Direction indirect
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9 General conclusions and reflections

9.1 Introduction

Chapter 1 discusses the aim of this thesis and the main research activities.

The aim of this thesis is to perform an integral assessment of freight transport systems, to design a prototype model based upon this integral approach and the large variety in the transport system and to assess options for medium and long term abatement strategies.

The research activities of this thesis have been:

1. Development of methodologies to calculate indirect energy requirements and indirect emissions of transport activities (and similar activities) and the collection of basic data sets.

2. Calculation of the indirect energy requirements and indirect emissions for freight transport by rail, road over the inland waterways in The Netherlands. These indirect impacts of transport are compared with the direct energy use and emissions related to driving or sailing.

3. Development of a prototype freight transport impacts model embodying the variety in the freight transport system regarding vehicle fleet and goods characteristics explicitly and which can be applied to study future strategies to reduce the direct and indirect energy requirements and emissions from freight transport. (Basic data sets derived from the research activity 1 and results from research activity 2 are inputs for the model.)

Research activities 2 and 3 have lead to the identification of successful abatement strategies aiming at the reduction of the indirect energy requirements and emissions for freight transport. These are summarised and discussed in the concluding chapter.

The research activities have been addressed in the previous chapters. Chapter 2 treats the methodologies (research activity 1). The chapters 3 till 5 inclusive deal with the calculation of the indirect energy requirements (research activity 2). Chapter 6 summarises 3 till 5 inclusive and discusses the reliability of the results as well as the organisation characteristics of the transport system which influence the results of all transport modes and the comparison among them. Chapter 7 deals with the calculation of the indirect emissions (research activity 2). Most conclusions and discussions with regard to the reliability of the results and organisation of the transport system in chapter 6 are also valid for the emission results since the analyses in both chapters are based on the same basic data sets. Finally, chapter 8 deals with the model development addressed in research question 3.

Conclusions with regard to the research activities 1 to 3 inclusive have
already been drawn and discussed in the discussion sections of the separate chapters (3.4, 4.4, 5.4, 7.4) and in chapter 6. In section 9.2, the main conclusions are recapitulated. Besides, section 9.2 focuses on the general conclusions and reflections. Next, the formulation of strategies to reduce indirect energy requirements is discussed in section 9.3. Such strategies are derived from findings in all chapters and are related to possible future developments, both technologically and logistically, on the medium-long term.

9.2 Main conclusions and observations

Research activity 1: The development of methodologies to calculate the indirect energy requirements and indirect emissions of transport activities (and similar activities).

Chapter 2 discusses the development of methodologies and reference data sets in order to calculate the indirect energy requirements and emissions of freight transport systems in The Netherlands in the year 1990. In the chapters 3 till 7 inclusive, these methodologies are applied to road, rail and water transport and the results are discussed. The following methodological conclusions can be drawn.

Conclusion 1.1
Process Energy Analysis (PEA) and Input-Output Energy Analysis (IOEA) are suitable methodologies to calculate the indirect energy requirements of transport systems.

PEA, originally developed to be applied at product level, has been applied at a relatively high aggregation level in this study. Within the context of PEA, a transport system is regarded as a collection of products. IOEA, developed on the scale of economic sectors, and Natural Capital Accounting (NCA), originally applied at the level of the Dutch national economy, is applied at a relatively low aggregation level in this study. The application of both methodologies on transport system analysis leads to satisfying methodologies and reference data sets in the first place. Next, application of the developed methodologies to rail, road and water freight transport systems leads to estimates of the indirect energy requirements by PEA and IOEA for all transport (sub)systems which correspond reasonably to good. This supports the anticipated applicability of the methodologies.

Conclusion 1.2
The structure of the emission analysis methodologies PEmA (Process Emission
General conclusions and reflections

Analysis, IOEEmA (Input-Output Energy Emission Analysis) and IOEpPEmA (Input-Output Energy product Process Emission Analysis) is suitable to calculate the indirect emissions of transport systems. However, reference data sets, for PEmA and IOEpPEmA in particular, need to be improved in order to get more reliable results for the indirect emissions of transport systems.

PEmA is derived from PEA. IOEEmA is derived from IOEA and only takes into account the energy-carrier related emissions CO₂ and SO₂. IOEpPEmA has both process and input-output characteristics. Several methodological principles incorporated in the emission methodologies are similar to those of the energy methodologies. However, application of methodologies in chapter 7 shows a wide variety in the results for the various methodologies. More detailed analyses of the results show some inconsistencies in the reference data sets. As a result, the absolute values of the indirect emissions are not very reliable. Yet, for CO₂ emissions, one should use the IOEEmA results in cradle-to-grave analyses. They are most reliable due to methodological aspects. For the other emissions, one should use the PEmA results since they are based on calculations including process and material-specific emissions.

Conclusion 1.3
The methodologies developed to calculate the indirect energy requirements and emissions of freight transport systems are not unique for transport systems but they can also be used to calculate the energy requirements and emissions of other systems, e.g. the building sector. Besides, the methodologies are not unique for freight transport but can also be applied to passenger transport. The methodological principles discussed in chapters 2 and the general analysis structure of freight transport systems, as shown in figure 2.13, can easily be converted to other systems, e.g. the building sector. However, reference data sets have to be adapted in order to analyse such systems.

In case of passenger transport analysis, both the methodology and parts of the data sets are suitable for passenger transport analysis (cf. the section in this chapter dealing with the results of the indirect energy requirements.)

Observation 1.1
One of the main advantages of the IOEA and IOEEmA methodology developed in this study is that they are less time consuming than the process-based methodologies, i.e. if the data are available in a right format. However, also PE-A and PEmA have some advantages. By use of this methodology not only system averages but also the energy requirements for separate vehicles and kilometres of infrastructure can be calculated. Besides, due to the nature of PEmA, other emissions than the energy-related emissions can be incorporated.
in PEmA while this extension is not possible for the input-output based methodologies.

Observation 1.2
Several other studies calculated the indirect energy requirements of parts of the transport systems (Intron, 1994; TFD, 1979; Stripple, 1995). These studies are all based on process energy analysis and except one, that of the Transport Research Foundation TFD (1979), deal with parts of the transport systems in various countries. The only study we are aware of which uses IOEA to calculate the indirect energy requirements is a study dealing with passenger cars by Moriguchi (1993). Moriguchi does not deal with the indirect emissions of transport. Besides this thesis, we are not aware of any other studies dealing with the indirect emissions of transport calculated based on IOEEmA.

In this study, process-based and IOE-based methodologies have been developed. By use of these methodologies both the indirect emissions and indirect energy requirements can be calculated for road, rail and inland waterways transport. The reference data sets developed are valid for (freight) transport systems in The Netherlands. The results for the different transport modes are comparable since they are based on consistent methodological principles and consistent data sets.

Research activity 2: The calculation of the indirect energy requirements and indirect emissions for freight transport by rail, road and over the inland waterways in The Netherlands.

The rail, road and water transport systems considered in PEA and IOEA include the infrastructural networks, including the construction works required for infrastructure crossings, and the vehicles fleet in The Netherlands in the year 1990. Besides, IOEA considers capital goods owned by the Dutch railways and the professional road transport sector, such as industrial and commercial buildings, internal means of transport, computers etc.

Not included in any of the calculations in rail, road or water transport is the energy embodied in the equipment for transshipment owned by other companies than the Dutch railways and the professional road transport sector, the equipment present in the harbours and industrial and commercial buildings owned by transport-supporting companies. Unfortunately, these parts of the system are too complex to be analysed in any detail. The energy embodied in these parts should be included in a full-scope analysis of the freight transport (sub)systems. At present, these parts of the system could not be analysed due to the large variety in the (sub)systems and a lack of data. However, specifically in the case of harbours, the indirect energy requirements and emissions may not be neglected.
Conclusion 2.1

The indirect energy requirements of rail, road and water transport make up a considerable part of the sum of the direct and indirect energy requirements.

The indirect energy requirements of all freight transport modes are considerable. The estimate for the indirect energy requirements of both the vehicles and infrastructure in rail transport based on PEA is 0.34 MJ/tonkm; that of road transport is 0.46 MJ/tonkm. Both estimates based on IOEA are 0.25 and 0.48 MJ/tonkm, respectively. The capital goods owned by the Dutch railways and the professional road transport sector are not included in these values. For water transport, the estimate of the indirect energy requirements is 0.27 MJ/tonkm; the vehicle’s share of this value is based on PEA, the infrastructure share is based on IOEA.

For rail transport, the indirect energy requirements make up about 45% of the sum of the direct and indirect energy requirements. For road transport and inland waterways transport, they make up about 18% and 60% respectively. For the various transport modes, the share of the vehicles in the total indirect energy requirements varies between 25% and 40%. Thus, the share of the infrastructure is always larger than 50%.

The total amount of energy embodied in the road infrastructure in The Netherlands is about 3000 PJ, that in the rail infrastructure about 100 PJ and that in the inland waterways about 300 PJ. (For Comparison: the total primary energy use in The Netherlands in 1997 is about 3000 PJ.)

All rail, road and water transport results are sensitive to depreciation rates of vehicles and infrastructure. Also, all rail, road and water transport results, except for the IOEA results of rail transport, are sensitive to assumptions with regard to transport performance of the vehicles and transport performance on the infrastructure.

Besides, rail and road infrastructure results are sensitive to assumptions with regard to the share of the embodied energy of the rail or road infrastructure allocated to freight transport. Finally, PEA results for the road vehicles are sensitive to the materials requirements for spare parts and spare tyres and IOEA results for road infrastructure transport are rather sensitive to the construction costs of roads.

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1 These percentages are calculated by comparing the indirect energy requirements to the direct energy requirements according to Bouman (1990; cf. appendix A). This is in accordance with the indirect-direct comparisons in the discussion sectors of the chapters 3, 4, 5 and 6.
Conclusion 2.2
With respect to most compounds, the indirect emissions of rail, road and water transport make up a considerable part of the sum of the direct and indirect emissions.

The emission results calculated and presented in this thesis can be considered rough estimates of the indirect emissions of rail, road and water transport. They are only rough estimates since the results among IOEEmA, PEmA and IOEpPEmA differ widely and since data sets are incomplete or inconsistent. Nevertheless, they show the importance of the indirect emissions versus direct emissions. In cradle-to-grave analyses, indirect emissions should be included. The indirect CO$_2$, CO, SO$_2$ and aerosol emissions per ton kilometre form a substantial part of the sum of the direct and indirect emissions of rail transport. The same holds for the indirect CO$_2$ and SO$_2$ emissions of road transport. The CO and aerosols emissions are higher for rail transport due to the larger steel content of the rail system and the relatively high CO and aerosols emissions resulting from the production of steel. The indirect emissions of NO$_x$ in rail and road transport are of minor interest compared to the direct emissions. For water transport, conclusions can only be drawn from incomplete analyses. In these analyses, the indirect emissions of all substances contribute significantly to the sum of direct and indirect emissions.

Generally, infrastructure emissions per ton kilometre are higher than vehicle emissions. Once again, the relatively high CO and aerosols indirect emissions of road and rail vehicles are exceptions due to the steel-related emissions.

In addition to conclusion 2.1 and 2.2
The conclusions 2.1 and 2.2 are also valid for passenger transport as demonstrated in Bos and Moll (1997; cf. box 9.1). The indirect energy requirements and emissions of passenger transport are calculated by use of the methodologies developed in this study, intermediate results of this thesis and passenger cars results from Moll (1993). Although some of the results are calculated with simpler methodologies than the ones used in this thesis, it is obvious that also in passenger transport, the indirect energy requirements are considerable.

Conclusion 2.3
Results for the indirect energy requirements and emissions are annual system averages which incorporate:

- logistic characteristics of the transport systems,
- present infrastructure construction and composition of the vehicle fleet,
- state-of-the-art of production technologies,
- present role of rail, road and water transport, and,
- present infrastructure use.
These system averages do not represent the indirect energy requirements and emissions of each single transport activity. Besides, the results represent indirect energy requirements of stable transport systems, i.e. transport systems on the medium-long term. In case major shifts in transport systems occur, the results are no longer valid.

**Conclusion 2.3a - the indirect energy requirements and indirect emissions for single transport activities differ from the Dutch averages**

Chapter 6 presented data for different transport modes and various vehicles which express the indirect energy requirements to transport one fictive ton over one kilometre. In such data, there is no impact of an average load factor like there is in the system’s averages of the transport modes. If a shipping agency transports 1 ton over 1 kilometre, the data for the fictive tons express the actual energy use better than the system averages.

Another relevant factor with respect to the actual energy use per ton kilometre is the density of the goods. The case study in chapter 8 showed that the energy use per ton kilometre strongly depends on the density of the goods. In the system’s averages of the different transport modes, the densities of the commodities transported by this mode are incorporated. In fact however, these densities are not a real feature of the transport mode but a feature of the service provided by the transport mode. Therefore, in studying the energy requirements of a separate commodity flow, one should avoid the use the average energy requirements calculated for a transport mode.

Infrastructure results incorporate logistical characteristics of the transport systems. In 1990, 67% of truck kilometres took place on the main roads, representing 4% only. The additional 96% of the network is necessary for the remaining 33% of ton kilometres. The average indirect energy requirements per ton kilometre of road transport, which amount to 0.34 MJ/tonkm, include both the relatively energy-efficient ton kilometres on the highways and the relatively energy-inefficient ton kilometres on the other roads.

Again, these energy-inefficient ton kilometres are not a real feature of road transport but a feature of the service provided by road transport. If all roads except the state roads would be replaced by railway tracks, the indirect energy requirements of road transport would decrease and those of rails would increase. If only the motorways and the transport performances on these motorways are considered, the indirect energy requirements are 0.07 MJ/tonkm.

**Conclusion 2.3b - the indirect energy requirements and the indirect emissions of (un)stable transport systems differ from the Dutch averages**

The indirect energy requirements were calculated for transport systems in The Netherlands in 1990. The transport systems are regarded as being “stable”;
calculations are based on annual average transport performances and annual average depreciations. Therefore, the results for the transport systems are valid as long as the systems are more or less stable with respect to the logistic characteristics, the manufacturing technologies, etc., i.e. on the medium-long term. As soon as major shifts in the transport systems occur, the results are no longer valid.

Box 9.1 The indirect energy requirements and emissions from passenger transport (Bos and Moll, 1997).

In passenger rail transport, indirect energy requirements account for about 20% of the direct energy requirements. In case of transport by passenger cars, indirect energy requirements account for 40% of the direct energy requirements. The vehicle’s share is 40% of the indirect energy requirements in case of rail transport and between 55 en 65% in case in road transport.

In Bos and Moll (1997), also CO, SO₂ and NOₓ emission results are shown. In case of passenger rail transport, the indirect CO emissions exceed the direct emissions. SO₂ emissions are estimated at 20%-60% of the direct emissions. NOₓ emissions are of minor importance. In case of passenger transport by cars, the indirect SO₂ emissions exceed the direct SO₂ emissions, due to the low sulphur content of gasoline. For passenger transport by cars, the direct CO and NOₓ emissions are much larger than the indirect emissions even if one assumes a 100% introduction of the three-way catalyst.
In The Netherlands, no major changes are expected to occur with regard to the freight vehicle fleets on the medium-long term. Major changes are more likely with regard to the infrastructural networks. In the next few decades, such changes are the construction of huge infrastructural projects (such as the Betuwe rail line en de High Speed rail Line), the construction of new types of infrastructure (such as underground (freight) transport) and a relatively large expansion of the infrastructural networks while the traffic intensity increases gradually. These changes and the consequences of these changes on the direct and indirect energy requirements are discussed in greater detail in subsection 9.3 and box 9.2.

**Observation 2.1**
The main allocation problem addressed in this thesis was the allocation of the indirect energy requirements and indirect emissions of infrastructure to passenger and to freight transport.

In case of rail transport, the energy embodied in the infrastructure is allocated based on a damage factor which is defined based on wagon kilometres and axis loads (cf. subsection 3.2). In road transport, construction and maintenance energy are dealt with separately. Construction energy is allocated to passenger and freight transport based on the space the passenger and freight vehicles use in real traffic. Maintenance energy is allocated to passenger and freight transport based on the damage caused by the passenger and freight vehicles. As a result, outside the built-up areas 100% and inside the built-up city 50% of the indirect energy and emissions are allocated to freight transport. In case of inland waterways transport, allocation is based on the damage caused by the passenger and freight ships. For the large waterways under concern in this study, 100% of the indirect energy requirements and emissions is allocated to freight transport.

**Observation 2.2**
The indirect energy requirements and emissions of constructions required for infrastructure crossings are included in the infrastructure results (cf. subsection 6.3). In IOEA results they are included since their investment costs are included in the investments costs of the infrastructural networks. In PEA, they are included in the production energy (cf. appendix D).

In all analyses, the construction works are allocated to the transport modes based on ownership. The indirect energy requirements and indirect emissions of the construction works should preferably be allocated to the different transport modes based on for instance vehicle passages. However, for such an allocation one needs data, such as the numbers of construction works in The Netherlands, materials balances of the construction works, etc. which are not available at present.
Research activity 3
Development of a freight transport model:
- which explicitly takes into account the variety in the freight transport system with regard to the vehicle fleet and the goods characteristics, and
- which can be applied to study strategies to reduce impacts from freight transport with regard to both direct and indirect energy requirements and emissions.

The direct and indirect energy requirements and emissions discussed as part of research activity 2 refer to average Dutch circumstances. Such averages are not representative for each specific transport activity in The Netherlands. Direct and indirect energy requirements and emissions of a transport activity are likely to differ from the average Dutch energy and emission values if:
1 for a specific transport chain the goods, vehicles and infrastructure differ from the average goods density, the average truck and the average kilometre of infrastructure under concern in the calculations which led to the Dutch average, or,
2 the actual use of vehicles or infrastructure differs from the average use in the calculations which led to the Dutch average, or,
3 the situation under concern differs from the average Dutch situation in space and time.

It is important to know how key features, such as e.g. load factors and the size of the vehicles, influence the (average) energy requirements and emissions of a transport activity. A prototype model was developed in order to study the implication of various parameter value choices regarding these features. With the model, one can analyse the influence of the specific features of the freight transport systems related to specific transport chains, specific use and specific circumstances with regard to time and space.

Conclusion 3.1
The model is helpful in distinguishing between parameters which have a large direct and/or indirect energy and emission savings potential and those which have limited potentials. Therefore, by use of the model, one can study strategies to reduce impacts from freight transport with regard to both direct and indirect energy requirements and emissions.

The model has been applied in a case study on light and heavy commodities. This case study underlined the usefulness of the model and the reliability of the model results.

With the model, one can study the energy and emission savings potential of several abatement strategies by varying the values of some model parameters. However, model calculations do not fully represent reality. The energy and
emission savings potentials calculated by the model differ from reality due to implementation barriers of the measures or due to the fact that the model is an oversimplification of reality. Additional research is required to determine whether the theoretical potential may occur in a real transport network or to determine whether changing the values of the model parameters with strong influences has high or low implementation barriers.

**Conclusion 3.2**
Model results bring out relevant differences among the various goods groups, among the various vehicle and infrastructure types, differences between direct and indirect impacts and the differences between rail and road transport with regard to both energy requirements and emissions.

These insights can not be translated to daily practise right away. Nevertheless, they support the formulation of abatement strategies. Such strategies are more thoroughly discussed in subsection 9.3.

**Observation 3.1**
Before building the model, the energy requirements of specific transport activities were expected to differ from the energy requirements for an average Dutch transport activity. After all, the specific goods transported and the specific characteristics of vehicles and infrastructure and their use differ from the average goods, vehicles, infrastructure and use. These expectations have been confirmed by the analyses conducted in the case study.

**Observation 3.2**
When the model was built, several features of the rail and road transport system were selected which were expected to dominate in the calculation of the energy requirements and emissions related to specific transport chains. These features are the density of the goods, the size of the vehicles, the size of the infrastructure, whether the infrastructure is in use for mixed traffic or for freight traffic only, the production efficiencies of the construction materials steel, iron and asphalt used in vehicles and infrastructure, the load factor of the vehicles and the average driving speed.

From the analyses conducted in the case study, one can conclude indeed that the energy and emission results strongly depend on the values of some of the selected vehicles, infrastructure and use features. The production efficiency of both steel and asphalt as well as the size of the infrastructure turn out to exert only very limited influence on the energy requirements and emissions. All other features influence the results considerably.
A comparison among transport modes

The previous chapters showed and discussed various rail, road and water transport results. Chapter 1 showed the direct energy requirements and emissions. All other chapters thoroughly discussed the indirect energy requirements and emissions. With regard to the indirect energy requirements and emissions, actually, three types of rail, road and water transport results were presented: Dutch averages (chapters 3 till 5 inclusive and chapter 7), energy requirements and emissions for different transport modes and various vehicles which express the indirect energy requirements per ton of load capacity (chapter 6) and energy requirements for several types of vehicles and types of infrastructure per physical unit (chapter 8).

In comparing the direct and indirect impacts, it was already concluded that the indirect energy requirements and various compounds of indirect emissions make up a considerable part of the sum of the direct and indirect impacts. Next, comparing the various transport modes leads to the following conclusions. The indirect impacts of road transport are generally higher than those of rail and water transport. Those of rail transport and inland shipping are more or less equal regarding the energy requirements. The transport modes order from most to less polluting with respect to direct impacts is ‘road, rail, water’. Considering both the direct and indirect energy requirements does not change the order from most to less polluting based on the direct impacts only.

However, the results for the indirect impacts include system characteristics which are not all specific for the transport modes themselves but for the service provided by the transport modes, as is the case for the direct impacts. If only the main infrastructure is considered, results with regard to the indirect impacts show that road transport may not be more or even less polluting than rail transport. With regard to the direct energy requirements, on the main infrastructure, trucks are still more polluting than trains. However, here, the differences with rail transport are considerably smaller than in case Dutch averages are considered. Real competition between rail and road transport occurs on the main infrastructure only. Taking into account the direct and indirect energy requirements and emissions and the total distances over which transport takes place in case goods are transported by trucks only or by both trains and trucks, one can conclude that intermodal transport is not always as attractive as it may seem at first. On the other hand, on the main routes, the indirect energy savings potential for rail transport seems to be larger (cf. chapter 8). Therefore, on the main routes rail transport is probably less polluting if goods flows are sufficiently large and the transport system’s capacity is optimally used.
9.3 Strategies to reduce energy requirements and emissions related to future developments

This subsection discusses strategies to reduce energy requirements and emissions. These strategies are related to possible future developments on the medium-long term. First, it discusses strategies to reduce the direct energy requirements and emissions briefly. Next, it focuses on the indirect energy requirements and emissions. Finally, this subsection discusses the consequences for the indirect energy requirements changes and the ratio between direct and indirect energy in case a considerable decrease of the direct energy requirements occurs.

Strategies to reduce direct energy requirements and emissions

For all transport modes, considerable direct energy savings and direct emission reductions can be achieved on the medium-long term. Relevant in this respect is the 'trend interruption scenario for freight transport' for The Netherlands (Trendbreukscenario Goederenvervoer; Peeters, 1993). The study reports energy savings and emission reduction potentials. Therefore, results can be regarded as upper limits for what may be achieved by the year 2015 compared to the reference year 1990. The scenario assumes 15% energy savings for rail transport and 15% energy savings for inland shipping due to technological improvements. Besides, for both transport modes, NOx emissions reductions up to 80% can be achieved due to selective catalytic reduction (SCR). For road transport, energy savings of 20% are possible. Substantial NOx emission reductions are not included in the study since they lead to higher CO2 emissions at the same time.

Logistic improvements, such as an increase of the load factors, lead to large decreases of the traffic flows for all transport modes. The vehicle kilometres for road, rail and water transport decrease by 52%, 28% and 25% respectively. A shift towards transport by less polluting transport modes leads to a decrease of the CO2 emissions by 41% and a decrease of the NOx emission by 85%.

In general, technological options alone are not expected to be able to bring about the emission reduction options desired on the long term (Trendbreuk scenario). Logistic improvements and changes in the modal shift are necessary.

Yet, this paragraph focuses on strategies to reduce emissions from road transport since, usually, these emissions are considered as being most harmful. In general, emission reduction options are less promising for freight transport than for passenger transport, especially with regard to the CO2 emissions. In the past, many efficiency improvement have already been implemented for economic reasons mainly. This resulted for example in a high function differentiation in goods transport.
However, several emission reduction options still remain. Results of a workshop published by the Centre for Energy Conservation presents several promising options for CO₂ and NOₓ emission reduction in road transport. The time horizon of the study is 2030. According to that study, 1% reduction per year can be obtained by reducing the truck’s own weight, the truck’s aerodynamics and by down sizing the engines. This option is the most promising option for CO₂ emission reduction in road transport. Some other options with a relatively large potential are the reduction of the maximum speed (0.20% per year), an increase of the utilisation factor² (savings potentials ranging from 0.35 to 0.60% per year) and a shift from goods transport over the roads to goods transport over the rails or the inland waterways (savings up to 0.20% per year). This shift is mainly realised for tons transported in international road transport. Elzen (1996) also stated that improvements based on present technologies are most promising on the short and medium-long term.

Reduction options for the NOₓ emissions correspond to a certain extent to those discussed for the CO₂ emissions. However, the largest NOₓ decline can be obtained by engine improvements and the treatment of the exhaust fumes. Some new concepts for road transport discussed in Wit (1995) and Elzen et al (1996) are the electric truck with batteries or fuel cells and fuelled by hydrogen or methanol. These concepts lead to zero emissions and low noise levels in urban areas. However, the overall energy efficiency of fuel cell trucks, i.e. the efficiency inclusive the efficiency of the fuel production, is low and the action radius of the 100% electric truck is limited. For this reason, the introduction of a hybrid truck instead of an electric truck is expected to be more likely. In general, other disadvantages of such new technologies are the loss of some load capacity.

Some alternatives fuels for diesel may be methanol, ethanol, LPG (Liquid Petroleum Gas), NG (Natural Gas), with biofuel additives and hydrogen. Methanol and ethanol contribute to a large decrease of the particulate emissions. Large NOₓ emissions reduction can be achieved by both LPG and NG. However, due to the lack of an LPG infrastructure and for refinery-related technical reasons, a large degree of penetration of these fuels is unlikely.

Finally, several studies warn against too high expectations of the introduction of intermodal transport (Wit, 1995; Rutten, 1995a, 1995 b). Reasons for this are e.g. the fact that transport by trains or ships compete with the road transport in its most efficient field, namely on the main routes, the lack of sufficient large

² Also according to other studies, an increase of the truck’s load factors seems to provide considerable scope for reducing the environmental burden of freight transport (Wit, 1995; Bleijenberg, 1996).
goods flows to maintain regular transport services by trains or ships, and the
fact that the total costs of road transport are determined largely by the costs
related to the beginning and end of the transport chain.

Strategies to reduce indirect energy requirements and emissions

As indicated, the results for the indirect energy requirements and emissions in
these chapters are annual system averages which incorporate:
• the logistic characteristics of the transport systems,
• the present infrastructure construction and composition of the vehicle fleet,
• the state-of-the-art of production technologies,
• the present role of rail, road and water transport, and,
• the present infrastructure use.
The discussion of the strategies to reduce indirect energy requirements and
emissions is structured following these categories. Strategies are derived from
the model calculations related to the case study discussed in chapter 8 in the
first place and from findings in all chapters 3 till 7 inclusive. Strategies to
reduce the indirect energy requirements and emissions may also have
consequences for the direct energy requirements and emissions.
The discussion includes the consequences for the direct energy requirements
if the strategies influence both the indirect and the direct impacts or if gains
concerning the indirect impacts may have negative consequences for the direct
impacts.

The logistic characteristics of the transport system

A large energy savings potential exists by introducing larger vehicles, in case
of the low-density goods, and by an increase of the vehicles’ load factors.
Results for the case study dealing with the transport of low and high-density
goods on the main infrastructure and presented in chapter 8 support this
conclusion. In fact, both changes result in fewer vehicles required to transport
the goods. Therefore, these changes have considerable impact on both the direct
and the indirect energy requirements and emissions. The indirect impacts are
more important for rail than for road transport since the indirect energy
requirements of rail transport make up a larger part of the total energy
requirements than those of road transport.
The energy savings potentials calculated by the model are theoretical energy
savings. Additional research is necessary to determine whether such potentials
may occur in reality. Concerning the indirect energy requirements, attention
should be given to the utilisation of the infrastructure. One model premise is an
average use of infrastructure realised in The Netherlands these days expressed
in the number of vehicles. Indirect energy requirements and emissions decrease
if the introduction of larger vehicles leads to less vehicles on the road and next, leads to an increase of the road capacity expressed in tons due to the fact that vacant road capacity is utilised by other vehicles. The indirect energy impacts remain constant if no other vehicles reoccupy the vacant capacity.

The present infrastructure construction and composition of the vehicle fleet

In The Netherlands, no major changes are expected to occur with regard to the freight vehicle fleets on the medium-long term. Major changes are most likely with regard to the infrastructural networks. In the next few decades, such infrastructural changes are:

• The construction of huge infrastructural projects.
  Two large projects under construction in The Netherlands during the next decade are the 'Betuwe rail line' and the 'High Speed rail track (HSL)'.
• The construction of new types of infrastructure.
  One of the main current issues in The Netherlands is underground (freight) transport.
• A relatively large expansion of the infrastructural networks while the traffic intensity increases gradually.
  The traffic intensities on the Dutch roads have increased gradually in recent years. Yet, very regularly, the traffic intensities on many roads exceed the intensities the roads were developed for and many traffic jams occur. During the next decade, the road network will be expanded.

These infrastructural changes influence the indirect energy requirements in The Netherlands in the following way:

• The indirect energy requirements of construction projects such as the Betuwe rail line and the HSL are much larger than the average indirect energy requirements of rail construction activities. After all, these tracks are built in areas with dense infrastructural networks and will contain many bridges, tunnels etc. (cf. box 9.2).
• New infrastructure such as underground transport may require rather energy-intensive construction activities (cf. box 9.2).
• A large expansion of the road infrastructure in a short time period leads to high indirect energy requirements during this short period. Since in the meantime, the traffic density increases moderately, the system’s indirect energy requirements per ton kilometre increase strongly. The infrastructure system is temporarily out of balance but will stabilise again in the future. Direct emissions decrease if traffic jams are resolved (or diminished) because of infrastructure expansion. Also, the direct energy requirements decrease since less fuel is wasted due to the stop-and-go traffic. However, if new infrastructure leads to traffic flows with high average speeds while before the average speed was 80 to 100 kilometres per hour, the direct energy
requirements may also increase. Outside The Netherlands, large expansions of infrastructural networks occur in growing economies such as that of Poland. Results for a case study for Poland in Bos (1997) show that the annual primary energy demand by the transport sector during the period 1990-2010 increases by about 18% if the indirect energy requirements of vehicles and infrastructure are incorporated in the analysis. This 18% increase was calculated based on average indirect energy requirements for stable transport systems and by assuming that the Dutch data for the indirect energy requirements are valid for Poland. In practise, the increase is even higher than 18% in the beginning of the period 1990-2010 due to the same reasons discussed with regard to the expansion of the Dutch network.

The state-of-the-art of production technologies

Case study results, related to the main infrastructure, show that improved production technologies in case of the production of asphalt do not lead to substantial decreases in the indirect energy requirements. However, results in chapter 4 showed that a 25% recycling rate of asphalt, a percentage which was actually realised in 1996 (VBW asfalt, 1997), leads to 20% lower average indirect energy requirements for the road infrastructure. Paradoxically, both conclusions are correct.

Since on the main infrastructure, the direct energy requirements are far more important than the indirect energy requirements, 20% less indirect energy use related to the infrastructure does not contribute considerably to overall energy reductions. However, for secondary and tertiary roads, the indirect energy requirements and emissions are much larger (due to the combination of the somewhat lower embodied energy values per road kilometre of and the far lower truck kilometres on these roads; cf. section 6.4). They form a significant part of the sum of the direct and indirect energy requirements. Consequently, the impact of higher asphalt recycling rates on the total energy requirements will be important for secondary and tertiary (and other smaller) roads. The combined effect of an increase of asphalt recycling on the main roads and the secondary and tertiary roads is incorporated in and supported by the larger impact of the recycling rates on the values for the complete Dutch road infrastructural network.

Besides, the asphalt industry improved their energy efficiency index by 5% during the period 1989-1996 (Novem, 1997). In long term agreements with the government, the asphalt industry promised an increase of its energy efficiency
Box 9.2: Indicative calculations of the indirect impacts of huge infrastructural projects and underground transport.

The indirect impacts of large infrastructural projects and transport underground are probably large. Three examples which contain rough calculations underline this statement. The examples only discuss the indirect energy requirements.

*An underground metro tube*

In Amsterdam in The Netherlands, an underground metro tube connecting the north and south of Amsterdam will be constructed. The investment costs of this construction project are about Dfl 1 billion. The related energy requirements, estimated by multiplying the investment costs by the energy intensity of the construction sector (cf. 2.5.2), amount to 5 PJ. The annual energy use by public transport is about 10 PJ (estimated based on BGC (1991) and CBS (1998)). The energy required for public transport in Amsterdam is estimated at 10% of total annual Dutch energy requirements for public transport (1 PJ). This leads to the observation that the energy required to construct this metro line requires as much energy as required for the existing public transport system in Amsterdam for 5 years.

*The High Speed rail Line*

The High Speed rail Line (HSL) is being built for passenger transport. Investment costs for this rail line are estimated at Dfl 9 billions. The related energy requirements (45 PJ) are as much as the energy required for public transport in The Netherlands during almost 5 years.

*The Betuwe rail line*

The Betuwe rail line is constructed for goods transport over a distance of about 150 kilometres. The investments costs of the rail line are estimated at Dfl 8 billions. Therefore, the energy requirements for construction of the Betuwe rail line are about 267 TJ per kilometre. This value exceeds the average energy requirements for 1 kilometre of tracks in The Netherlands about 12 times. However, the capacity of the rail track is also larger than that of an average track. Several estimates are available for this capacity. Knight and Wendling (1992) and McKinsey (1992) claim values of 25 and 30 millions of tons each year. Many authors argue that these values are far too optimistic (Meydam, 1993; Rutten, 1993).

Official government values claim values between 8 and 12 millions of tons (PKB3, 1993). Besides, based on containers flows figures (Knight and Wendling, 1992), a value of 10 millions of tons can be derived. The national environmental assessment of The Netherlands uses estimates of 19 millions of tons (RIVM, 1997).

If in accordance with the national environmental assessment, the track’s capacity is assumed to be 19 millions of tons, the average energy requirements of the Betuwe rail line are 0.35 MJ/tonkm. This value is considerably higher than the Dutch average for rail tracks (about 0.20 MJ/tonkm). Above all, the real capacity of the Betuwe rail line may be considerably lower and the Dutch average is a value based on a not optimally utilised rail network while that of the Betuwe rail line is supposed to be.
Van Wee et al. (1994) studied the CO\textsubscript{2} and NO\textsubscript{x} effects of the construction of the Betuwe rail line for several scenarios. (They consider only the impacts on Dutch territory.) Van Wee assumes 25 million tons to be transported over the Betuwe rail line or by a mix of other transport modes; they consider three alternative scenarios. The alternative scenario with most environmental benefits due to the construction of the Betuwe rail line assumes 50% of the tons to be transported by road and 50% of tons to be transported over the inland waterways. A CPB scenario considers a higher share for the inland waterways, namely 64%.

CO\textsubscript{2} emissions related to the construction of the Betuwe rail line can be estimated based on the investments costs and the emission intensity of the construction sector (cf. 2.6). In case of the most environmentally friendly alternative scenario considered by Van Wee, 12 years of the CO\textsubscript{2} earnings of the Betuwe rail line are required for the construction of tracks. In case of the CPB scenario, the construction of tracks requires even 40 years of the CO\textsubscript{2} earnings of the Betuwe rail line.

Of course, the three examples are based on simplifications and some rough estimates. They are intended to be indicative only. However, they strongly indicate that the indirect impacts of such projects are large.

By the year 2010, the energy requirements for the manufacturing of iron and steel plates will have been reduced by 15% to 20% compared to the energy requirements of 1990 (Heijningen, 1992a; Gielen, 1997). However, a decrease of the manufacturing energy of steel does have limited influence on the indirect energy requirements of the vehicles for all transport modes. This statement is supported by both the case study results and by the sensitivity analyses results in the chapters dealing with the indirect energy requirements and emissions for the various transport modes. Strategies to reduce the indirect energy requirements from freight transport should therefore not focus primarily on the manufacturing energy of steel and steel plates etc.

An increase of the recycling rate of tyres has considerable influence on the indirect energy requirements and emissions from road vehicles (cf. subsection 4.3). For 1990, this study assumed that 35% of the tyres were recycled as material and 25% of the tyres were recycled as useful products. If one assumes that the remaining 45% is recycled as material as well, the indirect energy requirements and indirect emissions of the road vehicles decrease by 15% to 20%. To reduce the indirect energy requirements of the road vehicles, it is a good strategy to focus on the indirect energy requirements and indirect emissions of the tyres. However, the impact of this strategy is limited on the
level of the whole road transport system. After all, the indirect impacts of the vehicles make up a rather small share of the total direct and indirect energy requirements of road transport.

The infrastructure use

At present, infrastructure is constructed for mixed freight and passenger traffic mainly. Case study results show that by introducing infrastructure for freight transport only, considerable amounts of energy can be saved especially in the case of rail transport. These savings are explained by a large increase in the infrastructure’s capacity due to homogeneous traffic flows. In the case study, the introduction of road infrastructure for freight transport only shows a small decrease in the overall energy requirements. Besides, equal results were shown for the introduction of road infrastructure with more than two lanes. Both results are explained by the large share of the direct energy requirements and emissions for road transport. If one focuses on the decrease of the indirect energy requirements and emissions related to the infrastructure only, one observes that this decrease is considerable (and thus, the reduction options relevant). For road transport, under circumstances in which the share of the indirect energy requirements is larger, infrastructure for freight transport only or more-lanes infrastructure may contribute considerably to energy savings also. This may hold for the main infrastructure if the direct energy requirements and emissions diminish due to e.g. motor energy efficiency improvements, abatement technologies or a reduction of the maximum speed. Case study results showed that a decrease of the average speed on the main infrastructure has a large energy savings potential.

Cautiousness is due in drawing the conclusion that infrastructure for freight transport only is the best starting point for a decrease of the indirect energy requirements and emissions related to the infrastructure. The capacities and maintenance consequences related to this option and assumed in the model are based on very little experiences with infrastructure suitable for freight transport only. Such infrastructure has hardly been constructed until now. Therefore, model input data are based on expert estimates instead of realisations. Nevertheless, results suggest that separate freight infrastructure is a promising strategy in order to diminish indirect energy requirements and emissions. Induced by traffic jams problems, this option got some attention during the last decade in The Netherlands. Some truck lanes were constructed and the best known example of rail tracks constructed for freight transport only is of course the Betuwe rail line. However, for this specific case, it is doubtful if any (indirect) energy savings may occur due to the construction of infrastructure suitable for freight transport only (see box 9.2).
Finally, like stated in the paragraph dealing with the logistic changes, one should be aware of the fact that, in practise, the energy savings potential will only be realised in case the capacity of the tracks and roads constructed for is actually utilised. This is less likely in the case of secondary and tertiary roads than in case of the main infrastructure.

Another development in infrastructure use these days influencing the indirect energy requirements of the road infrastructure is the introduction of the tyres wider than those generally used until now. One such tyre generally replaces two standard truck tyres. The use of these tyres leads to more road damage since the contact area of the truck with the road decreases. Molenaar (Volkskrant, 1995) calculated that the asphalt construction layers should be 4 cm thicker in order to compensate the increase in the use of these tyres and the increase of the average mass of the trucks on the roads.

A 4 cm increase results in an increase of the average energy requirements by about 5%. However, using these "wide tyres", the truck’s indirect energy requirements decrease. And so do the direct energy requirements due to the smaller contact area with the road. Beforehand, it is not clear what the overall impacts will be of the introduction of the "wide tyres".

Finally, infrastructure results are sensitive to the values of the lifespan of the infrastructure and the transport performances on the infrastructure (cf. the subsections 3.2, 3.3, 4.2, 4.3 and 5.2). An increase of the lifetime or an increase of the transport performances on the infrastructure, which in fact both means a better exploitation of the infrastructure, leads to considerably lower indirect energy requirements and emissions. Therefore, a better exploitation of the capacity available should be stimulated. In The Netherlands, the traffic intensities on the roads virtually daily exceed the intensities the roads are developed for. Regularly, traffic jams occur. However, even on such roads, the infrastructure’s capacity is not fully exploited during large parts of the day. A better exploitation, e.g. during hours late in the evening and during night, will lead to lower average indirect energy requirements and emissions per vehicle kilometre or ton kilometre in spite of the fact that the total indirect energy requirements and emissions per infrastructure kilometre increase. The relation between the number of vehicles and the energy required for production and maintenance is non-linear. On roads, the truck intensity mainly determines the thickness of construction layer and not the maintenance energy requirements (cf. table 8.5).

Lower direct emissions of trucks; the consequences for the indirect emissions
The direct emissions of trucks will decrease in future. In the year 2000, the so-called euro III emission norms are probably realised; in 2005, the euro IV
norms may be realised. For the compounds CO, NO\textsubscript{x}, C\textsubscript{y}H\textsubscript{z} and the particulates, these euro IV norms mean that by the year 2005, the emissions per vehicle kilometre of newly built trucks will have been reduced 6 to 10 times dependent on the compound and since 1990. Since 1990, the energy requirements of trucks have not decreased (Dings, 1996; Waters, 1990). Up to 2005, they probably will not decrease also due to the severe NO\textsubscript{x} emission norms proposed and the negative impacts of reducing the NO\textsubscript{x} emissions on the energy use.

If the direct emissions of trucks decrease, the indirect emissions of the infrastructure will also decrease. After all, a considerable part of the indirect energy requirements of the infrastructure is connected with the transport of infrastructure materials by trucks. In case of roads, the share of the road’s total energy requirements required for the transport of asphalt and bed materials is estimated at 30\%. The remaining 70\% is related to the production of asphalt and related to road construction. Due to a decrease of the direct emissions, the indirect emissions of the infrastructure will also decrease. However, the indirect infrastructure emissions will make up a larger part of the total emissions of road transport. And so will the indirect energy requirements of the vehicles. Consequently, in future, the role of the emission reduction strategies concerning the indirect emissions will become more important. In case of rail transport, the indirect energy requirements of the rail tracks decrease. Consequences for the direct energy requirements depend on developments with regard to the direct emissions connected with the use of diesel and the production of electricity.

**Summarising**

This section discussed strategies to reduce direct energy requirements briefly and next, focused on emissions and strategies to reduce the indirect energy requirements and emissions. Some of the strategies, such as an increase of the load factor or the use of larger vehicles, are strategies by which both the direct and indirect impacts decrease. However, some other strategies, such as the construction of new infrastructure in order to reduce traffic jams and the energy use and local emissions due to the stop-and-go character of the traffic, lead to an increase of the indirect impacts.

Studying the strategies to reduce indirect impacts, one can conclude that more energy savings can be achieved by strategies related to the infrastructure than by strategies related to the vehicles. Regarding the infrastructure, a better exploitation, the introduction of main infrastructure suitable for freight transport only (in case freight flows are sufficiently large to utilise the full capacity) and an increase of asphalt recycling have quite a large energy savings potential.

Studying these strategies combined with strategies to reduce the direct impacts, one can conclude that for the road main infrastructure, strategies to reduce the direct impacts are most promising, although also strategies to reduce the indirect impacts are worthwhile considering. In case of the secondary and
tertiary roads and for rail transport, both strategies to reduce the direct and indirect impacts are relevant.

9.4 Overall conclusions, reflections and recommendations

- Relevance of the indirect impacts from freight transport

The average indirect energy requirements of all transport modes are considerable compared to the direct energy requirements. Generally speaking, the average indirect emissions are also considerable. The share of the indirect emissions in the total emissions depends on the compound and the transport mode. The indirect impacts of (freight) transport should be considered in energy policies on the medium-long and long term since they make up considerable parts of the total impacts and since they are likely to increase in future. The indirect impacts of freight should also be considered in energy policies on the medium-long and long term in case society wants to achieve a large decrease in energy use and emissions.

An important development in The Netherlands is the expansion of the existing infrastructural networks to resolve traffic jams. Due to the construction of new infrastructure, the direct impacts may decrease. However, the indirect energy requirements will increase. Another important development is the planned construction of large infrastructure works (the Betuwe rail line and the High Speed rail line) and transport systems underground. Large amounts of energy are required for such construction works. The indirect impacts of (freight) transport will increase due to the construction of such projects. The relative share of the indirect impacts in the total impacts of (freight) transport will increase even more since the direct impacts of transport decrease due to further sharpening emission standards.

An energy decrease by the transport sector by a factor 4 as discussed in Van Veen et al (1998) or even a factor 20 as discussed is DTO (1997) is not possible if the focus is on the direct impacts only. In case the direct energy requirements are decreased by a factor 10, in other words 90%, the cradle-to-grave energy and emissions are far less than 90%. After all, the indirect energy requirements make up 20% to 60% of the direct energy requirements (depending on the transport mode). Assume the indirect energy requirements to be 60% of the direct energy requirement, and assume the direct energy requirements to be reduced by 90%, then the cradle-to-grave energy requirements are reduced by 56% only (56%=100-((1.0x0.1+0.6))/(1.0+0.6)x100%).
Conclusion: The indirect impacts of freight transport should be considered in energy policies on the medium-long and long term since they make up a considerable part of the total impacts of freight transport and since they are likely to increase in future.

- Direct and indirect impacts; a comparison among transport modes

Generally, the average indirect impacts of road transport are the largest. Those of rail transport and inland shipping are somewhat lower and more or less equal regarding the energy requirements. The transport modes order from most to less polluting with respect to direct impacts is 'road, rail, water'. Considering both the direct and indirect energy requirements does not change the order from most to less polluting based on the direct impacts only.

However, for parts of the transport system, this order can be discussed. On the main infrastructure, it is not very clear yet if the overall impacts are in favour of rail or road transport although it may still favour rail transport (cf. at the end of section 9.3). A detailed analysis is required to determine the overall impacts. This observation concerning rail and road transport is relevant since real competition between rail and road transport occurs on this main infrastructure.

Conclusion: Generally, the transport modes order from most to less polluting based on the direct impacts only (road-rail-inland shipping) does not change if one considers both direct and indirect impacts. However, this may not be the case for specific parts of the transport system or for certain emission compounds.

- Methodologies to calculate the indirect impacts from freight transport

PEA and IOEA are suitable methodologies to calculate the indirect energy requirements of freight transport. The structure of PEmA, IOEEmA and IOEpPEmA is suitable to calculate the indirect energy requirements of freight transport. However, reference data sets, for PEmA and IOEpPEmA in particular, need to be improved in order to get more reliable results for the indirect emissions of transport systems. Improvement of these data bases is highly recommended. Nevertheless, the emission results presented in this study can be considered rough estimates.
The methodologies developed to calculate the indirect energy requirements and emissions of freight transport systems are not unique for transport systems but can also be used to calculate the energy requirements and emissions of other systems, e.g. the building sector. Besides, the methodologies are not unique for freight transport. They can also be applied to passenger transport. Conclusion: Suitable methodologies are available to calculate the indirect energy requirements and indirect emissions of the freight transport system and similar systems. However, in order to get more reliable emission results, reference data sets need to be improved.

- The variety in the freight transport system

An important observation is that the indirect impacts of parts of the transport systems may differ strongly from the system’s averages. E.g. vehicles with a small load capacity have relatively large indirect energy requirements. Similarly, for secondary and tertiary roads, the indirect impacts are much larger than for the main roads. This variety should be considered explicitly in studying transport flows and their related energy requirements and emissions and in formulating strategies to reduce the impacts from (freight) transport.

Several strategies are available to reduce the direct and indirect impacts of freight transport. Some strategies, such as an increase of the load factor or the use of larger vehicles, are strategies by which both the direct and indirect impacts decrease. However, some other strategies, such as the construction of new infrastructure in order to solve traffic jams and reduce the direct energy requirements lead to an increase of the indirect impacts.

Strategies to reduce the indirect impacts are more related to the infrastructure than to the vehicles. Examples of promising reduction strategies are a better exploitation of the infrastructure, the introduction of main infrastructure suitable for freight transport only (in case freight flows are sufficiently large to utilise the full capacity) and an increase of asphalt recycling. Which strategies are most promising may differ for the different parts of the transport system and for different goods groups. E.g., on the main infrastructure, strategies to reduce the direct impacts are most promising. In case of secondary and tertiary roads and for rail transport, strategies to reduce the direct as well as indirect impacts are relevant.

Impacts of strategies to reduce the impacts of freight transport discussed in this thesis include technical theoretical potentials. However, the real potential for change does not only depend on the physical potential. Economic, psychological and institutional aspects are relevant too (Noorman et al, 1998).
Conclusion: The variety of the freight transport system should be considered explicitly in studying transport flows and their related energy requirements and emissions and in formulating strategies to reduce the impacts from (freight) transport.