Direction indirect
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8 Modelling the energy and environmental consequences of freight transport

8.1 Introduction

Most values presented in the preceding chapters concern direct and indirect energy requirements and emissions referring to average Dutch circumstances, i.e. they are based on the existing vehicle parks, average load factors for the vehicles, the shared use of the infrastructure by passenger and freight transport, the commodities transported by the freight transport sectors, etc.

Knowledge of the average values presented for rail, road and water transport is useful in studying importance of indirect energy requirements and indirect emissions in relation to direct energy requirements and emissions. However, these averages are not representative for each specific transport activity. For instance, for a fully-loaded wagon of iron ore, the direct energy use per ton kilometre is lower than the Dutch average for rail transport. Thus, variance in the averages not only depends on the sensitivity for certain assumptions (this is the only variance discussed thus far) but also on underlying factors.

Three groups of underlying factors are distinguished and analysed. 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’ density, 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, which may be e.g. load factors and the size of the vehicles, influence the (average) energy requirements and emissions of a transport activity.

This part of this freight transport study identifies such features. A model has been developed in order to study the implication of various parameter value choices regarding these features. With this EEFT model¹, one can analyse the influence of the features of the freight transport systems related to specific transport chains, specific use and specific circumstances with regard to time and

¹ EEFT = Energy requirements and Emissions from Freight Transport.
space. Besides, with this model, one can analyse the impacts of new infrastructure. Also, the model can be helpful in developing main infrastructure.

PEA and PEmA results are required in order to build the model since they contain data for physical units, such as vehicles and kilometres of infrastructure. PEA and PEmA results are available for the rail and road transport system. Unfortunately, they are not available for water transport, i.e. they are available for the boats but not for the infrastructure. Therefore, the model includes the rail and road transport system but not the water transport system.

Section 8.2 discusses the basic elements and the structure of the model. Section 8.3 discusses the basic data sets and some formulas to derive these data sets. Next, in 8.4 a case study on ‘heavy and light commodities’ is presented as a model application. Section 8.5 draws conclusions with regard to the utility of the model and with regard to the relevant elements that need to be distinguished in energy and emission calculations for specific freight transport chains.

8.2 A model to calculate the energy requirements and emissions related to a specific transport demand

8.2.1 Basic elements of the EEFT model

Several features of the rail and road freight transport system are expected to dominate heavily in the calculation of the energy requirements and emissions related to specific transport chains. Such features concern the goods characteristics, the vehicles, the infrastructure, the production efficiencies of construction materials and the trip characteristics. They are supposed to be relevant in modelling the energy requirements and emissions of specific transport chains and are discussed below.

TRANSPORT SYSTEM FEATURES

Goods characteristics

Goods can be specified by their density (= mass/ volume ratio), hazardousness, perishableness, etc. (van Witsen et al, 1992). Many different types of freight transport vehicles have been designed for the transport of specific products. This specialization concerns the distinction between vehicles

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2 The EEFT model is a spreadsheet model and an in-house version. Since some instructions are still needed, the model is not yet ready for general distribution to outside users.
suitable for the transport of bulk products and vehicles suitable for the transport
of chemicals (or other special products) and the distinction between vehicles
suitable for the transport of heavy and light commodities. For heavy and light
commodities, the volume mass ratio differs strongly. If transported by the same
vehicles under the same circumstances, the direct energy use per ton kilometre
for heavy and light commodities is different since the direct energy use and the
emissions per vehicle kilometre depend more on the vehicle’s speed than the
vehicle’s mass.

**Vehicles**

Both small and large vehicles are used for freight transport. The choice for
the size of the vehicles depends on the amount of goods to be transported along
a certain route and the density of the goods. The energy use per tonkm for the
same goods transported by small or big vehicles (ceteris paribus) is different
due to the limited influence of the vehicle’s mass on the vehicle’s energy use
and emissions.

**Infrastructure**

Generally, infrastructure is constructed for the shared use of passenger and
freight transport. Characteristics of the construction (e.g. the thickness of the
asphalt layer) depend on both the numbers of vehicles and features of these
vehicles such as axis loads. Thus, the indirect energy requirements and
emissions related to the infrastructure also depend on these numbers and the
vehicles’ characteristics. Infrastructure constructed for passenger and goods
transport separately results in different indirect energy use and emissions.

**Production efficiencies of construction materials**

Steel plays a dominant role in the construction of rail and road vehicles and
rail infrastructure. Asphalt plays a dominant role in the road infrastructure.
The production efficiencies of these materials may therefore strongly influence
the indirect energy requirements of the transport systems.

**Trip characteristics**

The most relevant trip characteristics in relation to the energy use and
emissions are the driving speed of the vehicles, the load factors of the vehicles
and if the complete transport chain is studied, the number of empty trips.

**MODEL DESCRIPTION**

The model is an instrument by which direct and indirect energy requirements
and direct and indirect emissions of rail and road transport can be calculated on
the basis of explicit assumptions concerning transport demand and some trip
characteristics. The model distinguishes several types and sizes of vehicles,
several types of infrastructures and several goods groups and types of
containers.

The model concentrates on the main infrastructure. Generally, at least two
transport modes are available on the main routes. The model concentrates on the transport of containers in order to simplify calculations and to make rail and road transport results easier to compare. The capacity of vehicles is expressed in both the maximum number of containers and the maximum amount of tons of goods.

The transport demand is expressed in the numbers of tons T of goods G to be transported over Distance D by vehicle type V over infrastructure type I. In the model, tons of goods are translated into numbers of containers. The trip characteristics distinguished are speed, load factor and the number of empty trips.

Transport demand and trip characteristics have to be specified by the model user. In fact, the modal input to be defined by the user reflects aspects of the transport system which can be influenced by the shipper or transport organisations. (An exception is formed by the infrastructure choice for which public policy interference is necessary.)

**MODEL INPUT**

*Transport demand*

The transport demand to be fulfilled is expressed in tons T of goods G over distance D by vehicle type V over infrastructure type I.

*Trip characteristics*

Trip characteristics distinguished are speed, load factor and the percentage of empty trips.

*Goods*

The model distinguishes the NSTR commodity groups (van Witsen et al, 1992). The NSTR classification is an international classification which consists of ten main commodity groups. It uses a 1-, 2-, 3- and 4-digit division of the ten commodity chapters. The more digits, the more specific the commodity classification. Table 8.1 shows descriptions of these ten groups.

The NSTR commodity groups can be characterised by features such as density, hazardousness, perishableness, etc. The model focuses on one single feature: the density.

*Containers*

The model distinguishes between 20ft and 40ft containers. The 20ft containers are most suitable for the transport of goods with a high density, i.e. high mass/volume ratio, or in other words heavy goods. The 40ft containers are suitable for the transport of goods with a low density or voluminous goods. The 'maximum load / maximum volume - ratio' (MaxLoad/MaxVol-ratio) expresses
Modelling the energy and environmental consequences of freight transport

Table 8.1 Description of the 10 main NSTR commodity groups (van Witsen et al, 1992).

<table>
<thead>
<tr>
<th>NSTR category</th>
<th>Description NSTR commodity groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Agriculture products and live animals</td>
</tr>
<tr>
<td>1</td>
<td>Foodstuffs</td>
</tr>
<tr>
<td>2</td>
<td>Solid mineral fuels</td>
</tr>
<tr>
<td>3</td>
<td>Crude petroleum and petroleum products</td>
</tr>
<tr>
<td>4</td>
<td>Ores and iron steel waste</td>
</tr>
<tr>
<td>5</td>
<td>Metal products</td>
</tr>
<tr>
<td>6</td>
<td>Minerals and building materials</td>
</tr>
<tr>
<td>7</td>
<td>Fertilizers</td>
</tr>
<tr>
<td>8</td>
<td>Chemical products</td>
</tr>
<tr>
<td>9</td>
<td>Transport equipment, machinery, miscellaneous articles</td>
</tr>
</tbody>
</table>

this specialisation of the containers. The MaxLoad/MaxVol-ratio is 0.73 for a 20ft and 0.41 for a 40ft container.

Vehicles
The model distinguishes between vehicles of different sizes suitable for the transport of containers. Some of these vehicles are specialised for the transport of commodities with low and high densities. The vehicles considered are:

For road transport
1 A 20-tons truck.
2 A 40-tons tractor with semitrailer.

For rail transport
1 A 200m-container-train specialised in the transport of commodities with a low density.
2 A 200m-container-train specialised in the transport of commodities with a high density.
3 A 500m-container-train specialised in the transport of commodities with a low density.
4 A 500m-container-train specialised in the transport of commodities with a high density.
Infrastructure
The model focuses on main infrastructure for rail and road transport used by both passenger and freight transport as well as infrastructure used by freight transport only.

The infrastructure types distinguished are:

For road transport
1. Two-lanes road used by both passenger and freight transport.
2. Four-lanes road used by both passenger and freight transport.
3. Two-lanes road used by freight transport only.
4. Four-lanes road used by freight transport only.

For rail transport
1. One-track rail infrastructure used by both passenger and freight transport.
2. Two-tracks rail infrastructure used by both passenger and freight transport.
3. One-track rail infrastructure used by freight transport only.
4. Two-tracks rail infrastructure used by freight transport only.

MODEL OUTPUT

Energy requirements and emissions
The model calculates the direct and indirect energy requirements and the direct and indirect emissions of SO₂, CO, NOₓ, VOC and aerosols into the atmosphere that result from the transport of goods. The emissions distinguished are emissions for which transport activities attribute significantly to national emissions and for which both direct and indirect emission figures are available. CO₂ emissions are not calculated. In chapter 7, it was discussed that indirect CO₂ emissions calculated based on PEmA are not very reliable. However, PEmA results are the only suitable results with respect to the structure and purpose of the model. Calculation of the indirect CO₂ emissions based on IOEEmA, which was indicated as the most reliable methodology to calculate the indirect CO₂ emissions, is not an alternative methodology with this respect. After all, based on the IOEEmA methodology, only average fleet values can be calculated while the model distinguishes the separate vehicles explicitly.

Since based on PEmA, no reliable indirect CO₂ emissions can be calculated, CO₂ emissions are not incorporated in the model. However, energy requirements and CO₂ emissions are strongly related. Therefore, the energy requirements may be regarded as CO₂ emissions indicators.

8.2.2 The structure of the EEFT model

Figure 8.1 shows the structure of the model and the required input data. The input of the model is a specification of the transport demand, some characteristics of the container load and some trip characteristics. The model
output concerns the direct and indirect energy use and direct and indirect emissions (cf. subsection 8.2.1).

The main module of the model consists of three sections. The three steps of the main module of the model are outlined below. Next, the structure of the modules 1, 2 and 3 is discussed shortly. Results of these modules form input tables for the main module. More detailed information with regard to the modules 1, 2 and 3, such as underlying data sets, assumptions made and formulas used as well as the final data sets resulting from these modules is discussed in section 8.3.

Model sections

1 The numbers of 20ft and 40ft containers and the containers' load are calculated based on:
   a the number of tons T of goods G to be transported (model input data),
   b the share of 20ft and 40ft containers (a combination of model input data and results of module 1),
   c the load factor of the containers, i.e. average or maximum (model input data), and,
   d the mass of average-loaded or maximally-loaded 20ft and 40ft containers carrying goods G (results of module 1).

The average load of a 20ft or 40ft container is derived from values found in everyday practice (Rutten, 1995). The maximum load of a 20ft or 40ft container is determined by the volume of the containers, the maximum load of the containers and the volume mass ratio of the goods. The mass of the container loads and the total tons to be transported determine the total number of containers.

2 The loaded and unloaded vehicle kilometres are calculated based on:
   a the number of containers to be transported (results of section 1),
   b the vehicle choice, i.e. the transport mode and the vehicle choice (model input data),
   c the distance D over which the goods need to be transported (model input data), and,
   d the percentage of empty trips (model input data).

The number of containers per vehicle is determined by either the maximum number of containers which can be carried by the vehicle or the mass of the containers. The number of containers per vehicle determines the number of vehicles required to transport all containers.

3 The direct and indirect energy requirements and indirect emissions are calculated based on:
   a the number of loaded and unloaded vehicle kilometres (results of section 2),
   b the indirect energy requirements and indirect emissions of the vehicles and
Figure 8.1 The structure of the freight transport model EEFT.
infrastructure of choice expressed per vehicle kilometre (module 2),
c the direct energy requirements and emissions which are derived from the
mass of vehicles and load (results of section 2-1), the average speed of the
vehicles (model input data) and some basic formulas in which vehicles
characteristics are incorporated (results of module 3).
Both the energy and emissions related to vehicles and infrastructure are
calculated based on vehicle kilometres. For vehicles, the lifetime is simply
expressed in vehicle kilometres. For infrastructure, the vehicle kilometres are
a multiplication of the infrastructure’s capacity in vehicles per hour and its
lifetime expressed in hours.

**MODULE 1: the container shares and container load characteristics.**
The module 1 calculates the mass of average-loaded and maximally-loaded 20ft
and 40ft containers carrying goods of type G and the share of 20ft and 40ft
containers in transporting goods of type G as found in practice (cf. figure 8.2).
The groups of goods distinguished are groups based on the international NSTR
classification (cf. table 8.1 and Van Witsen et al, 1992). Each group is
characterised by the density, i.e. the ratio between volume and mass.
The volume and maximum load of a 20ft and 40ft container and the density of
the goods determine the maximum load of a 20ft and 40ft containers. Either the
volume or the mass of the goods determines the maximum load of the
containers.

The calculation of the average load of 20ft and 40ft containers carrying
goods of type G is more complicated. The average load of containers with
goods G is known but these loads are not known for 20ft and 40ft containers
separately. Therefore, the average loads of 20ft and 40ft containers are
calculated based on the average container load (ACL) of all containers as found
in practice (Rutten, 1995) and the container partition coefficients (CPC). The
CPC again is based on the mass partition coefficients (MPC).

Both MPC and CPC coefficients were derived by Rutten (1995). The MPCs
of goods G show the shares of the tons of goods which are transported by 20ft
and 40ft containers. They are derived from the ratios between the maximum
load and maximum volume of a 20ft and 40ft container and the density of the
goods. The MPCs are based on the principle that if the density of goods
resembles the ’MaxLoad/MaxVolume-ratio’ of a 20ft container, most tons are
transported by 20ft containers and if it resembles the ’MaxLoad/MaxVol-ratio’
of a 40ft container, most tons are transported by 40ft containers3.

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3 For a formal definition of the MPC and CPC, cf. box 8.1.
Box 8.1 The formal definition of the mass partition coefficient MPC and the container partition coefficient CPC (Rutten, 1995).

For the commodity group G with density $D_G$ and the container types 1 and 2,
- the mass partition coefficient $MPC_i$, i.e. the ratio of the total tons of goods of type G transported in container type i, and,
- the container partition coefficient $CPC_i$, i.e. the ratio of the numbers of containers of type i loaded with goods of type 'NSTR',
are defined by the following formulas:

$$MPC_i = \frac{D_{G} - D_i}{D_{G} - D_{i}}$$

$$CPC_i = \frac{MPC_i \times M_{i}}{MPC_i \times M_{3-i} + MPC_{3-i} \times M_{i}}$$

In these formulas:
- $D_{i}$ and $D_{G}$ are the MaxLoad/MaxVolume-ratios of the containers types 1 and 2 with $D_{i} > D_{G}$, and,
- $D_{G} \in [D_{1}, D_{3}]$; $MPC_i = 0$ if $D_{G} > D_{i}$, $MPC_i = 1$ if $D_{G} < D_{i}$, and,
- $M_{i}$ and $M_{3-i}$ are the masses of maximally-loaded containers $M_{i}$ and $M_{3-i}$. Maximally-loaded is fully-loaded with regard to volume or mass.
Next, the CPCs of goods G show the shares of 20ft and 40ft containers and are derived from the MPCs and the mass of maximally-loaded 20ft and 40ft containers (determined by either mass or volume of the goods). The CPCs are based on the assumption that a 20ft and 40ft container have the same ‘ActualLoad/MaximumLoad-ratio’.

Finally, the average container load of e.g. a 20ft container carrying goods G equals \( \frac{\text{MPC}_{20}}{\text{CPC}_{20}} \times \text{ACL}_{\text{good}G} \).

Module 1 results in a table which for all NSTR commodity groups contains:
- the mass of maximally-loaded 20ft and 40ft containers,
- the containers partition coefficients, and,
- the average container loads for 20ft and 40ft containers separately.

**MODULE 2: the embodied energy and the indirect emissions of rail and road vehicles and infrastructure.**

Module 2 combines the embodied energy and indirect emissions of types of vehicles and infrastructure and the lifespan of these capital goods expressed in vehicle kilometres (cf. figure 8.3). The vehicles’ lifespan can easily be estimated in vehicle kilometres. For infrastructure, this lifespan is defined as the product of the lifespan in years, the theoretical capacity expressed as the number of freight vehicles per year and a reality factor defined as the real use divided by the theoretical capacity (both real use and the theoretical capacity are expressed as the number of vehicles per year). The results of module 2 are the indirect energy requirements and indirect emissions of the vehicles and infrastructure expressed per vehicle kilometres.

**MODULE 3: the direct energy requirements and direct emissions of rail and road vehicles.**

Module 3 derives basic formulas for the direct energy use and emissions of trucks and trains by making use of technical vehicles’ characteristics such as rolling resistance, frontal surface, etc. (based on Van Laar, 1993; cf. appendix A). Result for the direct energy use and direct emissions are formulas in which the energy use and emissions only depend on the mass of the vehicle’s load and the speed of the vehicles (cf. figure 8.4).
Figure 8.3 The structure of module 2 dealing with the indirect energy requirements and emissions.

**FOR EACH VEHICLE**

\[
\text{Sen} / \text{Sem} = f (M_l, V, X_1, X_2, \ldots X_n)
\]

- \(\text{Sen}\) = energy requirements (MJ/ton\(\cdot\)km)
- \(\text{Sem}\) = emissions (g\(\cdot\)ton\(\cdot\)km)
- \(M_l\) = mass of load (kg)
- \(V\) = speed (km/h)

\(X_i\) can be any kind of fixed or non-fixed technical parameter such as air resistance, motor efficiency, frontal space, mass vehicle and the emission factors of the vehicles (g\(\cdot\)MJ).

\[
\text{Sen} / \text{Sem} = f (M_l, V)
\]

- \(\text{Sen}\) = specific energy requirements (MJ/ton\(\cdot\)km)
- \(\text{Sem}\) = specific emissions (g\(\cdot\)ton\(\cdot\)km)
- \(M_l\) = mass of load (kg)
- \(V\) = speed (km/h)

Figure 8.4 The structure of module 3 dealing with the direct energy requirements and emissions.
8.3 The underlying data sets

The modules 1, 2 and 3 provide the basic data sets for the main module of the model (cf. figure 8.1). The previous section discussed the structure of the main module as well as the structure of the modules 1, 2 and 3. This section presents the basic data sets resulting from the modules 1,2 and 3 which form the input for the model’s main module.

MODULE 1: the container shares and container load characteristics

Table 8.2 shows the MPC, the CPC and the average and maximum load of the 20ft and 40ft containers for three NSTR commodity groups. The first group has a relatively high density (van Witsen, 1992), the second a relatively low density and the third an intermediate density, i.e. a density in between the MaxLoad/MaxVolume ratios of a 20ft and 40ft container. Table 8.3 shows the MaxLoad/MaxVolume ratios of a 20ft and 40ft container and other container features necessary to calculate the MPCs.

Table 8.2 Container loads of two commodity groups with different densities.

<table>
<thead>
<tr>
<th>Commodity group</th>
<th>density (ton/m³)</th>
<th>MPC² share 20ft %</th>
<th>CPC² share 20ft %</th>
<th>Average container load (ton)</th>
<th>Maximum container load (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.55</td>
<td>45</td>
<td>55</td>
<td>18.0</td>
<td>14.7</td>
</tr>
<tr>
<td>5</td>
<td>2.3</td>
<td>100</td>
<td>100</td>
<td>19.0</td>
<td>19.0</td>
</tr>
<tr>
<td>99</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>11.4</td>
<td>11.4</td>
</tr>
</tbody>
</table>

*1 The commodity group 2 concerns the solid mineral fuels. The subgroup considered here has a relatively low density, i.e. a density in between the MaxLoad/MaxVolume ratios of a 20ft and 40ft container (cf. table 8.3). The commodity groups 5 are the ores and metal products; the commodity group 99 are the miscellaneous articles.

*2 MPC is the Mass Partition Coefficient; CPC is the Container Partition Coefficient (cf. box 8.1).
MODULE 2: the embodied energy and the indirect emissions of rail and road vehicles and infrastructure.

The tables 8.4 till 8.10 inclusive show the relevant basic data and main assumptions regarding road and rail vehicles and infrastructure. The energy and emission data expressed per vehicle kilometre are results which are used as input for the main module.

Table 8.4 The embodied energy of rail infrastructure.

<table>
<thead>
<tr>
<th>Rail type</th>
<th>TrafDens design</th>
<th>EE railbed TJ</th>
<th>EE steel TJ</th>
<th>EE other TJ</th>
<th>EE total TJ</th>
<th>EE MJ/F-vehkm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 TR, P+F</td>
<td>8</td>
<td>12.1</td>
<td>4.47</td>
<td>5.53</td>
<td>22.1</td>
<td>65.4</td>
</tr>
<tr>
<td>2 TR, F only</td>
<td>16</td>
<td>13.3</td>
<td>4.91</td>
<td>6.09</td>
<td>24.8</td>
<td>12.9</td>
</tr>
<tr>
<td>4 TR, both P+F and F only; twice the value of the 2-tracks variants</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations:
Rail infrastructure type: TR=tracks, P=passenger traffic, F=freight traffic.
TrafDensity=traffic density; defined as the number of trains an hour in both directions.
Others columns: EE = embodied energy, EE other = the energy embodied in the sleepers and the catenary and the production energy, F-vehkm = freight vehicle kilometre.

Main assumptions underlying the calculations:
1. The number of trains per hour in both directions are 24-hours-averages and based on Peeters (1988), Railned (1997), Rutten (1997).
2. In mixed traffic, 7% of the trains are freight trains (NS, p1992).
3. The embodied energy in rail infrastructure developed for freight transport only is supposed to be 10% higher than the embodied energy of rail infrastructure developed for mixed traffic (Railbouw, 1997).
4. The embodied energy values and densities of steel and sand are chosen as shown in the (sub)sections 2.5.3 and 3.3.
5. The depreciation rates of the sand and ballast subbase are 50 years. The depreciation rate of the tracks is 25 years in case of mixed traffic and 12.5 years in case of freight traffic only. (Thus, it is assumed to be dependent on the number of passing trains.) (Railbouw, 1993.)
6. In mixed rail traffic, 25% of the construction energy is allocated to freight transport (cf. 3.2).
Table 8.5 The embodied energy of road infrastructure.

<table>
<thead>
<tr>
<th>Road type</th>
<th>TrafDens design</th>
<th>EE/km roadbed TJ</th>
<th>EE/km asphalt TJ</th>
<th>EE/km maint TJ</th>
<th>EE/km total TJ</th>
<th>EE MJ/truckkm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2L,P+F</td>
<td>2000 PCU</td>
<td>6.1</td>
<td>14.2</td>
<td>15.8</td>
<td>36.2</td>
<td>0.73</td>
</tr>
<tr>
<td>2L,F only</td>
<td>2600 TR</td>
<td>6.1</td>
<td>19.0</td>
<td>15.8</td>
<td>41.0</td>
<td>0.12</td>
</tr>
<tr>
<td>4L,P+F</td>
<td>8800 PCU</td>
<td>12.3</td>
<td>34.8</td>
<td>31.7</td>
<td>78.8</td>
<td>0.17</td>
</tr>
<tr>
<td>4L,F only</td>
<td>5200 TR</td>
<td>12.3</td>
<td>42.2</td>
<td>31.7</td>
<td>86.0</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Abbreviations:
- Road type: L=lanes, P=passenger traffic, F=freight traffic.
- TrafDens=traffic density; PCU=passenger car unit; TR=trucks.
- The traffic intensity is expressed as PCU or TR in each direction per hour.
- Others columns: EE = embodied energy, maint=maintenance.

Main assumptions underlying the calculations:
1. The assumed design traffic densities are based on Bexelius (1997), Rutten (1997) and Schoemaker (1996).
2. The roads are designed for certain number of passenger car units (PCU) or trucks. In practice however, the average number of vehicles passing in 24 hours is about 30% of the theoretical design numbers (derived from AVV, 1992).
3. On main infrastructure, 1 Truck equals 2 PCU (PCU = passenger car unit; cf. section 4.2) (TRB, 1985); cf. footnote 9 in chapter 4.1 Truck equals 2 PCU (PCU = passenger car unit; cf. section 4.2) (TRB, 1985).
4. On 2-lane-roads, 10% of the vehicles are trucks, on 4-lane roads 20% of the vehicles are trucks (derived from AVV, 1992).
5. The construction thickness of the asphalt layers for the four types of roads 2L-P+F, 2L-F, 4L-P+F, 4L-F is 27, 36, 33 and 40 cm (derived from Medema, 1994; Vos, 1994; Otten, 1994), the width of 2L and 4L roads is 8 and 16 meter respectively. The construction thickness of the sand subbase is 1 meter for all types of roads.
6. The embodied energy values and the densities of asphalt and sand are chosen as shown in the (sub)sections 2.5.3 and 3.3.
7. The maintenance schedule of main roads equals 15 cm of asphalt every 20 years. For roads designed for mixed traffic or roads designed for trucks, the maintenance schedule does not differ much (Hoogvorst, 1997; Swart, 1997). The main difference between roads designed for both passenger and freight transport and roads for freight transport only is the thickness of the construction layer.
8. The depreciation rate of the infrastructure is 50 years (cf. subsection 4.2).
9. In mixed road traffic, 16% of the construction energy is allocated to freight transport (cf. subsection 4.2). Since the roads considered here are roads outside the built-up area, 100% of the maintenance energy is allocated to freight traffic.
Table 8.6 The embodied energy of rail and road vehicles.

<table>
<thead>
<tr>
<th>Embodied Energy (MJ/vehkm)</th>
<th>Trucks</th>
<th>Trains, 200 m.</th>
<th>Trains, 500 m.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20t</td>
<td>40t</td>
<td>SGNS</td>
</tr>
<tr>
<td>20ft</td>
<td>0.64</td>
<td>1.14</td>
<td>15.4</td>
</tr>
<tr>
<td>40ft</td>
<td></td>
<td>1.11</td>
<td>14.2</td>
</tr>
</tbody>
</table>

Descriptions of the vehicles:
A 20t-truck carries one 20ft container.
A 40t-truck with semitrailer carries one 40 ft container or, depending on the mass of the 20ft containers, one or two 20ft containers.
A 200-meter freight train consists of 1 diesel-electric (DE) locomotives and 10 SGNS wagons or fourteen LGNS container wagons.
A 500-meter freight train consists of 2 diesel-electric (DE) locomotives and 25 SGNS or thirty-six LGNS container wagons.
SGNS and LGNS container wagons have been designed for the transport of goods with high and low densities respectively; for more details and explanation of the SGNS and LGNS wagons, cf. section 3.3 and below.

Main assumptions underlying the calculations
1 The mass balances of the trucks, a DE-loc and the LGNS-container wagon vehicles are chosen as shown in subsection 3.3. For the mass balance of a container, cf. table 8.9. A SGNS container wagon consists of 19393 kg of steel (NS, p1993).
2 The embodied energy value of steel is chosen as shown in subsection 2.5.3.
3 The lifespan of the truck is estimated at 1,000,000 km (van Lent, i1993; Daf, l1994) as is the lifespan of a DE locomotive and the freight wagons (derived from NS, p1992; NS, i1997; TFD, 1979).
Table 8.7 The maximum load of rail and road vehicles.

<table>
<thead>
<tr>
<th>Maximum load</th>
<th>Trucks</th>
<th>Trains, 200 m.</th>
<th>Trains, 500 m.</th>
</tr>
</thead>
<tbody>
<tr>
<td>20t</td>
<td>40t</td>
<td>SGNS(^1)</td>
<td>LGNS</td>
</tr>
<tr>
<td>in no of containers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20ft</td>
<td>1</td>
<td>2/1(^1)</td>
<td>30</td>
</tr>
<tr>
<td>40ft</td>
<td>-</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>in tons</td>
<td>20ft</td>
<td>12.2</td>
<td>22.2/24.4(^1)</td>
</tr>
<tr>
<td></td>
<td>40ft</td>
<td>23.0</td>
<td>582</td>
</tr>
</tbody>
</table>

\(^1\) It depends on the mass of a 20ft container if a 40t container carries one or two 20ft containers. If the truck carries one 20 ft container, the maximum payload is higher than if it carries two.

\(^2\) For more details and explanation of the SGNS and LGNS wagons, cf. section 3.3 and table 8.6.

Table 8.8 The embodied energy of containers.

<table>
<thead>
<tr>
<th>Container type</th>
<th>Mass kg</th>
<th>EE steel TJ</th>
<th>EE other TJ</th>
<th>EE tot TJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>20ft</td>
<td>2320</td>
<td>61.3</td>
<td>14.8</td>
<td>76.1</td>
</tr>
<tr>
<td>40ft</td>
<td>3760</td>
<td>96.6</td>
<td>26.9</td>
<td>124</td>
</tr>
</tbody>
</table>

**Abbreviations:**

EE = embodied energy, EE other = the energy embodied in materials other than steel and the production energy.

*Main assumptions underlying the calculations.*

1. The steel content of a 20ft container is 2030 kg, the steel content of a 40ft container is 3200 kg. Mass and steel content are derived from Tele-atlas (1990) and Nedlloyd lines (d1994).
2. The embodied energy values of steel are chosen as shown in subsection 2.5.3.
3. The production energy of a 20ft and 40ft container is calculated based on the production energy of sector 34 (cf. appendix A) and assumed container prices of a 20ft and 40ft container of respectively Dfl 4600,- and Dfl 7300,- (Nedlloyd lines, d1994). The production energy amounts to 3.4 and 5.3 TJ respectively.
Table 8.9 The indirect emissions of rail and road infrastructure.

<table>
<thead>
<tr>
<th></th>
<th>SO₂</th>
<th>CO</th>
<th>NOₓ</th>
<th>VOC</th>
<th>Aerosols</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Road infrastructure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2L,P+F</td>
<td>0.1442</td>
<td>0.1061</td>
<td>0.2506</td>
<td>0.0364</td>
<td>0.00679</td>
</tr>
<tr>
<td>2L,F only</td>
<td>0.0231</td>
<td>0.0163</td>
<td>0.0391</td>
<td>0.0058</td>
<td>0.00103</td>
</tr>
<tr>
<td>4L,P+F</td>
<td>0.0323</td>
<td>0.0233</td>
<td>0.0550</td>
<td>0.0082</td>
<td>0.00144</td>
</tr>
<tr>
<td>4L,F only</td>
<td>0.0266</td>
<td>0.0165</td>
<td>0.0393</td>
<td>0.0060</td>
<td>0.00102</td>
</tr>
<tr>
<td><strong>Rail infrastructure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2TR,F only</td>
<td>2.59</td>
<td>7.25</td>
<td>4.65</td>
<td>0.38</td>
<td>2.67</td>
</tr>
</tbody>
</table>

*1 All calculations are based on the same assumptions as used in the embodied energy calculations.
*2 L=lanes, TR=tracks, P=passenger traffic, F=freight traffic.
*3 As in the embodied energy calculations, for rail infrastructure with 4 tracks, all values for both P+F and F only are twice the value of the 2-track variants.

*MODULE 3: the direct energy requirements and direct emissions of rail and road vehicles.*

Basic formulas for the direct energy requirements and the direct emissions, or in other words, fuel-related emissions of specified rail and road vehicles, are presented in appendix A. The results of the combination of these basic formulas and the specification of the rail and road vehicles as shown in tables 8.11, 8.12 and 8.13 are formulas for the direct energy requirements and emissions that only depend on the speed of the vehicle and the mass of the load.
Table 8.10  The indirect emissions of rail and road vehicles.

<table>
<thead>
<tr>
<th>g/vehkm$^{*1,*2}$</th>
<th>SO$_2$</th>
<th>CO</th>
<th>NO$_x$</th>
<th>VOC</th>
<th>Aerosols</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Road vehicles</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20t</td>
<td>0.085</td>
<td>0.306</td>
<td>0.206</td>
<td>0.028</td>
<td>0.136</td>
</tr>
<tr>
<td>40t</td>
<td>0.171</td>
<td>0.659</td>
<td>0.365</td>
<td>0.047</td>
<td>0.029</td>
</tr>
<tr>
<td><strong>Rail vehicles, SGNS, 200m.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20ft</td>
<td>2.94</td>
<td>12.4</td>
<td>2.83</td>
<td>0.26</td>
<td>5.42</td>
</tr>
<tr>
<td>40ft</td>
<td>2.69</td>
<td>11.3</td>
<td>2.60</td>
<td>0.24</td>
<td>4.93</td>
</tr>
<tr>
<td><strong>Rail vehicles, SGNS, 500m.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20ft</td>
<td>7.02</td>
<td>28.8</td>
<td>6.75</td>
<td>0.61</td>
<td>13.01</td>
</tr>
<tr>
<td>40ft</td>
<td>6.38</td>
<td>27.0</td>
<td>6.15</td>
<td>0.56</td>
<td>11.78</td>
</tr>
<tr>
<td><strong>Rail vehicles, LGNS, 200m.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20ft</td>
<td>2.61</td>
<td>11.0</td>
<td>2.54</td>
<td>0.23</td>
<td>4.78</td>
</tr>
<tr>
<td>40ft</td>
<td>2.51</td>
<td>10.5</td>
<td>2.44</td>
<td>0.22</td>
<td>4.68</td>
</tr>
<tr>
<td><strong>Rail vehicles, LGNS, 500m.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20ft</td>
<td>6.33</td>
<td>26.8</td>
<td>6.13</td>
<td>0.55</td>
<td>11.7</td>
</tr>
<tr>
<td>40ft</td>
<td>6.00</td>
<td>25.5</td>
<td>5.87</td>
<td>0.53</td>
<td>11.1</td>
</tr>
</tbody>
</table>

$^{*1}$ All calculations are based on the same assumptions as used in the embodied energy calculations.

$^{*2}$ For the vehicles definitions, cf. the tables 8.6 and 8.7.
**Table 8.11** Specification road vehicles in order to calculate the direct energy requirements.

<table>
<thead>
<tr>
<th>Technical specifications*1</th>
<th>20t truck</th>
<th>40t truck with semi-trailer</th>
<th>Emission factors (mg/MJ)</th>
<th>20t truck</th>
<th>40t truck with semi-trailer</th>
</tr>
</thead>
<tbody>
<tr>
<td>no of containers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1x20</td>
<td>2x20</td>
<td>1x40</td>
<td>1x20</td>
<td>1x40, 2x20</td>
</tr>
<tr>
<td>n(t)</td>
<td>0.35</td>
<td>0.37</td>
<td>0.37</td>
<td>SO₂</td>
<td>93</td>
</tr>
<tr>
<td>f(r), x 10⁻³</td>
<td>5.85</td>
<td>5.85</td>
<td>5.85</td>
<td>CO</td>
<td>535</td>
</tr>
<tr>
<td>Cw</td>
<td>0.60</td>
<td>0.85</td>
<td>0.85</td>
<td>NOₓ</td>
<td>1350</td>
</tr>
<tr>
<td>A, m²</td>
<td>10.0</td>
<td>10.0</td>
<td>10</td>
<td>VOC</td>
<td>413</td>
</tr>
<tr>
<td>Mveh, ton</td>
<td>7.35</td>
<td>15.2</td>
<td>16.3</td>
<td>Aer</td>
<td>219</td>
</tr>
</tbody>
</table>

*1 n(t) is the total efficiency, f(r) is the rolling resistance, Cw is the air resistance coefficient, A is the frontal surface, Mveh is the mass of the vehicle inclusive that of the containers.

**Table 8.12** Specification rail vehicles in order to calculate the direct energy requirements.

<table>
<thead>
<tr>
<th>Technical specifications*1</th>
<th>Emission factors (mg/MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n(t)</td>
<td>SO₂ 85</td>
</tr>
<tr>
<td>A, m²</td>
<td>CO 353</td>
</tr>
<tr>
<td>g, m/s²</td>
<td>NOₓ 824</td>
</tr>
<tr>
<td>f(r), x 10⁻³</td>
<td>VOC 118</td>
</tr>
<tr>
<td>C, x 10⁻³</td>
<td></td>
</tr>
<tr>
<td>f(l), x10⁻³</td>
<td></td>
</tr>
</tbody>
</table>

*1 n(t) is the total efficiency, A is the frontal surface, g is the gravity, f(r) is the rolling resistance, C is a constant which depends on the ton/m-mass of the fully-loaded train, f(l) is the course resistance coefficient.
8.4 Case study heavy and light commodities

8.4.1 Introduction

Section 8.2 distinguished several features of transport systems which are considered to be of special interest in the context of this study which takes into account the energy requirements and emissions of specific transport chains: features with regard to the goods characteristics, the vehicles, the infrastructure, the production efficiencies of construction materials and the trip characteristics.

This section presents model results for a case study in which the energy requirements and emissions are studied for two commodity groups, one with a high density and one with a low density, and for both rail and road transport. Energy requirements and emissions are related to the following transport system features: 'size of the vehicles', 'infrastructure suitable for passenger and freight transport or suitable for freight transport only', 'the size of the infrastructure', 'the production efficiency of the main construction materials of vehicles and infrastructure', 'driving speed' and 'load factor'.

The commodity groups distinguished are the goods group 99, the ores and metal products with a density of 2.3 kg/m³, and goods group 5, the miscellaneous articles with a density of 0.4 kg/m³ (van Witsen, 1992). For each commodity group and for both rail and road transport, 64 cases have been defined. In these cases, the transport system features, defined as system parameters, are varied systematically. Each system parameter is assigned to two

<table>
<thead>
<tr>
<th>Mtr, max(^1)</th>
<th>Mass vehicles(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SGNS (heavy commodities)</td>
</tr>
<tr>
<td>200m, 1 loc</td>
<td>1000 ton</td>
</tr>
<tr>
<td>corresponding</td>
<td>10 /</td>
</tr>
<tr>
<td>no of wagons /</td>
<td>30x20ft</td>
</tr>
<tr>
<td>no of containers</td>
<td></td>
</tr>
<tr>
<td>500m, 2 locs</td>
<td>2000 ton</td>
</tr>
<tr>
<td>corresponding</td>
<td>25 /</td>
</tr>
<tr>
<td>no of wagons /</td>
<td>75x20ft</td>
</tr>
<tr>
<td>no of containers</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) Mtr\(_{\text{max}}\) is the mass of the train if fully-loaded.
\(^2\) Mass vehicle is the total mass of the vehicle inclusive that of the containers.
possible values. The values leading to the highest energy requirements and highest emissions comprise the reference case.

Table 8.14 shows the structure of the 64 cases, defines the values of the 6 system parameters and defines the values of the reference case. For all cases, by use of the model, the energy requirements and emissions have been calculated resulting from the transport of 1000 ton over a distance of 100 kilometres. Next, the energy and emission results have been analysed and summarised.

Subsection 8.4.2 discusses the energy results. Subsection 8.4.3 discusses the emission results. Finally, subsection 8.4.4 summarises the energy and emission results and conclusions.

8.4.2 Energy results

The results of the energy requirements and the emissions, i.e. NO\textsubscript{x}, SO\textsubscript{2} and CO emissions, are shown in figures of which many have a common design. The first bar shows the results of the reference case. In accordance with table 8.14, this reference case comprises small vehicles (200m long trains or 20-tons trucks), infrastructure suitable for passenger and freight transport, 2-tracks or 2-lanes infrastructure, the production energy of the materials according to the 1990 state-of-the-art, an average vehicle speed of 90 km per hour and an average load factor. Next, each following bar shows the impact of the change of one system parameter. Based on the figures 8.5 and 8.6 is explained in which manner the results of the cases have been reduced to figures as shown in this section.

Figure 8.5 shows the energy requirements of the transport by train of 1000 tons of low density goods (0.4 kg/m\textsuperscript{3}) over 100 kilometres. The left bar shows the energy requirements for the reference case. Each following bar shows the energy requirements for the case which differs from the reference scenario with regard to one single parameter. That parameter is indicated below the bar. The abbreviations of the parameters as used in the figures are shown in table 8.14. From figure 8.5 can be derived which parameters influence the energy requirements more than others. The sequence from ‘most to least’ influence determines the sequence from left to right in figure 8.6.
### Table 8.14 The structure of the cases.

<table>
<thead>
<tr>
<th>System parameter$^1$</th>
<th>REFERENCE case$^2$</th>
<th>Alternative case$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vehicle size$^3$</td>
<td>20t/200m</td>
</tr>
<tr>
<td>2</td>
<td>Infrastructure 1$^4$</td>
<td>P+F</td>
</tr>
<tr>
<td>3</td>
<td>Infrastructure 2$^5$</td>
<td>2L/2T</td>
</tr>
<tr>
<td>4</td>
<td>Production efficiency materials$^6$</td>
<td>St90</td>
</tr>
<tr>
<td>5</td>
<td>Speed$^7$</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>Load factor$^8$</td>
<td>Av</td>
</tr>
</tbody>
</table>

*1 In this case study, two model parameters are constant: ‘the percentage of empty rides’ is zero and ‘the share of 20 and 40-feet containers’ is the share as found in practice (cf. subsection 8.2.2).

*2 The REFERENCE case is the scenario with the highest energy requirements and emissions by reasoning. For each commodity group 99 and 5, 64 cases are formed by changing the features 1 to 6 one by one.

*3 The sizes of the vehicles are:
  - 20-tons trucks or 200 meter trains (small), and,
  - 40-tons trucks or 500 meter trains (large).

*4 The types of infrastructure distinguished are:
  - infrastructure designed for mixed traffic, i.e. passenger and freight transport (P+F), and,
  - infrastructure designed for freight transport only (F).

*5 A second distinction with regard to the infrastructure is:
  - 2-lanes roads (2L) and two tracks (2T) rail infrastructure, and,
  - 4-lanes roads (4L) and four tracks (4T) rail infrastructure.

*6 The materials taken into account with regard to the production efficiency are steel and asphalt. The production efficiencies distinguished are ‘the state of the art 1990’ (St90) and ‘improved’ (Imp). Improved is defined as a 50% decrease of the energy required for the production of steel and asphalt.

*7 The driving speed of the vehicles is 90 km/h (90) or 65 km/h (65).

*8 The load factor of the vehicles is ‘average’ (Av) or ‘maximum’ (Max).
As in figure 8.5, the left bar in figure 8.6 shows the results for the reference case. The second bar shows the energy requirements for the case in which the average load factor has been changed from average to maximum. This change has the largest impact on the decrease in energy requirements compared to that of the reference case (cf. figure 8.5). The third bar shows the energy requirements for the case in which additionally trains of 200m are replaced by trains of 500m. This change has the second largest impact on the decrease in energy requirements compared to the case shown in the previous bar which includes the reference case and a maximum load factor. Bars 4 up till 7 inclusive show the energy requirements resulting from each following additional parameter change. The change of the value of the parameter indicated below the bar has the largest impact on the energy requirements shown in the previous bar out of all remaining parameters, i.e. the parameters were not yet included in the case shown in the previous bar.

Figure 8.5 and 8.6 show that both a shift towards a maximum load factor and the use of larger rail vehicles are the most effective ways to reduce the energy requirements. Both a maximum load factor and longer rail vehicles lead to a smaller number of vehicles necessary to carry the goods and therefore account for less direct energy requirements and less indirect energy requirements. For instance, vehicles carrying for instance twice as much goods as other vehicles do not use twice as much electricity. And the use of 500-metre rail vehicles instead of 200-metre rail vehicles does not result in the use of 2.5 times as much infrastructure-related embodied energy since these energy requirements mainly depend on the infrastructure’s capacity which is related to the number of rail vehicles instead of to their lengths.

Figures 8.5 and 8.6 show that the total theoretical energy savings are more than 80%. Most energy savings are direct energy requirements or indirect energy requirements related to the infrastructure.

Of interest are the non-multiplicative impacts of the model shown by the figures 8.5 and 8.6. Compared to the reference case, the introduction of an infrastructure suitable for freight transport only accounts for 26% energy savings. The energy requirements decrease only by about 20% if one introduces an infrastructure suitable for freight transport only compared to the case which differs from the reference case with regard to the load factor and the lengths of the trains.

The figures 8.7 and 8.8 show the energy requirements of the transport of low density goods over 100 kilometres by trucks. Figure 8.7 shows the impacts of changes in the single parameters on the energy requirements of the reference
case. Figure 8.8 shows the decrease in energy requirements by changing the values of the parameters one after the other while the sequence of the parameters from left to right, like the sequence in figure 8.6, is based on the rule of diminishing returns.

The figures 8.7 and 8.8 show an even more striking example of the non-multiplicative impacts of the model. Figure 8.7 shows that the energy savings are 3.7% in case one introduces a 4-lanes infrastructure instead of a 2-lanes infrastructure compared to the reference case. However, no energy is saved in case one introduces a 4-lanes infrastructure instead of a 2-lanes infrastructure compared to the case in which the infrastructure is used by freight transport only. In that case, there is even a small energy increase due to the fact that the thickness of the asphalt layer increases caused by a doubling in the traffic density (cf. table 8.5). For this reason, a switch to a 4-lanes infrastructure is eliminated from figure 8.8.

The fact that most energy savings in case of transporting low density goods by trucks are direct energy savings is a relevant result shown by the figures 8.7 and 8.8. These direct energy savings result from a switch from average to maximum load capacity and by an average speed of 65 instead of 90 km/hour. A switch from small (20-tons) to large (40-tons) trucks is not included in the figures 8.7 and 8.8 since already in the reference case, goods with low densities are transported in 40ft containers and thus by large vehicles. Total theoretical energy savings are about 60%.

The figures 8.9 and 8.10 show the energy requirements of high density goods (2.3 kg/m³) by trains. The figures 8.11 and 8.12 show those of high density goods by trucks. Again, for both rail and road transport results, the first figure shows the impacts of changes in the single parameters on the energy requirements of the reference case and the second figure shows the impacts of the parameters in a sequence based on the rule of diminishing returns.

Figure 8.9 shows that for trains carrying high density goods a shift towards larger vehicles represents quite high energy savings. Also considerable savings can be achieved by switching to infrastructure used by freight transport only; homogeneous traffic flows lead to an increased capacity while the embodied energy of the infrastructure only increases slightly. Both savings consist of direct energy requirements and infrastructure-related indirect energy requirements. The change from an average to a maximum load factor is not included in the rail transport analyses shown in the figures 8.9 and 8.10 since the rail vehicles considered can not carry maximum loaded containers due to the maximum axis load of the vehicles. Total theoretical energy savings in case of rail transport are about 60%.

The road transport analyses for high-density goods shown in the figures 8.11 and 8.12 do not include a switch from 20-tons to 40-ton trucks since in the
reference case 40-tons trucks are already used due to the already substantial mass of only average-loaded containers. A switch to a 4-lanes infrastructure is not included for the same reasons discussed with regard to figure 8.8. Total energy savings in case of the transport of goods by truck are about 40%.

The results shown in the figures based on the rule of the diminishing return (the figures 8.6, 8.8, 8.10 and 8.12) are also compared per freight category.

A comparison of the transport of low-density goods by trains or trucks (the figures 8.5 and 8.6 versus the figures 8.7 and 8.8) leads to the following observations:

- A shift from average-loaded vehicles to maximally-loaded vehicles accounts for most energy savings in both rail and road transport.
- A shift towards longer trains in rail transport also accounts for a large impact on the energy savings due to both direct and indirect effects. A shift to bigger trucks in road transport is not possible since for goods group 99, 40-tons-trucks are used in the reference case.
- The total theoretical energy savings potential is larger for rail than for road transport.
- For road transport, the direct energy requirements make up the largest part of the energy requirements of the reference case and the main energy savings potential consists of direct energy savings. For rail transport, the indirect energy share of the reference case is much larger than for road transport and the indirect energy savings potential equals the direct energy savings potential.

A comparison of the transport of high-density goods by trains or trucks (the figures 8.9 and 8.10 versus the figures 8.11 and 8.12) leads to the following observations:

- The energy requirements for the reference case is the lowest for rail transport. This is due to the high direct energy requirements of road transport; because of the high density of the goods of group 5, many trucks are needed for the transport of 1000 tons of goods.
- For rail transport, the relative energy savings potential is larger for the indirect energy requirements than for the direct energy requirements. The opposite holds for road transport.

A comparison of the transport of low-density and high-density goods (the figures 8.5 till 8.8 versus the figures 8.9 till 8.12) leads to the following observations:

- The total energy requirements for the transport of 1000 tons of low-density goods are much higher than those of high-density goods.
• A shift from average-loaded vehicles to maximally-loaded vehicles represents a much larger energy savings potential for the light commodities than for the heavy commodities.

The indirect energy requirements
From all figures 8.5 till 8.12 inclusive, one can conclude that:
• energy efficiency improvements in steel, iron and asphalt production have little influence on the total energy requirements.

Next, the figures 8.13, 8.14 and 8.15 summarise some of the vehicle and infrastructure results of the figures 8.5 till 8.12 inclusive. The figures 8.13 and 8.14 show the consequences of a move towards infrastructure used by freight transport only. Figure 8.15 shows the consequences of a move towards a 4-lanes infrastructure.

From the figures 8.13 and 8.14, one can conclude that,
• The energy savings potential is larger (relatively and absolute) for rail than for road transport and is to be found in the infrastructure part.
• Light commodities offer the largest (absolute) energy savings potential.

In comparing the figures 8.13 and 8.14 with figure 8.15, one finds that,
• A shift from an infrastructure used by both passenger and freight transport to an infrastructure used by freight transport only has a larger energy savings potential than a shift from ’2 tracks or 2 lanes’ to ’4 tracks or 4 lanes’. The ratio between the capacity gain and the extra energy required for the infrastructure’s construction and maintenance is larger in case of a switch towards infrastructure used by freight transport only.

From all figures, one can conclude that,
• The energy savings potential is present much more in the infrastructure than in the vehicles.

Finally, figure 8.16 shows energy results for low density goods in which rail and road transport results are combined. Figure 8.17 shows combined rail and road results for high density goods. The left bar in both figures shows the energy requirements of the transport of 1000 tons of goods by trucks since for the transport of the goods by trucks more energy is required than for the transport of these goods by trains. Next, each following bar shows the energy requirements of each following additional change in an order based on the rule of diminishing returns. The changes possible are those shown in table 8.14 and a switch of road to rail transport.

For low-density goods, figure 8.16 shows that the potential energy decrease is larger by increasing the load factor than by a shift from rail to road transport. For high-density goods, a shift from road to rail transport accounts for most energy savings.
Figure 8.5 The influence of changes in single parameters on the energy requirements of the transport of low-density goods by rail.

Figure 8.6 The combined impact of parameters changes on the energy requirements of the transport of low-density goods by rail.

Figure 8.7 The influence of changes in single parameters on the energy requirements of the transport of low-density goods by road.

Figure 8.8 The combined impact of parameters changes on the energy requirements of the transport of low-density goods by road.

Figure 8.9 The influence of changes in single parameters on the energy requirements of the transport of high-density goods by rail.

Figure 8.10 The combined impact of parameters changes on the energy requirements of the transport of high-density goods by rail.

Abbreviations used in all figures on this page:
EE = embodied energy, V = vehicles, I = infrastructure, Dir En = direct energy.
For the abbreviations indicated below the bars, cf. table 8.14.
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Figure 8.11 The influence of changes in single parameters on the energy requirements of the transport of high-density goods by road.

Figure 8.12 The combined impact of parameters changes on the energy requirements of the transport of high-density goods by road.

Figure 8.13 The decrease in energy requirements due to a change towards infrastructure used by freight transport only; low-density goods.

Figure 8.14 The decrease in energy requirements due to a change towards infrastructure used by freight transport only; high-density goods.

Figure 8.15 The decrease in energy requirements due to a shift from a 2-lanes to 4-lanes infrastructure.

Abbreviations used in all figures on this page:
EE = embodied energy, V = vehicles, I = infrastructure, Dir En = direct energy.
For the abbreviations indicated below the bars, cf. table 8.14.
8.4.3 Emission results

The figures 8.18 till 8.29 inclusive show the SO$_2$ and NO$_x$ emission results. Similar results are shown for CO, aerosols and C$_x$H$_y$ emissions. However since these results show comparable trends as the SO$_2$ and NO$_x$ emissions, and since SO$_2$ and NO$_x$ are important transport-related emissions, here only results for SO$_2$ and NO$_x$ emissions are shown.

The figures 8.18 till 8.25 inclusive focus on the emission results associated with the transport of the low-density goods. The relative differences among the influences of the separate parameters on the emission results correspond with the relative differences among the influences of the separate parameters on the energy results. However, the indirect share of the SO$_2$ emissions and the impacts of changes in the values of separate parameters are higher for the emission results than was the case for the energy results. And so is the total reduction potential of the SO$_2$ emissions compared to the energy reduction potential; cf. the figures 8.6, 8.8, 8.19 and 8.21. The indirect SO$_2$ emissions of the reference case for rail transport are even higher than the direct emissions. These indirect SO$_2$ emissions result mainly from the production of steel and the extraction of sand. The reduction of the indirect emissions is the highest in case of a shift towards an infrastructure suitable for freight transport only, that is, in case of rail transport. In case of road transport, the reduction of the indirect emissions is the highest due to a change towards a maximum load.

For the low-density goods, the relative share of the indirect NO$_x$ emissions is
much lower than for the high-density goods. However, for rail transport, the indirect share is not negligible. Contrary to the $\text{SO}_2$ emissions, almost all indirect emissions result from the infrastructure. The most important difference between the $\text{SO}_2$ and $\text{NO}_x$ emissions is the relatively small reduction of $\text{NO}_x$ emissions compared to the reduction of $\text{SO}_2$ emissions due to a reduction in driving speed (cf. the figures 8.18 and 8.22). The figures 8.24 and 8.25 show that the indirect $\text{NO}_x$ emissions are negligible for road transport.

The figures 8.26 till 8.29 inclusive show the $\text{SO}_2$ emission results for the high-density goods. Of interest are the differences among the $\text{SO}_2$ emission results for low and high density goods. As shown in figure 8.26, an effective way to reduce $\text{SO}_2$ emission in case of the transport of high-density goods by rail is to switch towards an infrastructure suitable for freight transport only. This is as effective as a switch towards 500 meter trains. A comparison between the figures 8.18 and 8.26 shows that this result differs from the results for low-density goods. The impact of a switch towards a maximum load factor is negligible in case of the transport of high-density goods transported by rail.

Maximally-loaded containers carry only slightly little more goods than average-loaded vehicles due to the maximum (defined) axis load of the rail vehicles. The $\text{SO}_2$ savings potential by road transport of high-density goods turns out to be relatively small, and is found in speed reduction mostly. However, a shift towards a maximum load factor also contributes reasonably to $\text{SO}_2$ emission reduction.

The results for the $\text{NO}_x$ emissions of high density goods are not shown. The trends in the results are comparable with the $\text{NO}_x$ emission results for the low-density goods. For both rail and road transport, the main difference between the high and low-density goods results is the lower total energy savings potential for the high density goods than that of the low-density goods. This corresponds with the differences between the low and high density goods results for the energy requirements and the $\text{SO}_2$ emissions.

8.4.4 Conclusions regarding energy and emission results

In 8.4.2 and 8.4.3, the energy requirements and emissions were studied for two commodity groups, one with a high density and one with a low density, and for both rail and road transport. These energy requirements and emission were studied in relation to the following transport system features: 'size of the vehicles', 'infrastructure suitable for passenger and freight transport or suitable for freight transport only', 'the size of the infrastructure', 'the production efficiency of the main construction materials of vehicles and infrastructure', 'driving speed' and 'load factor'.
This section summarises the energy and emission results and conclusions. Next, some limitations of the model calculations and the consequences of these limitations on the conclusions are discussed.

Conclusions with regard to the case study on heavy and light commodities

With regard to low and high-density commodities

• For low density goods, the total energy requirements and total emissions as well as the total energy and emission savings potential for the transport of 1000 tons of goods are much higher (relatively and absolute) than for high-density goods.

• A shift from average-loaded vehicles to maximally-loaded vehicles has a much larger energy and emission savings potential for the light commodities than it has for the heavy commodities.

With regard to rail and road transport

• The energy and emission savings potential is larger for rail than for road transport.

• For rail transport, the indirect energy, SO$_2$ and NO$_x$ emissions share of the reference case is much larger than for road transport. For energy and SO$_2$ emissions, the indirect energy savings potential is as big as or even bigger than the direct energy savings potential.

• For road transport, the direct energy requirements and direct emissions make up the largest part of the energy and emissions of the reference case. However, indirect energy requirements and indirect SO$_2$ emissions are not negligible. The energy savings potential for road transport consists of direct energy savings mainly.

• For rail transport and for low density goods only, a shift from average-loaded vehicles to maximally-loaded vehicles accounts for most energy savings. For both low and high-density goods transported by rail, a shift towards larger vehicles and a shift towards infrastructure used by freight transport only are effective ways to reduce energy requirements and emissions.

• For road transport, a decrease in speed and a shift towards a maximum load factor are the most effective ways to reduce energy requirements and emissions.
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Figure 8.18 The influence of changes in single parameters on the SO₂ emissions of the transport of low-density goods by rail.

Figure 8.19 The combined impact of parameters changes on the SO₂ emissions of the transport of low-density goods by rail.

Figure 8.20 The influence of changes in single parameters on the SO₂ emissions of the transport of low-density goods by road.

Figure 8.21 The combined impact of parameters changes on the SO₂ emissions of the transport of low-density goods by road.

Figure 8.22 The influence of changes in single parameters on the NOₓ emissions of the transport of low-density goods by rail.

Figure 8.23 The combined impact of parameters changes on the NOₓ emissions of the transport of low-density goods by rail.

Abbreviations used in all figures on this page:
IE = indirect emissions, V = vehicles, I = infrastructure, Dir Em = direct emissions.
For the abbreviations indicated below the bars, cf. table 8.14.
Figure 8.24 The influence of changes in single parameters on the NOx emissions of the transport of low-density goods by road.

Figure 8.25 The combined impact of parameters changes on the NOx emissions of the transport of low-density goods by road.

Figure 8.26 The influence of changes in single parameters on the SO2 emissions of the transport of high-density goods by rail.

Figure 8.27 The combined impact of parameters changes on the SO2 emissions of the transport of high-density goods by rail.

Figure 8.28 The influence of changes in single parameters on the SO2 emissions of the transport of high-density goods by road.

Figure 8.29 The combined impact of parameters changes on the SO2 emissions of the transport of high-density goods by road.

Abbreviations used in all figures on this page:
IE = indirect emissions, V = vehicles, I = infrastructure, Dir Em = direct emissions.
For the abbreviations indicated below the bars, cf. table 8.14.
With regard to the indirect energy requirements and indirect emissions

- Energy efficiency improvements in steel, iron and asphalt production have little influence on the energy requirements and emissions.
- The infrastructure represents a higher energy savings potential than the vehicles.
- A shift from an infrastructure used by both passenger and freight transport to an infrastructure used by freight transport only has a larger energy savings potential than a shift from ‘2 tracks or 2 lanes’ to ‘4 tracks or 4 lanes’. The ratio between the capacity gain and the extra energy required for the infrastructure’s construction and maintenance is larger in case of a switch towards infrastructure used by freight transport only.

Limitations of the model calculations

The conclusions above are based on calculations in which the values of the transport system features were varied. Based on the calculations, energy requirements and emissions and energy and emission savings potential were calculated. However, these savings potential are theoretical potentials only. For instance, in practise, in transport networks, it is not possible to reach a maximum load factor and drive with fully-loaded trucks and trains. Also in practise, the infrastructure capacity may not be fully utilised. The calculated potential is not the real potential due to the logistic and organisation characteristics of the transport system.

Besides, in practise, the energy use for driving strongly depends on the number of stops and the amount of other traffic on the roads and tracks, instead of on the average driving speed. Therefore, in practise, a decrease of the average driving speed from 90 to 65 km/hour will lead to different changes in the energy requirements and emissions than calculated by the model. In this case, the real energy savings potential differs from the calculated potential due to the fact that the model is a simplification of a real transport system.

The examples show that the real energy and emission savings potentials differ from the theoretical potentials due to implementation barriers of the measures, due to assumptions incorporated in the model or due to the fact that the model is an oversimplification of reality. However, the model calculations are helpful to distinguish between parameters which have a strong energy and emission savings potential and those which do not have such a high potential. Additional research is required to determine whether the theoretical potential exists 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. Besides, the model calculations give insight in the differences among the various goods groups and the differences among rail and road transport.
Chapter 8

8.5 General conclusions

In section 8.1, it was stated that the energy requirements of specific transport activities probably differ from the energy requirements for an average Dutch transport activity because the goods transported and the characteristics of vehicles and infrastructure and their use differ from the average goods, vehicles, infrastructure and use. Next, in section 8.2.1, several features of the rail and road transport system were selected which were expected to dominate in the calculations 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, the load factor of the vehicles and the average driving speed. The freight transport model which was built incorporated all these features (cf. section 8.2 and 8.3). Next, in the case study 'heavy and light commodities, for two goods groups with different densities the influence of the vehicles, infrastructure, production and trip characteristics were analysed.

Indeed, from the analyses discussed in section 8.4, one can conclude that the energy requirements and emissions for specific transport activities differ from the Dutch averages for transport activities. (For the indirect emissions, similar observations can be made.) The energy requirements of the reference case of the transport of low-density goods by rail and road are 2.5 and 2.6 MJ/tonkm, respectively. Those of the transport of the high-density goods by rail and road are 0.8 and 1.7 MJ/tonkm, respectively. Thus, these values differ for the different type of goods and some of these values differ from the average energy requirements of rail and road transport which are 0.95 and 3.0 MJ/tonkm for rail and road transport⁴, respectively.

The different results between the low-density goods and high-density goods can be explained as follows. Less vehicles are necessary to transport 1000 tons of high-density goods than 1000 tons of low-density goods. Therefore, the total indirect energy requirements are lower for the high-density goods. The total direct energy requirements are also lower for the high-density goods than they are for the low-density goods. The direct energy requirements of each separate vehicle carrying high-density goods is higher. However, since speed and not load is the most determining factor for the direct energy requirements, the

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⁴ 0.94 MJ/tonkm for rail= 0.60 direct (cf. appendix A) + 0.34 indirect (process analysis estimate, cf. subsection 3.3); 2.96 MJ/tonkm for rail = 2.5 direct (cf. appendix A) + 0.46 indirect (cf. process analysis estimate, subsection 4.3).
energy requirements of vehicles do not double in case the load doubles. Less vehicles for the high-density goods therefore also result in lower total direct energy requirements. The difference between road and rail transport for the high-density goods is explained by the large difference in mass of the rail and road vehicles and therefore, the relatively low energy requirements for rail transport.

The average energy requirements for rail transport (0.94 MJ/tonkm) resemble those of the high density goods transported by rail. This meets expectations since rail vehicles in practise carry more high than light density goods. The average energy requirements for road transport resemble those of the low density goods. The average values are higher than the values calculated in the model since the model considers the main infrastructure only while the average values incorporate the total transport systems. For the direct and indirect emissions equal observations can be made.

Next, one can conclude indeed that the energy and emission results considered strongly depend on the values of some of the selected vehicles, infrastructure and use features. The features which influence the results considerably are the driving speed, the load factor, the size of the vehicles and whether the infrastructure is used by both passenger and freight traffic or freight traffic only. The production efficiency of both steel and asphalt as well as the number of lanes on the infrastructure have very limited influence on the energy requirements and emissions.

For rail transport, the indirect energy savings and energy savings potentials are as big as the direct energy savings and energy savings potentials. Increasing the load factor, introducing larger vehicles and introducing infrastructure for freight transport only are the most important energy savings options. For road transport and low density goods, the direct impacts are the largest. The largest energy savings can be reached by increasing the load factor. However, also large savings are obtained by a decrease of the average speed and a switch from road to rail transport. The energy savings potential for rail is larger than the one for road transport.

As was also stated in 8.4.4, real energy and emission savings potentials differ from the energy savings potential calculated by the model due to the fact that the model is an oversimplification of reality. For instance, the model does not fully represent the Dutch rail and road network since the model only incorporates the main infrastructure. Besides, real energy savings potentials differ from calculated potentials due to implementation barriers. It is possible that a measure with a relatively small energy savings potential is much easier to implement than a measure with a large energy savings potential. Therefore, in practise, the former measure may be more successful in reducing energy
requirements and emissions than the latter. Implementation barriers of the transport system features are not included in the model. Additional research is required to explore whether the potential energy and emission savings may occur in a real transport system.

The case study shows that the model is a helpful instrument to distinguish between the parameters with potential large energy and emission savings and parameters with limited potentials and is helpful to study strategies to reduce impacts from freight transport with regard to both direct and indirect energy requirements. Second, the model is helpful in studying the differences among various goods groups, the various vehicles and infrastructure types, the direct and indirect impacts and the differences between rail and road transport. Third, the model is a helpful instrument in order to study the impacts of new main infrastructure and therefore, in developing main infrastructure.

Finally, possibly undesirable consequences of energy and emission savings measures as investigated in the case study have not been discussed in this chapter. Among such consequences are the increase in delivery time of the goods due to a lower average speed of the vehicles. This may be unacceptable for the receiver of the goods. Such consequences of energy savings measures are outside the scope of this model and thesis. However, they are relevant and they should be included in additional research dealing with the feasibility of the measures.