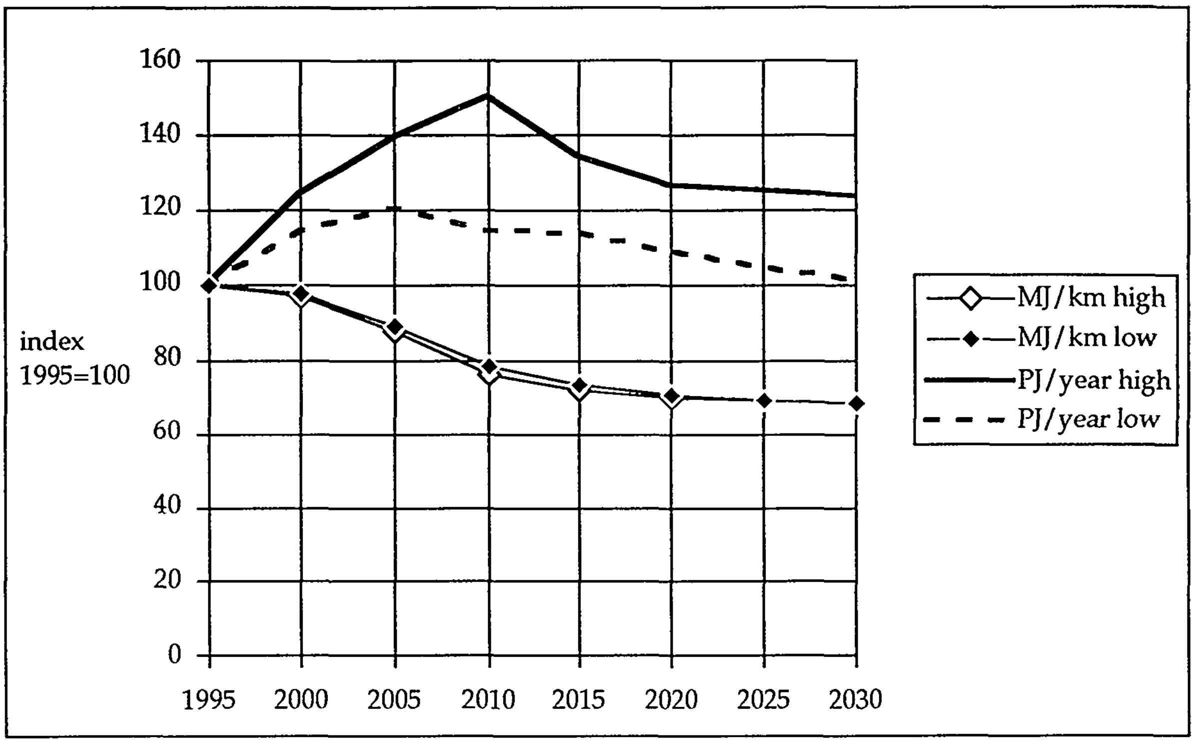

Figure 8.6. Projected development of average specific energy consumption and total primary energy consumption of the passenger car stock in conjunction with level DEV, indexes with 5-years intervals. High and low economical growth rates.

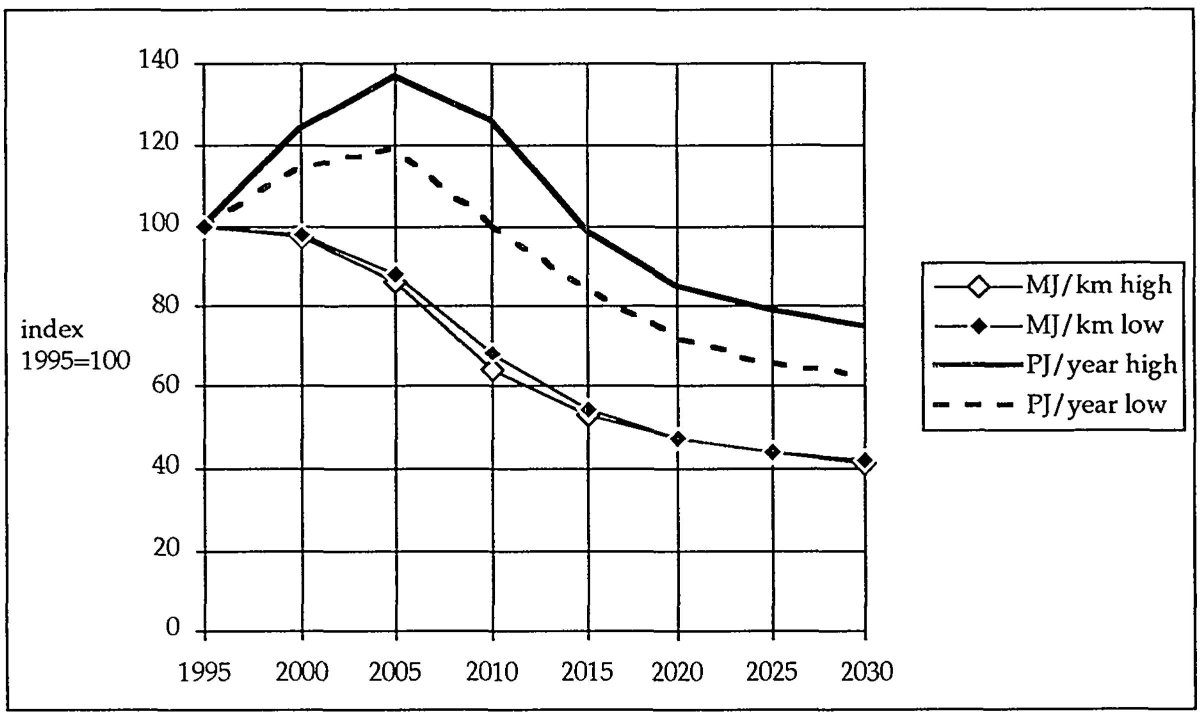

Figure 8.7. Projected development of average specific energy consumption and total primary energy consumption of the passenger car stock in conjunction with level EFF, indexes shown with 5-years intervals. High and low economical growth rates.

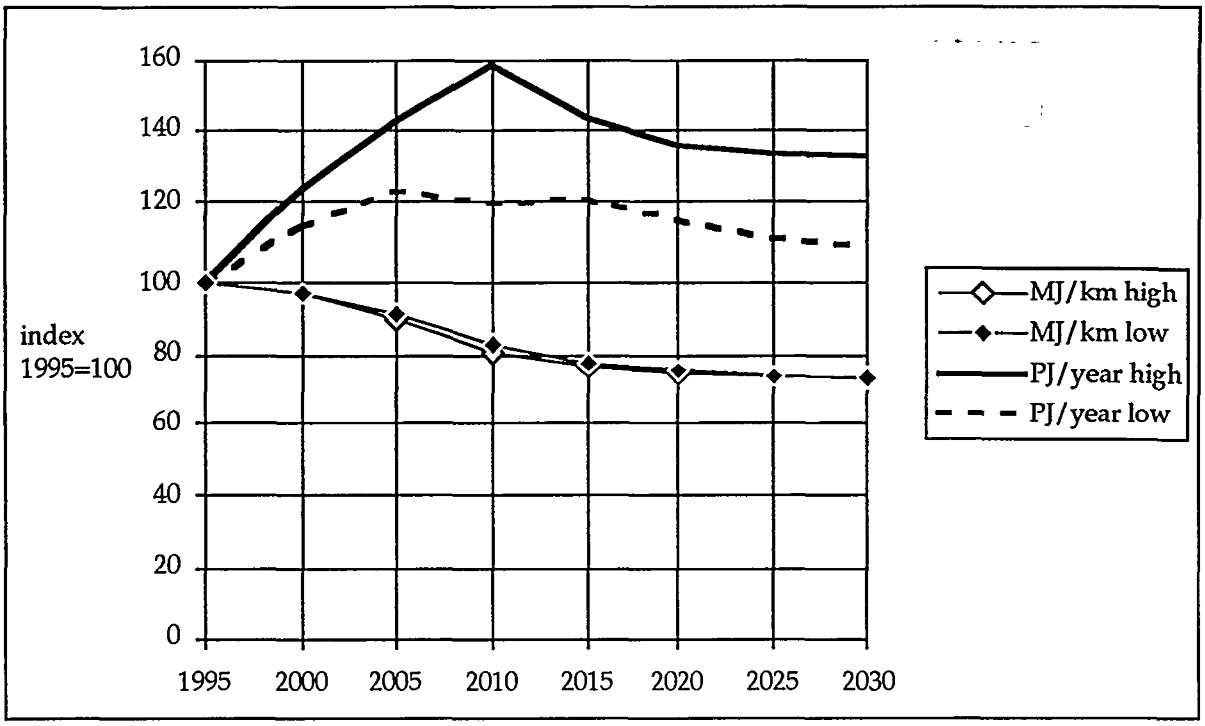

Figure 8.8. Projected indexed development of average specific energy consumption and total primary energy consumption of the passenger car stock in conjunction with level AFV1. High and low economical growth rates.

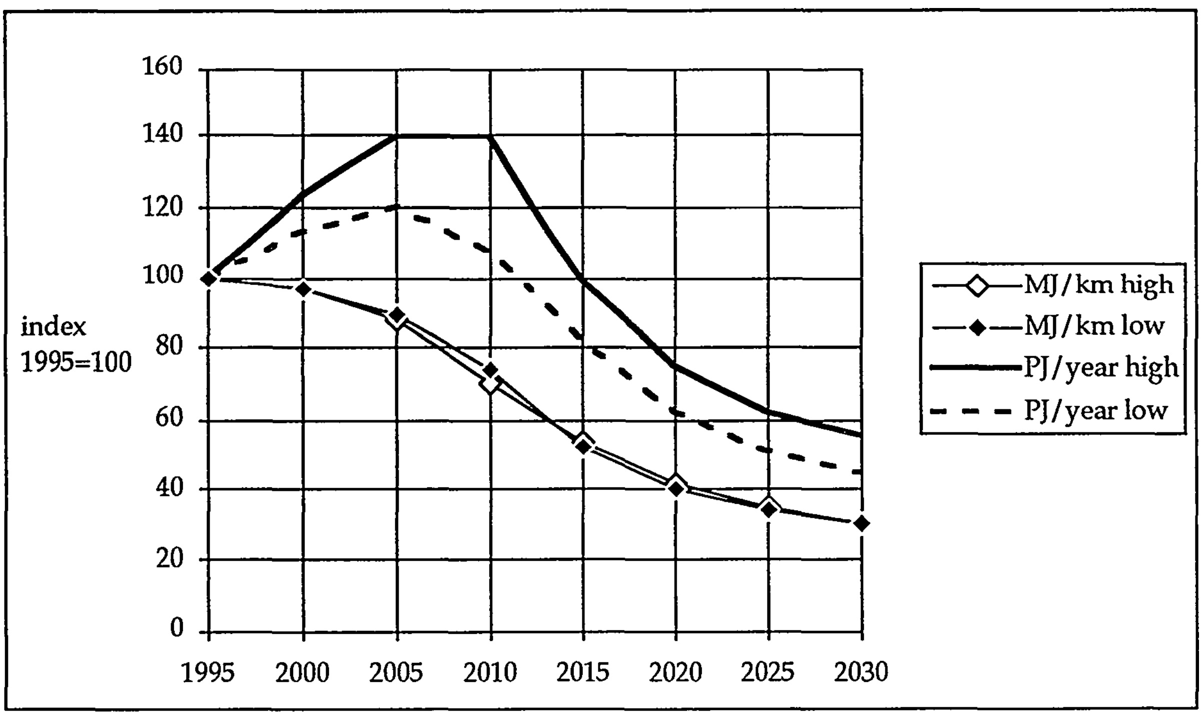

Figure 8.9. Projected development of average specific energy consumption and total primary energy consumption of the passenger car stock in conjunction with level AFV2. High and low economical growth rates.

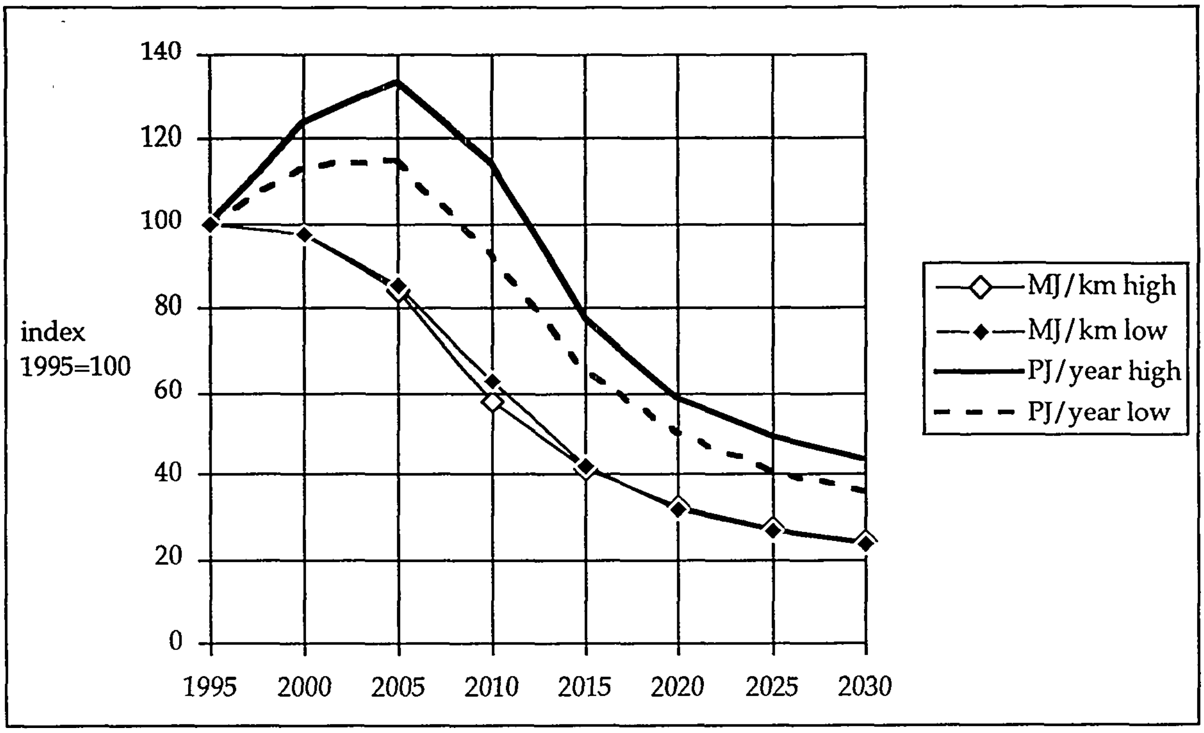

Figure 8.10. Projected development of average specific energy consumption and total primary energy consumption of the passenger car stock in conjunction with level ADV. High and low economical growth rates.

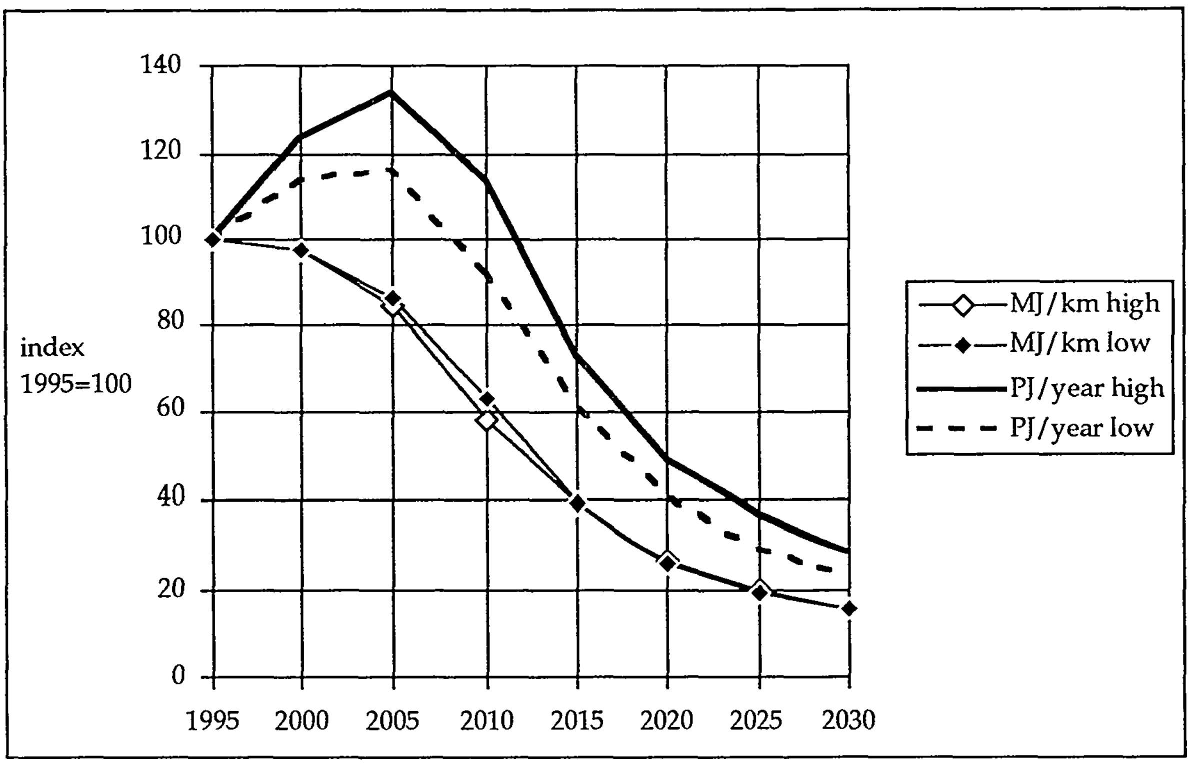

Figure 8.11. Projected development of average specific energy consumption and total primary energy consumption of the passenger car stock in conjunction with level HYP. High and low economical growth rates.

The higher economical growth rates result in higher vehicle sale rates and consequently higher penetration rates of the vehicle stock, but the effect is marginal. Also the earlier penetration on a mileage basis as compared to the stock based average (due to the higher mileage of newer vehicles) is relatively limited, the difference in penetration being generally less than a couple of years[115].

For most of the investigated Technology Levels, no fuel switch has been assumed, and therefore the impact on the CO2-emission is similar in relative terms to the development of the primary energy consumption. In conjunction with the levels including shifts to alternative fuels based on electricity off the grid - AFV1, AFV2 and HYP - the CO2-emission impacts depend on the fuel used for power generation. Figures 8.12, 8.13 and 8.14 illustrates the calculated total CO2-emissions of the passenger car stock based on the two developments of the power generation input described above.

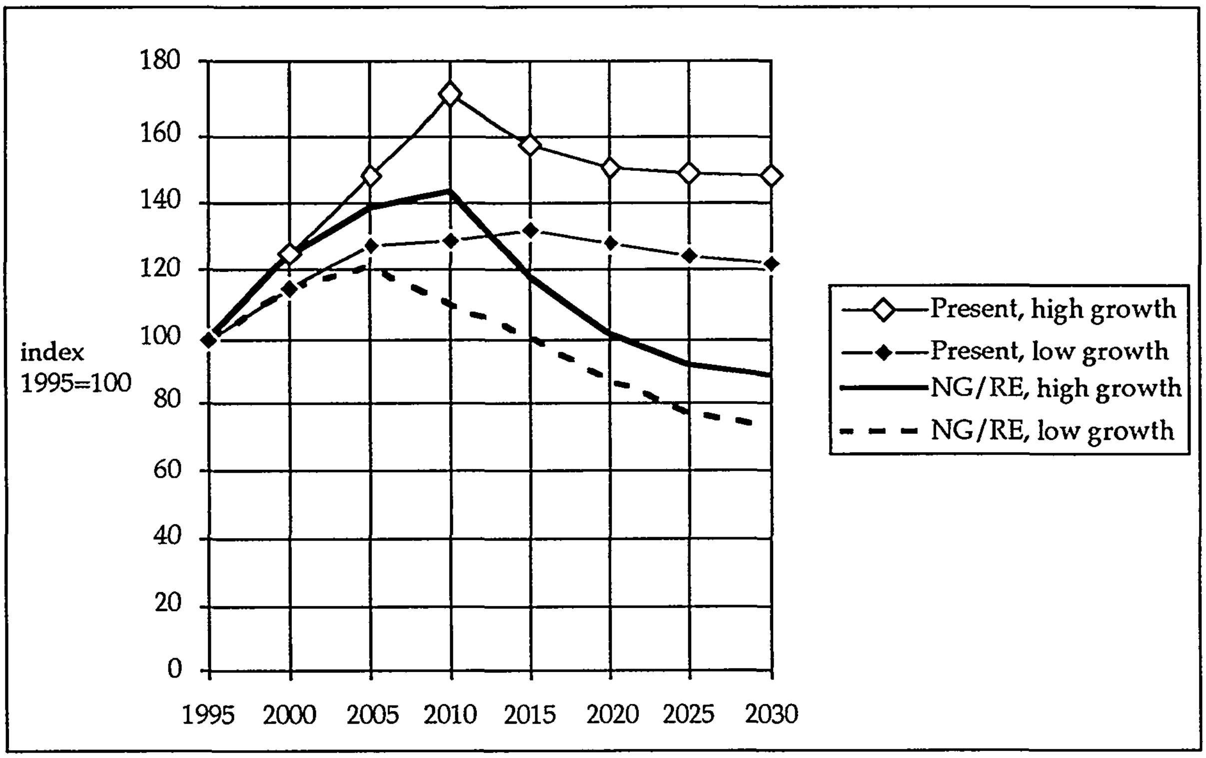

Figure 8.12. Projected development of the total CO2-emissions of the passenger car driving in conjunction with level AFV1, as 5-year interval indexes (1995=100). Present power generation fuel mix ("present") and shift to natural gas and renewable energy as described in the text ("NG/RE"). High and low economical growth rates.

The AFV1 level illustrates the introduction of electric vehicles based on the present technological level. It is a very interesting option representing a considerable reduction potential for

115 *These analyses are based on 1992 and 1993 driving patterns for passenger cars.*

a technology which is by and large ready to be introduced. However, its overall impact is limited by several factors:

- its overall penetration rate is limited to 50% of the stock due to the range limitations for these vehicles[116]
- the penetration is slow
- the impact on CO2-emissions is deteriorated for the present power generation fuel mix, and therefore it is vital to improve this in accordance with the targets of Energy 21.

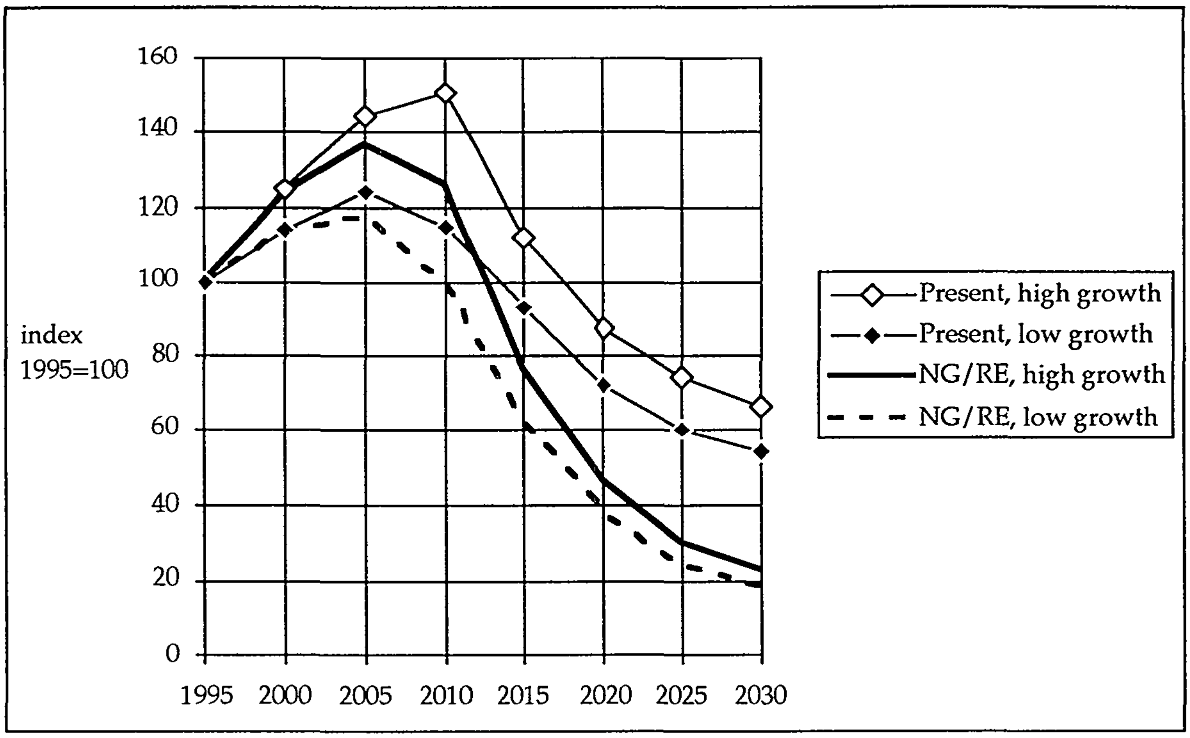

Figure 8.13. Projected development of the total CO2-emissions of the passenger car driving in conjunction with level AFV2. Present power generation fuel mix and shift to natural gas and renewable energy. High and low economical growth rates.

The AFV2 level - representing more advanced electric vehicle technologies - have a greater impact on the overall energy consumption and CO2-emissions, partly because the vehicles exploit the energy even more efficiently than the technologies applied in conjunction with the AFV1 level and partly because its greater range allows higher penetration rates. Again, the reduction potentials do not occur until the last part of the period, but the AFV2 level, combined with a shift of the power generation to natural gas and renewables, is only 6-7 years late in meeting the transport planning targets of stabilising the CO2-emissions on the 1988 level.

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116 *Indeed, a 50% penetration rate is a quite optimistic assumption given the range of 80-100 km per recharge.*

The "hypercar" (HYP) comes even closer, being less than 5 years behind the schedule, and it has even greater impact in the longer term, and in this case the energy consumption is so low that even based on a continuation of the present power generation fuel mix there will be substantial CO2-emission reductions. Even with more benign power generation technologies, it does not meet a target of reducing the CO2-emissions by a factor 15. This would require a renewable energy share in power generation of more than 80%, as compared to the slightly more than 50% in the Energy 21 projection.

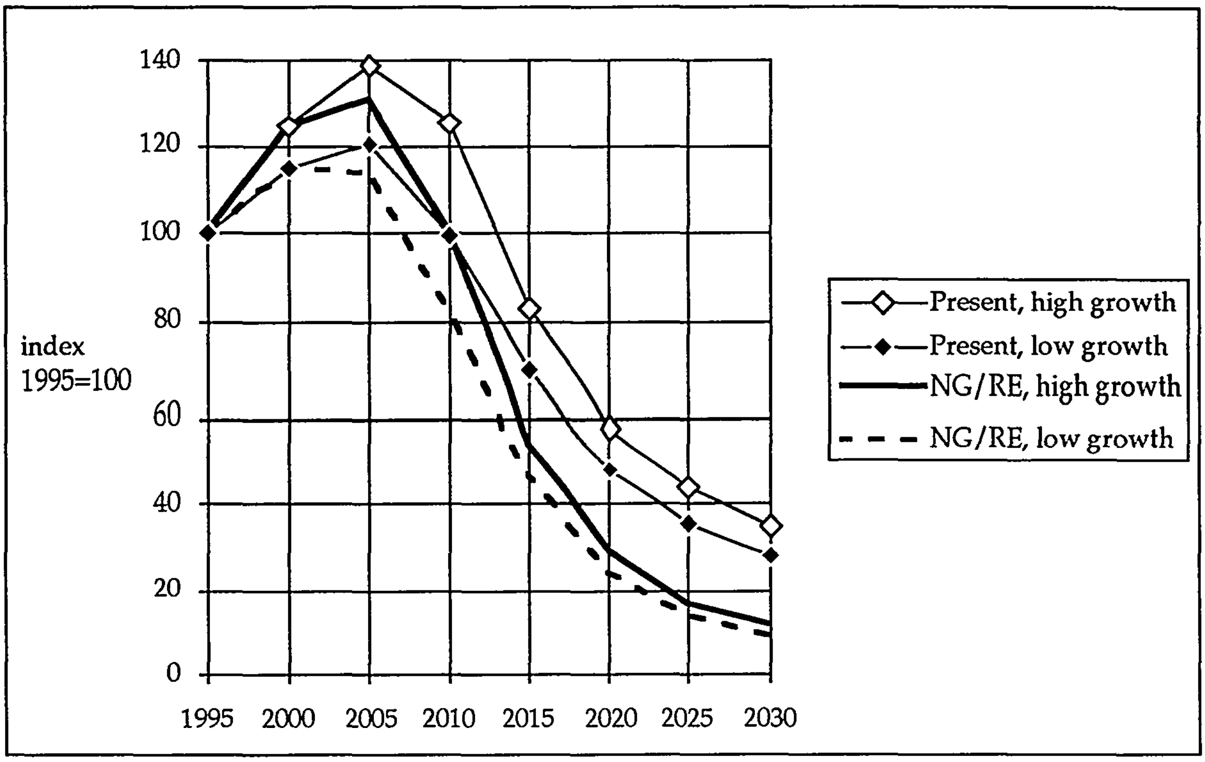

Figure 8.14. Projected development of the total CO2-emissions of the passenger car driving in conjunction with level HYP. Present power generation fuel mix and shift to natural gas and renewable energy. High and low economical growth rates.

A general feature of the seven Technology Levels is that they mainly work in the longer term and have relatively limited effects in the short term. None of them - with or without fuel switch - meet the transport planning targets for CO2-emissions in 2005. Indeed, the CO2-emissions (and primary energy consumption) are set to grow until around 2010-2015 in all seven levels. This is due to the slow penetration of these measures in the vehicle stock, but the problem is being aggravated by the nature of the transport demand growth with particularly strong growth during the first couple of decades and saturation in the longer term. Instead, the opposite pattern would be better, since the penetration of the technical improvements allow stronger growth beyond the 2010-2015 time-scale.

Any technical means for impacting the CO2-emissions in the very short term would have to be introduced without shift of vehicles and also (preferably) without substantially altering the vehicles (for instance, in the form of engine shifts). An option could be bio-fuels applied in existing engines, which could be implemented almost from day to day. However, the options are limited to a shift to rape-seed oil in existing diesel engines (roughly half of the total transport energy demand) and to adding up to 10-15% alcohol to the present gasoline engines. In addition, this option is limited by the bio-fuels available.

If the fuels are based entirely on renewable energy sources, the CO2-emissions will be reduced to zero (or close to zero). Instead, there would be land requirements to generate the renewables, as shown in Table 8.8[117].

	REF	AFV1	AFV2	HYP
Bio-fuels, ICE, km2	8000-9500	7200-8700	2700-3300	1600-2000
Bio-fuels, FC, km2	3900-4800	3500-4500	1300-1700	750-1000
Biomass-powered EV, km2	3200-3900	3000-3600	1100-1400	650-825
Photo voltaic EV, km2	65-80	60-75	20-25	13-17
Wind powered EV, km2	400-500	375-460	140-175	80-100
- GW wind power	13-16	12-15	4-5	2.5-3
Photo voltaic hydrogen, ICE, km2	400-500	400-480	150-180	85-110
Photo voltaic hydrogen, FC, km2	175-200	170-200	60-80	35-45

Table 8.8. Calculated land requirements in the year 2030 to cover the passenger car energy demand based on the present stock average (REF) and given the implementation of three Technology Levels: AFV1, AFV2 and HYP. Also, the estimated requirements to the installed power of the windmills to supply the wind based alternatives are shown. The intervals show low and high economical growth rates, whereas average figures have been used for the system efficiencies of the different energy paths (cf. Table 8.5).

This table illustrates the significance of improved efficiency even for scenarios based on renewable energy, reducing, for instance the land requirements for bio-fuels in passenger cars to 2-5% of the total area of Denmark.

[117] *Passenger cars account for roughly half of the total Danish transport energy demand.*

9 Conclusions

9.1 Transport, Traffic Patterns and Fuel Consumption

The development of the grocery sector - viewed as a case study of the large-scale introduction of the motor vehicle - is not used to explain the role of the automobile, but rather to illustrate various aspects. Grocery distribution accounts for about 12-13% of the total transport energy consumption in Denmark.

The analysis of the grocery sector indicates that there is no simple answer to the question whether the motor vehicle and the associated increase in both passenger and freight transport can be seen as a gain or loss for society and individuals. The findings of the study indicate that the transport demand of grocery distribution has increased substantially in the period from 1960 to the present: 3.7 times in the shopping transport and almost 3 times in the wholesale distribution to the shops. On top of this, any increases in the transport of imported goods must be added since only national transport is included in these results.

Thus, much more transport is required today, in spite of the fact that we consume roughly the same quantity of groceries (by both weight and costs). The transport distances in grocery distribution have grown by approximately the same factor as the travel speeds, which means that the time spent on grocery distribution is roughly the same today as 3-4 decades ago. Naturally, the development has yielded many other opportunities, e.g. much greater assortments to choose from. At the same time, however, it has eliminated other opportunities, for instance the option of shopping in the immediate neighbourhood. This probably reflects a general characteristic of the introduction of the motor vehicle: at first providing liberty and increased opportunities for those in possession of a vehicle but later, with social structures adapting to the availability of the motor vehicle, enforcing new transport patterns on all, including those without access to a vehicle. The exploitation of the opportunities that it provides further deepens the dependency on the automobile, adding to the pressures on households without car access.

Ivan Illich terms the automobile's role in modern society a "radical monopoly", i.e. a profound control of the transportation industry over natural mobility, which "constitutes a monopoly much more pervasive than either the commercial monopoly Ford might win over the automobile market, or the political monopoly car manufacturers might wield against the development of trains and buses" (Illich 1974). The radical monopoly of the automobile causes not only other firms, but entire lifestyles to disappear.

Generally, it can be concluded that the development cannot be explained either by structural factors or individual lifestyle changes. Rather, it is linked to both and these, in turn, are inter-related. On the one hand, the individual cannot choose freely - for instance, with regard to shopping patterns - when many choices are denied by the development of society. The closing down of a shop mostly is the result of marginal reductions of the turnover - frequently in the range of 10-30% - and therefore is not a majority decision.

On the other hand, many are making decisions that increase the shopping transport demand more than necessary even given the reduction of neighbourhood retail shops. In other words, the development has eliminated the choice of shopping locally but to a great extent the shopping is not even carried out in the nearest shop of those left. The hyper markets profit from this but the trend applies to many other, smaller, shop types as well. Moreover, the structural changes are influenced by behavioural changes, albeit not linked directly to the actions of the individual. Generally, a fundamental change in lifestyles has taken place in which the approach to limitations has been altered thoroughly. While in the 1950s, most people adapted their shopping demands to the options available, today such restrictions are much less accepted.

It deserves notice that the transport demand has increased on both wholesale side and shopping side. Hence, the centralisation of the retail shop structure has not resulted in shorter distribution paths from the suppliers to the shops, as could probably be expected. This is probably due to the centralisation of both manufacturing and distribution structures.

9.2 Technical Improvement - Potentials and Practical Results

There is scope for substantial reductions of the energy consumption and emissions through technical improvements of vehicles and fuel cycles. Just by choosing the most efficient models currently on the market (including down-sizing) a reduction of the average specific fuel consumption and CO_2-emissions per km by 25% can be achieved for passenger cars, provided down-sizing is accepted. Near-term improvements increase the potentials to between 30% and 60%.

Switching to different fuels can be a means to introduce cleaner fuels, not least with regard to CO_2-emissions. Notably, fuels based on renewable energy represent a very interesting option. At the same time, alternative fuels can improve the fuel cycle efficiency even based on fossil fuels. For instance, electric propulsion can reduce the specific fuel consumption of a passenger car by 25% based on the present technology and by as much as 70% if advanced drive systems are employed. If based on power from the present Danish power generation system and with the present fuel mix, the reduction of the specific CO_2-emission would be relatively small, but if the power generation system is converted to natural gas and renewable energy as projected in the energy action plan, Energy 21, the average specific CO_2-emissions could be reduced by more than 40% based on current electric propulsion technology and by about 90% based on advanced electric vehicles.

Breakthrough technologies, notably the hyper car concept advanced by Rocky Mountain Institute, could increase the savings potentials to 80-90%.

The theoretical potentials are much higher, though, particularly if the requirements regarding certain vehicle standards (comfort, performance, safety) are relaxed.

The savings potentials are generally well documented by both theoretical studies and practical studies. The hyper car targets, however, are based on computer modelling only.

Naturally, the most decisive factor regarding the future development of fuel economy is to what extent - and in which form - the hyper car is implemented. It promises not only the most radical fuel savings but also the easiest path towards these.

9.3 Barriers to Technical Improvements

The question is not whether it is possible to substantially reduce the specific energy and emission impact of transportation but whether there are barriers to this development which may delay or even stop the introduction of super-efficient vehicles - and whether the obstacles are perceived to be simple to overcome. For example, the automotive industry frequently is seen as the main obstacle due to its conservatism or even outright hostility to the new technologies.

In practice, there are barriers of different nature which means that it is probably not realistic to rely on technical improvements in every respect - such as energy efficiency, performance, costs, recyclability etc. At the very least, delays can be expected in the process. Therefore regulation is needed to promote the development, since the obstacles are more complex than simply pointing out the automotive industry as the main enemy. Also, it is unlikely that all the above-mentioned demands can be met at the same time. Therefore, a change in the image of vehicles are required to promote the efficient vehicles.

Also, the achievements - even by the hyper car - should be put into the right perspective. While it is appropriate to speak of a leapfrog technology (if the RMI projections are to materialise), it is not a different world with regard to physical properties and inter-relationships. For instance, the mass of the hyper car is not being decoupled from the other physical features of the vehicle and the hypercar will by no means eliminate the many weight related problems of conventional cars, just reduce them substantially. In practice, the weight is reduced by an impressive 50-70%, but this does not substitute the need to reduce vehicle size, motorisation etc. Likewise, the cost projections - according to which the hyper car will not be more expensive than a conventional vehicle - is highly speculative and contradicted by other informed sources (OTA 1995).

Moreover, there should be reservations in conjunction with any strategy relying heavily on "leapfrog developments" as to unexpected side-effects. While such developments may be necessary to meet the energy and environmental targets, they do not allow learning from experiences. This prevents adapting to changed circumstances and implies a risk of running into great problems - for instance, in conjunction with the large-scale introduction of composites. It is worth remembering that some of today's environmental hazards - e.g. CFCs in the 1960s - initially were introduced as "pollution free" solutions to environmental problems. There are many other examples of attempts to launch initiatives and programmes deemed as "ultimate solutions" to various problems, such as energy shortage, pollution, housing standards and congestion: the large-scale housing programmes and the traffic infrastructure programmes of the 1950s and 1960s; and the rapid shift of power plants from coal to oil in the 1950s and 1960s and back to coal again in the 1970s and 1980s - and away from coal again in the 1990's. Moreover, breakthrough developments increase the dependence on technocratical elites (Illich 1973). Certainly, the "leapfrog" should not be considered as an end, as done by Amory Lovins[118].

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118 *Lovins critises approaches allowing other solutions than leapfrog technologies, e.g. in connection with the PNGV.*

In addition, there are social and democratic problems linked to the leapfrog technologies if a very rapid introduction curve is followed. The RMI strategy underestimates - indeed, ignores - most of the problems related to the breakthrough technologies.

Furthermore, there is a long way from identifying technical improvement potentials to the actual implementation of these improvements in a commercial environment. In between, there are a variety of technical, industrial and marketing barriers that limit the share of the improvements reaching the marketplace and defer their implementation. There are three main steps towards the successful large-scale application of the hypercar (OTA 1995): demonstrating its technical feasibility; producing a mass-market vehicle at competitive costs; and selling the vehicle.

As pointed out by Lovins, any strategy for the introduction of leapfrog technologies probably needs to break with the present "steel culture" of the automotive industry. Therefore, such technologies are most likely to come from other companies than the present car manufacturers. But there are many other obstacles to the development, too. The RMI draws a parallel to the development of the computer industry, although these experiences should not as a matter of course be transferred to other industries. In any case, the development of the computer industry has taken several decades, whereas Amory Lovins expects the hypercar industry to be up and running around the change of the century.

Finally, there is a risk of idealising the present motor vehicle as the development goal thereby ignoring the further improvement potential in conjunction with different vehicle types[119]. The technological development has not necessarily provided the best vehicle in relation to the demands, and, moreover, it appears unlikely that the different demands are covered in an appropriate manner by all-round vehicles. Rather, it is important to diversify vehicles rather than focusing on out-performing specific existing vehicles. Indeed, Lovins points to the scope for product differentiation in conjunction with hypercars, but the starting point of these different products are the present passenger car (or other dominant vehicle types). In a wider perspective there are many other appropriate transport modes that tend to be excluded from the view: walking, cycling, public transport, various intermediate forms etc.

9.4 The Impact of Technical Development - Is Green Growth Possible?

In Section 9.3 it was shown that the specific energy and emission, in principle, can be reduced to a very low level, though this is not the direction the development has been in practice. Therefore, it would seem that there is a considerable scope for continuing the transport growth - in principle, for a very long time, if not forever.

Table 9.1 shows the potentials with respect to energy consumption in the long term. It can be seen that - provided the technical accomplishments are considered to be realistic - it is possi-

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119 *At the ISATA hypercar meeting in 1994 Amory Lovins critisised the "Swatchmobil" vehicle, developed jointly by Daimler Benz and the Swiss company "Swatch" for aiming at a small vehicle, since it would, according to Lovins, be possible to build a large vehicle without (significant) increases in the fuel consumption. But the Swatchmobil engineer replied that only a small vehicle would be marketable as a "green car" in Europe.*

ble to reduce the energy consumption to a very low level, even accounting for the effect of transport growth[120]. For the three Technology Levels with fuel shift, the total fossil fuel use is reduced to an even lower level if the projected conversion of the power supply to renewable energy - with more than half of the power supply being based on renewables in 2030 - is implemented.

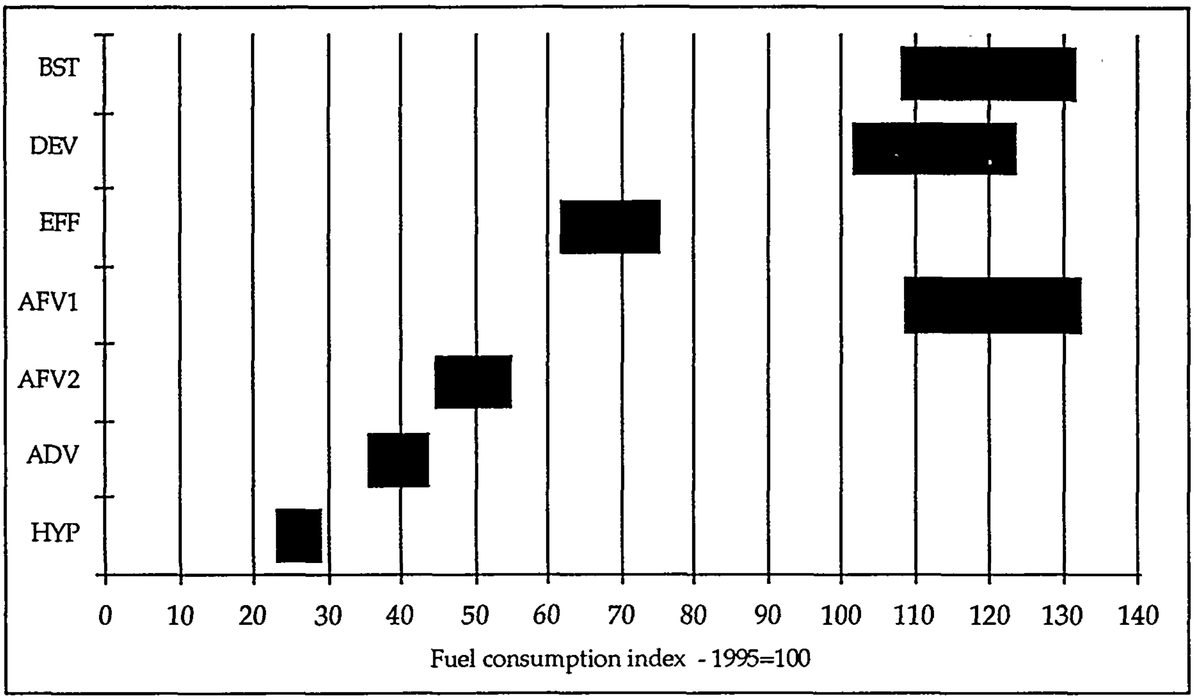

Figure 9.1. Calculated index for total fuel consumption of the passenger cars in the year 2030. The reduction potentials are based on the Technological Levels investigated in Chapter 8. The ranges illustrate the impact of different economical growth rates.

Figure 9.2 compares the technical potentials for reduction of the CO2-emissions with different reduction targets. The option of choosing more efficient vehicles among those presently available is insufficient on its own even to reach the present target of the official transport plan. Incremental changes, on the other hand, would suffice to reach the transport plan goal but hardly the general energy plan target of halving the CO2-emissions[121]. The different hypercar concepts could ensure that the target is met by the year 2030, but not even the most radical - and extremely optimistic - version of the hyper car reaches the reduction require-

120 *It should be said that the transport demand prognoses used have characteritics that are making the task easier since they operate with a saturation of the vehicle density at a relatively low level and presume that the annual mileage per vehicle will be declining beyond 2005. These prognoses are based on (Ministry of Environment and Energy 1995).*

121 *Not a binding target but rather a "sighting point" (Ministry of Energy 1996).*

ments to match the "sustainable development" target[122]. Thus, even in conjunction with the breakthrough technologies it is important that they do not substitute other measures aimed at curbing transport growth or advancing more efficient transport systems. Nevertheless, Lovins, in effect, argues against a comprehensive strategy to curb transport, in particular arguing against the application of fuel tax.

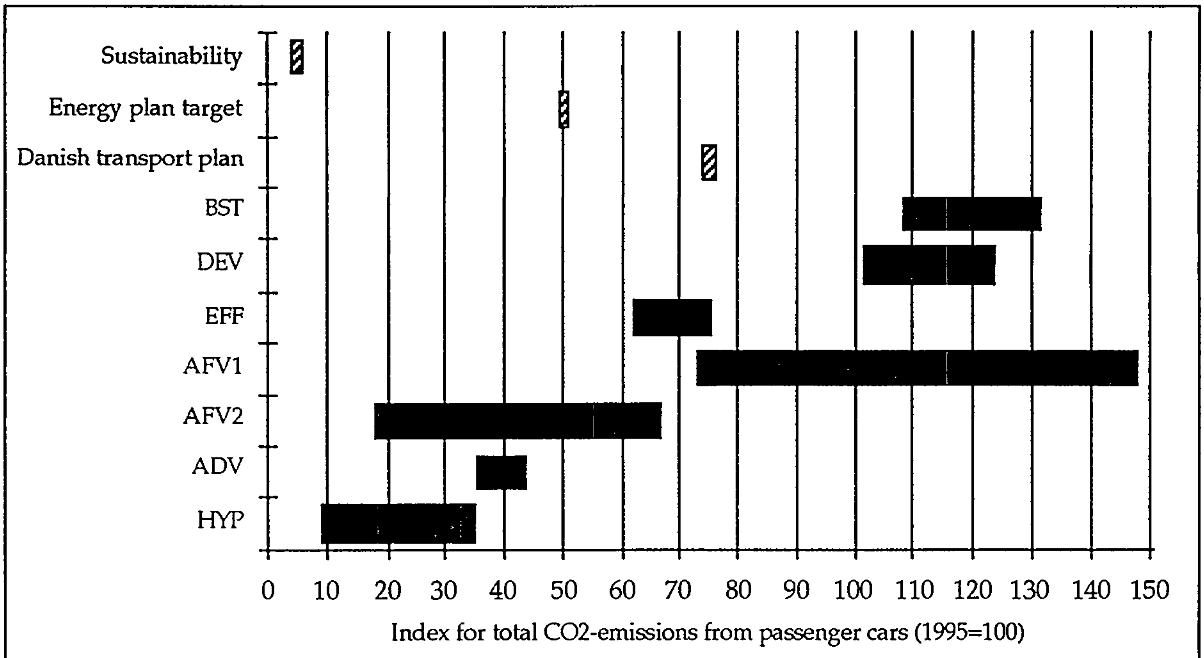

Figure 9.2. Estimated indexes for CO2-emissions in the year 2030 (black bars) and required indexes to meet different CO2-emission targets (hatched) - all in the year 2030. The reduction potentials are based on the Technological Levels investigated in Chapter 8. The reduction targets are based on the official Danish transport plan, the official Danish energy plan and the estimated development of the CO2-emissions to ensure sustainable development (see Section 3.3). The ranges illustrate the influence of different economical growth rates (see Chapter 8) and for AFV1, AFV2 and HYP, in which there is a shift of fuel, the impact of different power supply influence the ranges, too.

Secondly, the analysis indicates that the major problem is meeting the short-term targets, due to the slow penetration of the vehicle stock. Technical measures with a more rapid penetration - such as bio-fuels - have limited potentials. Therefore, it could be argued that it is particularly important to slow the transport growth during the next 1-2 decades.

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122 *Based on the following assumptions: a 50% cut in global CO2-emissions; an increase of the world transport standards to the same level as that in the industrial countries today; a doubling of the world population. See Section 3.3.*

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