7 Conclusions and discussions

7.1 Conclusions on main research question

The main research question, formulated in section 1.6, is how transport infrastructure developments can help to minimise the energy use of the transport system. The transport system in general consists of several transport modes. The thesis answers the main research question by considering mainly the transport mode that currently uses the most energy of all transport modes in the Netherlands: the road transport. The energy use of the road system originates in the energy requirements of the road infrastructure and of the road vehicles. The question of how developments can help is implicitly preceded by the question whether developments can help.

The thesis interprets road infrastructure developments as improvement or reduction of the road capacity. Generally speaking, improving capacity increases the energy requirements of the road infrastructure. In the public debate, traffic jams are often seen as environmentally bad. Following this line of reasoning, improving capacity might lead to reduction of the fuel consumption of the vehicles. Improving capacity would then lead to higher energy requirements for the infrastructure but to lower fuel consumption of the vehicles. Conversely, lower capacity would lead to lower energy requirements of the infrastructure but to higher fuel consumption. Therefore, it seems indeed that infrastructure developments can balance the energy requirements of the infrastructure and the fuel consumption of the vehicles, minimising the total energy use of the transport system.

The thesis only partly confirms the assumption of the previous paragraph. Indeed, inadequate road capacity leads to congestion and congestion leads to an increase in fuel consumption of the vehicles considered. However, the fuel consumption per vehicle per kilometre increases at high velocities too. The thesis shows that there is an optimal velocity at which the fuel consumption per vehicle to cover a specific distance is minimal. Besides the combined fuel consumption of the vehicles, the energy requirements of the infrastructure also influence the optimal velocity of the vehicles to minimise the energy use of the road transport system. First, the improvement of capacity requires energy during construction. Second, the existing capacity needs to be maintained in the future and third, an uncertainty arises due to the expected life time of the infrastructure. Therefore, the optimal capacity at which the energy use is optimal, does not equal the capacity at which the traffic flows with the velocity at which the fuel consumption is optimal. The difference between the optimal capacity and the latter capacity increases with the energy intensity of the road construction.

The thesis shows that the main research question cannot be unequivocally quantified for every road separately. The impact of the road construction on traffic flows over the road network must be taken into account when answering the question. As road construction can lead to an increase in total travel volume (through so-called generated traffic), any relative reduction in fuel consumption per vehicle can be offset by an absolute increase in transport performance. Induced travel over the network further emphasises the importance of adequately taking into account the behaviour of travellers as road construction activities change the characteristics of the road network. Construction strategies that fail to do so risk inefficient construction activities, lock-in situations and multiple network end states.
7.2 Conclusions on derived questions

7.2.1 Introduction

The thesis’ research resulting in the answer to the main question has raised several other questions on which this section will further elaborate, mainly by reflecting on examples in the transport system of the Netherlands.

7.2.2 The energy requirements of existing infrastructure

7.2.2.1 Rail infrastructure results

The first premise is that new infrastructure requires more energy than existing infrastructure due to the increased complexity of infrastructure systems and land use. The rail infrastructure developments in the Netherlands in the period 1990-1999 support the premise as the track length increased less than 1% while the embodied energy (with capital goods stocks as proxy) increased more than 25%. The indirect energy requirements of rail passenger traffic dropped from 0.31 MJ/pkm in 1990 to 0.22 MJ/pkm in 1991 due to increased rail travel as result of policy intervention in rail travel fees. In 1999, the energy requirements of rail traffic rose to 0.31 MJ/pkm. The energy requirements for rail freight remained constant at around 0.28 MJ/tonkm. The thesis observes that the decline in energy requirements of the rail infrastructure per passenger per kilometre due to increased travel was being compensated after ten years of construction, although the thesis does not establish a direct correlation between passenger traffic and construction activities.

7.2.2.2 Methodology

The input-output energy analysis is useful for quantifying the energy embodied in an entire network, e.g. the Netherlands’ rail network. A smaller geographical scale of subjects of study leads to decreasing accuracy of the analysis. The IOEA seems useful for quantifying the annual changes in energy efficiency of a specific transport mode. In determining the trends in energy efficiency, it is more accurate to use an analysis’ time scale in the order of the economic life time of the capital goods stocks.

7.2.3 The energy requirements for new infrastructure construction

7.2.3.1 Rail and road tunnels

The second premise of the thesis is that because increased complexity of the infrastructure systems and land use nowadays implies a better incorporation of new infrastructure in the existing landscape and surrounding environment, and because this incorporation increasingly takes place through the construction of artworks like viaducts and tunnels, the complexity therefore leads to increasing energy requirements of infrastructure. The premise is supported by the results on the energy requirements of the construction of major artworks. The thesis shows that the major artworks of road and rail tunnel require substantially more materials per distance than regular road or track amounting to 1.2±0.3 PJ/km for road tunnel construction, which is more than ten times the energy requirements of regular road construction.

7.2.3.2 Methodology

The energy analysis is useful for quantifying the energy required for specific construction projects. Although is it known that the upscaling of the results lead to decreasing accuracy of the analysis, the results can be applied nationwide for partial explanation of increased energy requirements of an increasingly complex network.
Therefore, it is concluded that the energy analysis can be used in research that focuses on the dynamical changes within a transport system.

7.2.4 The dynamic impact of infrastructure and traffic on energy use

7.2.4.1 Westerschelde road tunnel
The environmental cost-benefit analysis of the construction of the Westerschelde road tunnel shows that an energy efficiency improvement is possibly achievable through construction activities. Although the 3 PJ of energy used in the construction of the tunnel might be recoverable in only nine years, the analysis shows that the construction-induced changes in the transport volume most likely nullify the efficiency improvement.

7.2.4.2 Methodology
The environmental cost-benefit shows the balance of energy efficiency improvements through the infrastructure improvement and adverse effects on the energy use of the vehicles. The environmental cost-benefit analysis uses results of the environmental input-output analysis or the energy analysis as input. The annual changes in the energy balance show the importance of determining the life time of the infrastructure, a problem also notoriously present in stand-alone energy analyses.

7.2.5 The optimal road construction that minimises the total energy use

7.2.5.1 Single road
The optimal single-road capacity that minimises the total energy use of the single-road system depends on the available construction resources. First, there is a specific road capacity in the mathematical sense that requires the least energy. Second, if the optimal road capacity cannot be reached (or if the latter capacity cannot be maintained e.g. due to insufficient funds), the highest maintainable capacity is preferred. Third, the road should be upgraded as fast as possible to the preferred optimal capacity.

7.2.5.2 Methodology
The optimal control theory is a useful theory for simplifying the dynamic relation between the construction phase of infrastructure and its usage phase. The module developed using the optimal control theory quantifies the optimal road capacity with an uncertainty in the same order of magnitude as the uncertainty commonly encountered in an energy analysis.

7.2.6 The optimal network state that minimises the total energy use

7.2.6.1 Road network
The optimal network configuration consists of roads with similar ratios of traffic intensity to road capacity. The combination of the energy optimising construction strategy and the time-minimising behaviour of the travellers leads to two optimisation criteria within a single model.

7.2.6.2 Methodology
The module developed to optimise the energy use through capacity improvement is successfully integrated with a second module that optimises the travellers’ time. The resulting model contains two optimisation criteria, reflecting the complex interaction between road construction and traffic flows.
7.3 Discussions on the dynamics of the interactions encountered

7.3.1 Introduction

The relations between construction, capacity and use of infrastructure play an important role in the main conclusions of the thesis. The categorisation of the interactions as shown in figure 7.1 is the basis that this section uses for further discussions on the interactions possible occurring in infrastructure capacity planning.

Figure 7.1 Categorised overview of interactions between construction, capacity and use.

7.3.2 Efficiency improvements of capacity change

Insufficient road capacity leads to inefficient traffic flows, such as the existence of traffic jams. The latter congestion results in a higher energy use of the vehicles per kilometre than optimal. The combined traffic flows during the day that minimise the energy use consist both of free flowing traffic at off-peak hours and traffic jams at peak hours. The balance between them implies that at a given traffic intensity and road capacity, a certain congestion risk exists.

Capacity planning in the Netherlands takes the congestion risks into account; see e.g. A12. The congestion risk is defined as the probability of the occurrence of a traffic jam. Its probability calculation considers the traffic intensity distribution, but excludes the capacity effects of bad weather, accidents or junctions. Assuming a traffic jam being defined as a traffic flow with a velocity less than 60 km/h, the optimal capacity as calculated by the thesis can be recomputed into a congestion risk.

The thesis computes an optimal capacity of 1.4 times the average traffic intensity. However, figure 4.8 shows that the optimal capacity increases to 1.6 times the average traffic intensity if one ignores the capacity fluctuations due to bad weather and accidents. The default load-duration curve implies that a road with an optimal capacity has a velocity that is at 20% of the time lower than the optimal velocity of 80 km/h. Assuming linearity in velocity and i/c-ratio, the chance of a velocity lower than 60 km/h is 15%. Should any increase in capacity only be realised through energy intensive constructions, the congestion risk at roads with optimal capacity is even greater. The Netherlands’ capacity planning authority aims to keep the congestion risk below the 5% and preferably below 2%.

Large road capacities also lead to inefficient use of energy in the transport sector. From figure 4.2 follows that the higher velocities related to the large road capacity
imply a high fuel consumption of the vehicles. The traffic on a road with traffic intensity of 2000 vkm/h and a capacity of 5000 vkm/h uses 300 MJ/h more energy than optimal, or 0.15 MJ per kilometre per vehicle. With a total traffic performance of 47 · 10^9 vkm/yr on the Netherlands’ highways and with a CO₂ emission of 0.070 kg CO₂/MJ, this equals a reduction potential for CO₂ by reducing highway capacity of 0.5 Mton CO₂/yr. The result is in the same order of magnitude as the CO₂ emission reduction that would be achieved by preventing all traffic jams, which was 0.3 Mton CO₂/yr (see section 1.5.2).

7.3.3 Indirect effects of capacity improvement

Section 7.3.2 concluded that infrastructure construction can reduce the energy use of transport by changing the road capacity and providing an optimal capacity-intensity ratio. The thesis further shows that an increase in capacity leads to a greater appeal for a traveller to journey, or road construction leads to generation of traffic, which are often referred to as volume effects. These volume effects can also be regarded as societally beneficial, as transport volume is a proxy for the service volume rendered to society. The transport volume increase can be counteracted by (an increase in) road pricing; the success depends on the specific price-elasticity. General road transport pricing in the Netherlands in 2004 occurs among others through fuel taxes of 0.665 €/ℓ. Should the latter road pricing be replaced by an emission trading system, the level of fuel taxes would equal an emission price of €236/ton CO₂ ([Kok et al., 2001]: 2.819 kg CO₂/ℓ).

The thesis seems to indicate that the expected price of CO₂ emissions of €7.7/ton CO₂ barely influences the optimal road capacity. Only at a hundredfold CO₂ price, clearly different values for the optimal capacity emerge. Using the input data for the socio-economic analysis, the CO₂ emission price of emission reduction through capacity change can be computed. Figure 7.2 shows the costs in narrow sense, i.e. only based on the costs of the construction project. The figure shows that infrastructure construction as a measure to reduce CO₂ emissions is financially inefficient as the CO₂ abatement costs are more than €100/ton CO₂ while the expected CO₂ emission trading price is below the €10/ton CO₂.

![Figure 7.2 Abatement costs of CO₂ reduction by means of road construction strategies in narrow sense (‘financial’). The dotted lines show a CO₂ price that is comparable to the 2004 fuel taxes.](image-url)
The financial costs of reducing CO\(_2\) of road transport through construction strategy exceed €100/ton CO\(_2\). However, due to the indirect societal benefits of improved road capacity, a win-win situation occurs up to the energy optimum in the road capacity of 2700 vkm/h. Figure 7.3 shows that beyond the latter capacity, up to the socio-economic optimum of 3500 vkm/h (deduced from figure 6.13), the energy use rises with increased capacity.

![Figure 7.3 Comparison of the direct project-based costs of CO\(_2\) reduction through infrastructure construction and the indirect socio-economic benefits at the expense of an increase in CO\(_2\) emissions.](image)

In the latter capacity range, socio-economic benefits occur at the expense of increased CO\(_2\) emissions. However, the societal benefits (~€100/ton CO\(_2\)) outweigh the mitigation costs (€7.7/ton CO\(_2\)). Given the current socio-economic context, construction improvement strategy is not a cost-effective method of reducing CO\(_2\) emissions. Wherever the road capacity is larger than the socio-economic optimum, it is not only beneficial from a socio-economic perspective to reduce the capacity, but the latter capacity reduction is indeed a cost-effective method of reducing CO\(_2\) emissions.

The socio-economic context is likely to change within the time span of the current analysis of at least 80 years. A greening of the tax system might lead to a reduction in labour costs. As travel time savings are related to labour costs, the impact of travel time savings in the analysis will diminish too. Furthermore, the CO\(_2\) emission trading price is related to the Kyoto-agreed emission ceilings. The thesis expects (see figure 6.11) and calls for (see section 1.1) lower emission ceilings in the future. The thesis supposes therefore that the CO\(_2\) emission trading price will rise significantly above the €7.7/ton CO\(_2\), while the social-economic benefits of improving the road capacity beyond the energy optimum will drop significantly below the 2004 social-economic benefits in the order of €100/ton CO\(_2\). As a result, it is expected that the future socio-economic optimal road capacity slowly shifts towards the energy-optimal road capacity the thesis has determined.
7.3.4 Path-dependency

The occurrence of path-dependency requires two necessary conditions. First, at some point in the transition the effects of two different policy measures should only be marginally different. Second, multiple optimisations occur simultaneously. To answer the question whether path-dependency can occur in a system of several transport modes, this section considers a transport corridor comprising of a motorway and a competing railway. The public rail transport is fed by a city bus network, see figure 7.4 and figure 7.5. The quality of the city bus network is a proxy of the delay time for a public transport passenger on the corridor.

Figure 7.4 Schematic view of the system considered: a railway and motorway corridor, with the rail transport being fed by a city bus network.

Figure 7.5 System overview showing the three different optimisations and the feedback loop that might result in path-dependent behaviour.

The system considered includes three optimisations, see also figure 7.5: 1) the bus company optimises on finances, implying a ‘financially optimal’ delay time for train passengers; 2) the train passengers optimise on travel time, implying a
preferable travel mode; 3 the government optimises on energy, implying an ‘energy optimal’ motorway and railway capacity.

A possible decoupling point exists when the governments puts the city bus transport out to tender. A policy measure to cut subsidies in the tender of the city bus transport would lead to a reduction of the quality of the bus transport and thus to an increase in delay times for the train passengers. Increased delay times enhance the appeal of road transport to the passengers. As a result, the traffic intensity on the motorway will increase. The increased traffic intensity will result in higher road capacities by the energy minimising behaviour of the road planning authority. Gradually, passenger will change from train travel mode to road travel mode until eventually, only some autonomous number of train passengers, for whom road transport is never a reasonable option, remains in the public transport mode.

Alternatively, sufficiently fast and frequent bus transit possibilities exist, ensuring that for many people travel by public transport on the corridor is faster than the road travel on the motorway which its optimal velocity of 80 to 90 km/h. A free public transport system as introduced in the Belgium city of Hasselt is an example of a policy measure which might induce this alternative transition path. All possible mode-shifters will shift from road transport to rail transport, necessitating a reduction of the motorway capacity. Through this reduction, the motorway velocity is constant at the optimal velocity, while increasingly more people are using the train travel mode. Essential in this line of reasoning is the absence of energy efficiency losses when the traffic intensity on the railway increases. The IOEA analysis of chapter two shows that the rail network can accommodate large traffic intensity rises without a substantial rise of the energy requirements of rail infrastructure (0.30 MJ/pkm). Furthermore, the fuel and electricity use of trains of approximately 1 MJ/pkm is probably less than the minimum energy use of of road travel, although the latter is dependent on changes in the car occupancy.

7.4 Concluding remarks
The interaction between infrastructure planning, policy and traffic is shown by a weak coupling of traffic increase leading to infrastructure planning, see the developments in the Netherlands’ rail sector. The interaction is shown by a strong coupling of infrastructure planning leading to traffic increase (see Westerschelde road tunnel) and by the impact policy has on infrastructure planning directly, and on transport volume indirectly. The potential of road construction to reduce the energy use in the transport sector seems to be largest in cases of bottlenecks or missing links. Adversely, road construction generates most traffic just in the cases of bottlenecks and missing links.

The conclusions of chapter two are largely methodological. The problems encountered in applying the selected methodologies on the thesis’ main question are inherent to the common usage of the methodologies. However, the energy analysis – or the life cycle assessment in broader context – does not commonly include a spatial or temporal differentiation in environmental pressures. The absence of time differentiation is a weakness of the life cycle assessment, causing a substantial uncertainty in the field of environmental transport research due to the difficulty in determining the average life time of the infrastructure elements. The CEMENT module is a time discounting energy analysis and the module shows the strength of including time discounting in energy analyses that cover a large time span.
The mathematical framework developed in the thesis focuses on the improvement of existing road infrastructure and on the impact the congestion has on energy efficiency of transport. The framework can be adjusted to include the abandoning of ferry connections and other phenomena. However, the thesis uses the framework to assess the dynamics of the relation between road construction and total energy use. By adopting a minimalist approach, the dynamics described in the thesis are representable for the transport network in general.

The dynamics imply a weighing of energy use for construction at one time and the subsequent future energy use of the transport. The latter weighing of energy use in time or the so-called time preference of energy use is primarily based on the expected functional life time of the infrastructure. Alternatively, a valuation method has been applied based on emission ceilings. It shifts the preference for energy use reduction backwards in time. Anticipating the introduction of low emission vehicles or zero emission vehicles, one might assume that the future benefits of infrastructure improvement diminish, which would result in lower optimal capacities. Instead, the transition to sustainable transport through the introduction of zero or low emission vehicles occurs at a slower pace than required by the need to reduce emissions as a transition to sustainable development. The slower pace increases the need to reduce the energy use in the near future. Until 2030, the potential of energy use reduction through infrastructure improvement as stated in the thesis is therefore a lower bound estimate.

The thesis uses the fossil fuel based energy use as optimising variable, since it is mostly concerned with the greenhouse gas emissions. However, even the low or zero emission vehicles still require a source of energy. The introduction of those vehicles might therefore result in a future trade-off of emissions from the transport sector to the electricity sector. Other trade-offs are also a point of caution for interpreting the results of this thesis, as the thesis only looks at energy use. One point of attention is already given in the case of the construction of urban bypasses as deepened roads. The pressures on the local landscape and environment are in the case of deepened roads limited on the expense of energy use. Therefore, a trade-off from local pressures to global pressures occurs, now and in the future. Conversely, a construction strategy that is solely based on the minimisation of energy use does not care for e.g. the health issues related to the transport and unjustly so. The risk of similar reverse trade-offs from energy use to other environmental pressures diminishes as the introduction of zero or low emission vehicles proceeds.

The total energy use of the transport system remains a persistent problem, and it is generally good practice to consider multiple options to reduce the energy use. The thesis’ main CONCRETE model assumes the transport performance as an invariable parameter. However, if a policy aimed at reducing the traffic and transport performance is successful, the success implies that the capacity of the infrastructure should be improved less since the roads will be used less. The latter policy is aimed at end use savings of energy, while the thesis shows possibilities to increase the efficiency of energy use, with or without substitution of currently used fossil fuels by future renewable ones.
7.5 Final considerations

The thesis sets the research scope against the current decision-making status on transport and the environment in the Netherlands. At the end of 2004, relevant policy documents published are the National Spatial Strategy [MinVROM, 2005], the Mobility Policy Document [MinV&W, 2005], and the Traffic Emissions Policy Document [MinVROM, 2004b]. The National Spatial Strategy aims to concentrate infrastructure and urbanisation. The thesis acknowledges the interaction. Regarding the infrastructure foremost as connection between cities, the thesis only comments that spatial planning can contribute to a better use of existing infrastructure. Secondary effects of spatial planning are outside the scope of the thesis. The co-existence of an infrastructure planning document and a transport emission reduction plan remained since the previous National Traffic and Transport Plan and the Climate Policy Implementation Plan. It puts a major emphasis on vehicle efficiencies of energy use, while it fails to consider the impact transport infrastructure can have on the transport emissions. The Mobility Policy Document discusses the road transport mode separately from other transport modes. The thesis indicates that the latter optimisation of a subsystem might lead to a different end state of the infrastructure than one that is optimal, from both an environmental and socio-economic perspective.

The thesis promotes a change in road capacity to meet the transport demand. The capacity should match the transport demand to ensure an average traffic flow velocity of 80 km/h to 90 km/h, and preferably a constant traffic intensity throughout the day. Disregarding the potential of temporary additional lanes (spits-, wissel- and plus-strook), the occurrence of traffic jams during rush-hours, up to 15% of the time, are more environmentally preferable than infrastructure without any traffic jam. The latter temporary lanes are also energy intensive, as secondary research [Alberts, 2002] has shown, which make them most likely unsuitable as energy reduction measure. In line with the reasoning of the Mobility Policy Document, road pricing is the environmentally best auxiliary policy measure as it has the potential to redistribute the traffic intensity during the day. The more even the intensity distribution, the less traffic jams will occur and the less energy will be used. The thesis shows that there is no aggregated correlation between the frequency of traffic jams and the relative energy use of road transport, so road pricing can lead to a win-win situation for energy and socio-economics.

Even with the gradual introduction of zero-emission vehicles or low-emission vehicles, it is environmentally more sustainable to reduce the capacity of most Netherlands’ highways, and improving only the most congested bottlenecks. The capacity improvements of bottlenecks should be constructed as simply as possible. Careful embedding of the improvements to safeguard the natural surroundings and living environment will be at significant expense of energy use. The only apparent sustainable alternative is a significantly faster introduction of zero-emission vehicles, including their supply of renewable energy, than currently expected. The thesis falsifies the aggregated statements that combating traffic jams is good for the environment, although the statements can hold for some rare bottlenecks. Therefore, the dynamic relation between infrastructure planning and the energy use of travelling requires more attention in policy. It requires attention especially in long term policy planning, since transport will always require energy and transport will always remain. After all, always has been and always will be the fact that people travel.