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Development of a dynamic supply model on passenger transportation

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Abstract

This paper describes the development of a dynamic supply model on passenger transportation. The model can be used to calculate future energy use, space use, travel time and costs of passenger mobility. Next to that, the model can be used to point out whether there are optimal transportation modes, i.e. transportation modes that score equal or better on each of the four variables than all the other modes. In order to do this, a distinction is made between two societal variables (energy use and space use) and two individual variables (travel time and costs). For this analysis, the concept of Pareto optimality is used. A system is Pareto optimal if no other system scores equal or better on each of the criteria used.

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About the Author

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Development of a dynamic supply model on passenger transportation

Mirjan Bouwman

1. Introduction

Transportation is generally considered a positive good. Mobility offers the opportunity to expand a persons' world. Transporting a person over a distance has a lot of side effects on other fields, too: it requires energy, it takes time, causes noise, etc. Often, these side effects of mobility are taken for granted. However, side effects are generally not considered desirable. On the contrary, in general, the aim could be to minimise these side effects.

There is a large variety of transportation systems, each with its own characteristics. This means that every system shows different side effects or a different amount of the side effects. This points to the existence of efficient transportation systems. An efficient transportation system is defined as a system in which it is no longer possible to reduce any of the side effects of passenger transportation without increasing another effect.

The analysis made in this paper is based on the Dutch situation in 1996 and makes forecasts until 2025. Mobility is considered a derived good, making it possible to achieve other goals. This is valid for the majority of all trips made. Only those trips with the explicit purpose to go for a ride (four per cent of all kilometres) should be excluded in this analysis as in these trips the mobility is a goal in itself.

2. Various side effects of passenger transportation

This section describes a variety of side effects that occur using various transportation modes. These effects are more pronounced for some modes than for others.

The first effect normally visible for an individual is that, dependent on the average speed of the transportation system, travelling a certain distance requires a certain time investment. Since time is valuable, people like to reduce the travel time spent.

Another way to look at the phenomenon of minimising the travel time is by looking at travel time budgets. According to various sources (Hupkes, 1977; Schafer and Victor, 1997), individuals have a relatively constant travel time budget of about an hour and a half per day. Reasoning this way, people can extend their mobility as soon as quicker means of transportation are available. Minimising transportation time is than more complicated: it would in fact be a derived goal, since the main objective is to maximise travelling distance, which in turn is only possible with a fixed time budget if the speed of the system increases.

A second effect that is visible for an individual for most trips is that one has to pay to use a transportation system. Each mode has some costs, sometimes very well visible (for example in the case of public transportation, where one has to buy a ticket for each trip), and sometimes almost invisible (the costs of walking might only be visible in an increased wear for shoes). In general, the most important distinction in costs is between fixed and variable costs. Fixed costs are independent of the amount of travel: they have to be paid anyway e.g. the purchase of a car. Variable costs only occur when an actual trip is made e.g. the costs of fuel.

Somewhat less visible, and perhaps not even a consequence, but more a restriction to make transportation possible, is the space needed for infrastructure. Space use is generally not an issue at the individual level, but may be an important issue at a governmental level, especially in countries like the Netherlands, where space is a scarce good.

Transporting persons also requires energy. The energy requirements of transportation can be divided in direct energy use, i.e. energy use associated with the actual driving of a vehicle, and indirect energy use, comprising the energy needed to produce and maintain a vehicle. This division corresponds with the fixed and variable costs.

Directly related to the use of energy are the emissions associated with transportation. Combustion of fossil fuel results in the generating of CO_2, H_2O, NO_x, SO_x, etc. Some of these components may give rise to environmental problems. Transportation has a big share in several of these emissions. In 1995, it emitted 61 % of all CO in the Netherlands, 62 % of the NO_x, 40 % of particles and 22 % of all SO_2, and had a share of 18 % in energy use and CO_2 emissions (RIVM, 1997).

A lot of accidents occur in transportation. In 1990, 1376 people were killed in traffic, while 13 652 people were injured so seriously that they went to hospital (CBS, 1995a). This means that on average for every 100 million kilometre travelled, 0.7 persons are killed (CBS, 1995b; CBS, 1996). Although it is normally not regarded as such, mobility has some serious inherent risks.

Moving vehicles normally also generates noise. This might not be a real problem for the users of the system, but is very annoying for the inhabitants next to the infrastructural provisions. In 1995, 30% of the Dutch population said to be annoyed by the noise caused by road transportation, 5 % by the noise of rail traffic (RIVM, 1997).

3. Side effects of transportation comprised in the model

This paper describes the development of a dynamic model, in which these side effects of mobility are included. Not all side effects mentioned are included. A selection of four criteria was made. Two criteria at the individual level (costs and travel time) and two at a societal level (space use and energy use). The choice was made to model energy use, because it is quite a good representative of at least the CO_2 emissions. But other emissions are generally related to the amount of energy used. Including these other emissions associated with transportation in a later stage might be a valuable extension of the model.

Space use is included in the model, because it is a clearly limiting factor in a densely populated area as the Netherlands. The extension of any infrastructural system faces a lot of difficulties. A system using less space is therefore preferable over systems using more space.

At an individual level, several criteria seem to influence the preference for a certain system, for example habits, comfort, costs and travel time. The latter two will be included in the model. Since other criteria are less easily translatable in model terms, they are not included in the first version of the model.

4. Structure of the model

4.1 Basic scenario input: mobility demand

The model is not a traditional optimisation model, but it is based on scenario inputs. The main input of the model consists of the average mobility demand per inhabitant per day specified by mode and trip length. The figures for 1996 are listed in table 1.

Table 1. Average mobility demand in kilometre per inhabitant per day, the Netherlands, 1996, by mode and trip length.

	Car	Train	Bus, tram metro	Bicycle	Walking	Other modes	Total
Under 2.5 km	0.53	0.00	0.03	0.74	0.56	0.03	**1.90**
2.5 – 5 km	0.96	0.00	0.09	0.74	0.15	0.05	**2.01**
5 – 10 km	2.30	0.02	0.27	0.66	0.13	0.12	**3.48**
10 – 20 km	4.55	0.18	0.46	0.43	0.05	0.21	**5.88**
20 – 50 km	6.53	0.55	0.37	0.22	0.00	0.20	**8.19**
Over 50 km	10.20	2.05	0.16	0.08	0.00	0.28	**12.77**
Total	**25.07**	**3.10**	**1.38**	**2.88**	**0.89**	**0.89**	**34.22**

Source: (CBS, 1997c, figures modified)

This table shows the average daily mobility. On average, people travelled 25.07 kilometre by car each day, of which 6.53 km in trips between 20 and 50 kilometre. For interpreting this figure, it is useful to have a look at the number of trips that inhabitants made during one day (see table 2). Then one can see that the total of 25.07 kilometre is made on average in 1.67 trips, which means a total average length of the car trips of 15 kilometre. If one takes a look at the trips between 20 and 50 km, the average 6.53 km is made in 0.27 trips, implying an average length of 24 kilometre for trips in this category.

The information from table 2, however, is not needed for the model, it only helps in interpreting the input.

Table 2. Number of trips travelled per inhabitant per day, the Netherlands, 1996, by mode and trip length.

	Car	Train	Bus, tram metro	Bicycle	Walking	Other modes	Total
Under 2.5 km	0.36	0.00	0.01	0.61	0.58	0.03	**1.59**
2.5 – 5 km	0.29	0.00	0.02	0.19	0.04	0.00	**0.54**
5 – 10 km	0.35	0.00	0.03	0.14	0.02	0.02	**0.55**
10 – 20 km	0.29	0.01	0.03	0.04	0.00	0.01	**0.38**
20 – 50 km	0.27	0.03	0.03	0.01	0.00	0.00	**0.34**
Over 50 km	0.11	0.03	0.00	0.00	0.00	0.00	**0.14**
Total	**1.67**	**0.07**	**0.10**	**0.98**	**0.64**	**0.08**	**3.54**

Source: (CBS, 1997c, figures modified)

The model calculates the four outcomes for a period of 30 years. The base year is 1996, the last year is 2025. A 30 years period is interesting because it creates the opportunity to make changes in both the vehicle fleet and the infrastructural facilities. The disadvantage is that it is not possible to make good forecasts on the long-term developments in mobility demand on a detailed level like required in table 1. In this paper, only one scenario will be run with a continuously increasing mobility demand. This is described in more detail in section 5.

4.2 Translating mobility demand into vehicle kilometres

The main input of the model consists of the mobility demand by mode and trip length. First this should be translated into a demand for vehicle kilometres. For doing so, one needs the average occupancy rate of vehicles. It is assumed that this rate differs per vehicle type but is equal for each trip length (this is a simplification, since it is known that at least for passenger cars there are small differences in the average occupancy rate by various trip lengths).

4.3 Vehicle characteristics

In order to calculate the various model outcomes, the characteristics of the various vehicles providing the mobility should be calculated. For each construction year, average characteristics on the various vehicles should be defined as model input. The new sales of the past thirty years should also be defined. As of that moment, the composition of the fleet is determined by a function that calculates for each year which share of the original sales of a construction year is still functioning. This function is shown in figure 1.

It shows the number of vehicles left after a certain amount of time. In this example after ten years 50% of the original sales have disappeared from the fleet.

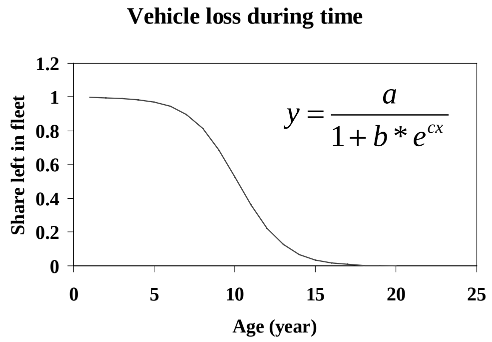


Figure 1. Share of vehicles left in the fleet

By using this function for each construction year, the composition of the fleet in a certain year can be calculated. For each construction year, it is calculated how many vehicles remained in the fleet by using the function from figure 1. Summing this for all construction years gives the number of vehicles left from former years. The total fleet needed to fulfil the mobility demand in a certain year is calculated by dividing the total mobility demand by the average yearly number of kilometres driven by car. The difference between this amount of vehicles and the number of vehicles that are still in the fleet from former years forms the new sales. In the next step of the model calculations, these new sales are added to the vector containing the new sales of the former years, and the calculations can start all over again.

Another characteristic in transportation is that new vehicles are, generally, used more than older vehicles. The annual use is described as a logarithmic function of the age of the vehicle. Multiplying for each construction year the number of vehicles by the annual use, results in the total number of kilometres by construction year.

The characteristics of the vehicle fleet can in turn be used to calculate the average value for the fleet. For example, in order to calculate the average energy use per car kilometre for the total car fleet, one should multiply the number of kilometres driven by cars from a certain construction year with the average energy use of the vehicles built in that year. Dividing this result by the total number of kilometres driven results in a fleet average energy use per vehicle kilometre.

In this way, also other fleet characteristics can be calculated, like the average weight of the vehicles, or the material composition.

4.4 Calculating the travel time

The first model outcome to be calculated is the average travel time. The average travel time depends on both the trip length and the average speed of the vehicle. The average speed is calculated based on the speed distribution per infrastructure type. This is another model input. In order to calculate the average speed of a vehicle out of the speed distribution by type of infrastructure, one also need to know the division of the trip over the several types of infrastructure.

The speed distribution by type of infrastructure is normally defined in terms of time. A typical distribution of highway traffic may show that the vehicle is working idle for five per cent of the time (due to congestion), a few percent of the total time working in low speeds, but most of the time in the higher speed regions. With this information, the average speed of the vehicle on the highway can be calculated. Crucial assumptions in the mobility scenarios may also result in changes in the speed distribution. When for example a big increase in mobility is expected, this may lead to an increase of the congestion on highways, and thereby in an increase of the share of idle running in the speed distribution.

The final travel time by trip length is calculated by dividing the trip length by the corresponding average speed.

4.5 Calculating the energy use

The second of the four model outcomes to be calculated is the energy use by trip length and mode. The energy use of a vehicle is closely related to the average speed of the vehicle, as is shown in figure 2.

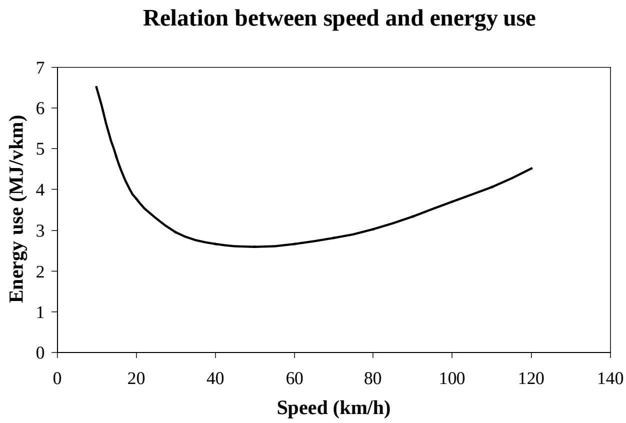


Figure 2. Relation between speed and energy use

Therefore, the calculation of the direct energy use is based on the same speed distribution as the calculation of the travel time. The energy use is calculated for various speeds according to the relation in figure 2. Combined with the fleet composition information providing the number of kilometres driven by each construction year, the direct energy use can be calculated.

The indirect energy use, the energy use associated with the production and maintenance of the vehicles, is calculated in another way. Once more, it is based on the subdivision of the fleet.

The indirect energy use is calculated, based on the material composition of a car (and the GER –Gross Energy Requirements- values of the various materials, this means the amount of energy needed to produce a unit of the material), the production energy use and the maintenance energy use. This information is defined in the vehicle characteristics. The value per kilometre is calculated by dividing the total value by the number of kilometres driven throughout the whole lifetime. By means of the distribution of the total annual mobility over the various construction years, the average indirect energy use can be calculated in the same way as the direct energy use.

The energy use figures are given in those three formats: the direct, indirect and total energy use per kilometre by mode and trip distance.

4.6 Calculating the space use

The space use of transportation is directly related to the infrastructure provided for a certain transportation mode. Infrastructure is provided for a long lifetime and is generally also used for freight transportation. We divide the infrastructure use for freight and passenger transportation along the same system as used in (Bos, 1998). A second division is made for various modes, in case they use the same infrastructure (for example buses and passenger cars both use the roads within the built up area).

Space use is limited to the direct space use of the system. Land losses due to, for example, noise nuisance are not included. In the calculations, the total area used for infrastructure is divided by the number of passenger kilometres made by that mode. This means that there is no distinction among the various trip lengths in terms of space use.

The total area of land covered with infrastructure depends on the total length of the infrastructure and the average width.

4.7 Calculating the costs

The last model result concerns the costs associated with transportation. For calculating costs, the same deliberations can be made as in the case of space use. There are a lot of costs that are caused by the use of transportation, but which are not paid for by the users. Examples of these costs are the decrease in land value around the infrastructure or the emissions caused by transportation. These costs are usually known as external costs.

External costs are not included in the model calculations. It requires a lot of effort to calculate them while they will not be of any importance for the individual user. They are called external costs because they are usually not included, which means that they will not influence any decisions at the individual level.

However, at least a few of the external costs are somehow included in the actual costs of transportation. For example, the costs for medical care after accidents are normally paid for by insurance companies, which charge the users for the same amount of money in form of insurances. The costs for constructing roads etc. are also paid by individual users, as they pay taxes to the government, which constructs them. So, the costs included in the model can be regarded as full user costs; all the costs associated with the ownership of a vehicle (taxes, insurance, maintenance) are included in the calculations.

The fixed costs of transportation are divided by the number of kilometres. In this way, the total costs become variable, and can be added to the real variable costs. Fixed costs comprise the subscription costs, vehicle purchase costs, taxes and insurance costs. The variable costs comprise the fuel costs/ticket costs and the maintenance costs.

The model calculates the variable costs by multiplying the energy use by the average fuel price in the case of passenger cars, and by the average price of tickets in the case of public transportation.

For the fixed costs, no distinction is made to age, although this is relevant in every day life (purchase costs of cars are written off faster in the first years of the vehicle lifetime).

5. Description of input data

For 1996, the figures for the mobility demand are used as shown in Table 1. The mobility demand for the period 1997-2025 is derived under the following assumptions. First, it is assumed that the subdivision of the mobility over the various modes remains the same, and so does the subdivision of the total demand over the various trip lengths. Next to that, there is an assumed increase in the mobility demand of one per cent per year.

The length and width of the various types of infrastructure are based on statistic sources (CBS, 1997a; CBS, 1997b). Table 3 shows the figures used for 1996.

Table 3. Figures on infrastructure in the Netherlands, 1996

Type of infrastructure	Length (km)	Average width (m)	Total area (ha)
Highways	2207	35	7 725
Primary roads	7296	12	8 755
Secondary roads	48700	10	48 700
Roads inner built-up area	55217	8	44 174
Single rail track	950	20	1 900
Double rail track	1810	45	8 145
Rail tram and metro	422	4	169
Cycle tracks	17075	3	5 123
Footpaths	40000	2	8 000

Several assumptions are made on the growth or decline of the types of infrastructure. For the four road types, an annual increase is expected with 1.0 %, 0.4 %, 0.2 %, and 0.05 % respectively. The total length of the rail infrastructure is assumed to be constant, although every year one per cent of the single rail track is expanded to a double rail track. The length of the rail infrastructure for tram and metro and the length of the cycle tracks and footpaths are kept constant during the period 1996 – 2025.

Most of the infrastructural categories are used both for passenger and freight transportation. The total area of infrastructure should therefore be allocated to both forms of transportation. Table 4 gives an overview of the share of infrastructure that can be assigned to passenger transportation.

Table 4. Share of infrastructure used for passenger transportation

	Highways	Primary roads	Secondary roads	Roads inner built-up area	Single rail track	Double rail track	Rail tram and metro	Cycle tracks	Footpahts
Share	0.4	0.5	0.6	0.8	0.8	0.8	1.0	1.0	1.0

The size of the Dutch population is assumed to increase from 15.4 million inhabitants in 1996 to 17.1 million in 2025 (CBS, 1997d). The average number of passengers in a vehicle is kept constant during that time at 1.66 passengers per passenger car, 127 per train, 10 per bus, tram or metro, and 1.5 per vehicle in other modes.

The size of the vehicle fleet depends on the new sales of former years. The new sales for the period 1966 – 1995 are used as model input. Table 5 lists the used values.

Table 5. New sales of various vehicle types, the Netherlands, 1966 - 1995

Year	Passenger cars	Trains	Buses, trams and metros	Bicycles	Other vehicles
1966	304 000	300	600	616 000	5 000
1970	432 000	300	500	850 000	5 000
1975	450 000	300	700	1 066 000	5 000
1980	450 000	300	1 100	1 453 000	5 000
1985	496 000	300	800	964 000	5 000
1990	503 000	300	1 100	1 350 000	5 000
1995	400 000	300	600	1 200 000	5 000

In order to calculate the travel time of the various modes, the speed distributions per type of infrastructure and the division of the trip over the various infrastructures should be defined. Both division are assumed to be constant in these calculations. No reliable sources are found providing detailed information on speed distributions. The distributions in table 6 are based on several assumptions. The average speeds resulting from the distributions match average speeds like they are found in literature.

Table 6. Speed distribution of vehicles on various types of infrastructure.

Speed (km/h)	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
pc-hw	0.05	0.02	0.03	0	0	0.02	0.01	0.02	0.02	0.05	0.2	0.22	0.33	0.03	0	0	0	0	0	0	0
pc-pr	0.08	0.02	0	0	0.01	0.05	0.02	0.15	0.5	0.05	0.1	0.02	0	0	0	0	0	0	0	0	0
pc-sr	0.1	0.05	0.02	0.02	0.02	0.09	0.15	0.15	0.4	0	0	0	0	0	0	0	0	0	0	0	0
pc-rib	0.2	0.1	0.1	0.18	0.15	0.22	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0
tr-rst	0.2	0.07	0.07	0.09	0.05	0.1	0.15	0.2	0.15	0.1	0.02	0	0	0	0	0	0	0	0	0	0
tr-rdt	0.1	0.02	0.02	0.02	0.04	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	0	0	0	0
btm-hw	0.02	0.02	0.03	0	0	0.02	0.01	0.02	0.2	0.24	0.19	0.15	0.1	0	0	0	0	0	0	0	0
btm-pr	0.05	0	0	0	0.01	0.05	0.02	0.22	0.58	0.05	0	0.02	0	0	0	0	0	0	0	0	0
btm-sr	0.1	0	0	0	0	0.08	0.18	0.18	0.46	0	0	0	0	0	0	0	0	0	0	0	0
btm-rib	0.15	0.08	0.08	0.21	0.18	0.25	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0
btm-rtm	0.12	0.12	0.05	0.05	0.4	0.38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
bi-sr	0	0.5	0.4	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
bi-rib	0	0.8	0.1	0.08	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
bi-ct	0	0.3	0.6	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
wa-rib	0.6	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
wa-wl	0.4	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ot-hw	0.05	0.02	0.03	0	0	0.02	0.01	0.02	0.02	0.05	0.2	0.22	0.33	0.03	0	0	0	0	0	0	0
ot-pr	0.1	0	0	0	0.01	0.05	0.02	0.15	0.5	0.05	0.1	0.02	0	0	0	0	0	0	0	0	0
ot-sr	0.15	0.05	0	0	0	0.1	0.15	0.2	0.35	0	0	0	0	0	0	0	0	0	0	0	0
ot-rib	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ot-ct	0	0.1	0.8	0.08	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Legend: pc –Passenger car; tr – Train; btm – Bus, tram and metro; bi – Bicycle; wa – Walking; ot – Other vehicles; hw – Highway; pr – Primary roads; sr – Secondary roads; rib – Roads inner built-up area; rst – Rail single track; rdt – Rail double track; rtm – Rail tram and metro; ct – cycle track; wl – walking lane.

Next to that, information is needed on the price of mobility. Prices for public transportation are based on the average ticket price. Values vary with distances. Especially short distance trips are more expensive as shown in Table 7. Prices for car mobility depend on the price of fuel (DFL 2/litre) and the fixed prices of ownership. Costs of travelling by bicycle consists of purchase costs of the bike, maintenance and clothing.

Table 7. Price of various modes by trip length, 1996 (DFL/passenger km)

Trip length	< 2.5 km	2.5 – 5 km	5 – 10 km	10 – 20 km	20 – 50 km	> 50 km
Passenger car	0.22	0.23	0.24	0.26	0.29	0.31
Train	0.98	0.52	0.26	0.24	0.22	0.21
Bus, tram, metro	1.00	0.60	0.35	0.20	0.17	0.14
Bicycle	0.07	0.07	0.07	0.07	0.07	0.07
Walk	0.02	0.02	0.02	0.02	0.02	0.02
Other modes	0.25	0.25	0.25	0.25	0.25	0.25

6. Interpretation of the model results

The model produces a large variety of results. The energy use (both direct and indirect), space use, costs and travel time per kilometre are calculated by year, mode and trip length per inhabitant. Summation of the results may lead to more easily comprehensible results, like for a whole population over a year, for all car trips, or for all short trips. The variety of results leads to a variety of purposes to use the information and outcomes of the model.

6. 1 Interpretation of the results

First of all, the dynamic model can be used to assess how overall energy use for passenger transportation changes during the next decades, and how big the influence of new technological developments may be on this. This result is comparable to that of several other models calculating energy use and emissions of transportation (Van den Broecke/Social Research, 1988; Schenk, 1998; Geurs *et al.*, 1998).

Next to that, the model results also tell which part of the total mobility costs most time, energy etc. This illustrates the effects of an increase of the mobility demand on the several scores. For example, one can clearly see whether an increase in short trips influences the model results stronger than an increase in longer trips or vice versa. This information is new compared to the traditional models, where such a distinction is not usually made.

The main interpretation of the model is the actual comparison of the different transportation modes for the various trip lengths. For this purpose, the modes should first be made comparable. In practice, not all of the modes mentioned in Table 1 can be used to make a door-to-door trip. For using any form of public transportation, a combination of public transportation with at least one of the soft modes is needed.

The statistics face the same problem. In table 2, the trips are ordered after main transportation mode. This means that a trip with a length of five kilometres which is made both by train and bike, is put in the statistics as a five kilometre trip by train in table 2. In table 1, this trip could show up in 3.0 km by train in the five kilometre trip category, and two km by bike in the five kilometre trip category.

For this reason, trips by public transportation can be regarded as a linear combination of the results of at least two different transportation modes. This means that one can compare a 15-kilometre trip by car with a trip by train consisting of 12 km by train and 3 km by foot. Besides that, a correction factor may be needed for the comparison of the two modes in order to correct for possible detours.

6.2 Pareto optimality

In making a comparison between several transportation modes and pointing out an optimal or most efficient mode, one can first consider whether there will be a system that scores better on all variables. The chance that this will be the case is very small. So, normally, another method is needed to arrive at the efficient system. A generally accepted way of doing this is to see which systems are Pareto optimal. According to the definition, a point is Pareto optimal if the score on either of its variables cannot be further optimised without having a negative influence on any of the other variables (Ba∏ar and Olsder, 1995). Figure 3 shows an example of this definition.

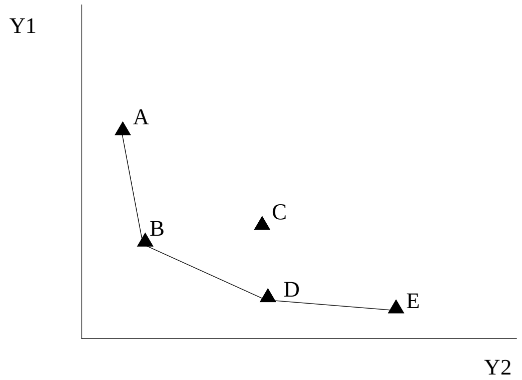


Figure 3. Pareto optimality

In figure 3, the aim is to minimise both outcomes Y1 and Y2. Five different points have been analysed, each with other scores on the two variables. In this case, there is not one point which scores better on both variables. This means that there is not a clear optimal or most efficient solution.

Four of the five points in figure 3 are Pareto optimal (A,B,D,E). In each of these points, one can only decrease the score on one of the variables by moving to another point by simultaneously increasing the score on the other variable. This means that none of these four points is apparently better then the others. Only point C is not Pareto optimal. In this point, one can improve both scores by choosing point B.

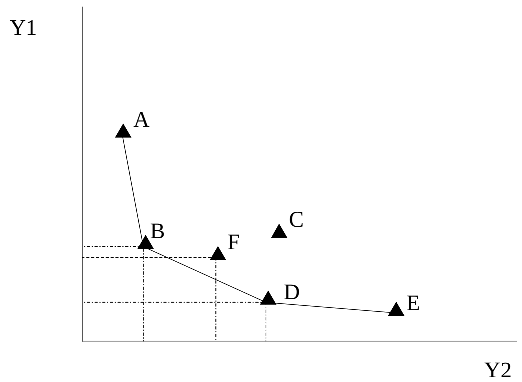


Figure 4. Pareto optimality and efficiency

Figure 4 shows a second example, with a point F added compared to figure 3. Point F is Pareto optimal, because at least one of the outcomes worsens if one travels from point F to point B or D. However, point F is not efficient. A linear combination of point B and D would do better than point F alone. So, although point F is Pareto optimal, it is not necessarily efficient.

The points in figure 3 and 4 can be interpreted as the different scores of the different transportation systems. In that case, the lines between those points form the linear combination of the systems, or the scores in case of a combined trip in two modes. This represents the cases presented above, in which one mode cannot fulfil the total mobility demand.

The example in figure 3 uses only five points and two outcomes. In this case, already four out of five points are Pareto optimal. If another two dimensions are added, the chance is considerable that a lot of points are Pareto optimal. In that case, pointing out Pareto optimal points does not really offer additional information. Besides that, looking at the Pareto optimal points for all four criteria does not take into account the different characteristics of the four criteria.

As was mentioned before, there seem to be to major interests in choosing an optimal transportation system. Besides the individual interests of minimising both costs and travel time are societal interests minimising energy and space use of transportation. Therefore, the analysis of the model results is made in two phases.

6.3 Two-level Pareto optimality analysis

In order to interpret the model results, a distinction is made between the individual criteria and the societal criteria. In the first part of the analysis, the Pareto optimal points for both the individual and the society are calculated, according to the system from figure 3. The Pareto optimal points can be extended to a linear combination of optimal systems for both levels.

In the second step any of the linear combinations of Pareto optimal points of the societal level can be compared to a linear combination of Pareto optimal points at the individual level. When one would change from the societal to the individual optimal point, this would introduce losses for the society on energy and space use. When one would change from the individual to the societal optimal point, this would imply losses for the individual on their scores: costs and travel time. So, comparing two points on the two linear combinations of Pareto optimal points results in four losses. For every combination of points, these losses can be calculated. These losses can then be analysed by subjecting them to a Pareto analysis, thus pointing out the systems which are also Pareto optimal in the second order.

In this way, less points will be regarded Pareto optimal, so some more detailed considerations can be made on the model outcomes. By making the subdivision into the societal and individual level, several weights can be adjusted to both levels, thus making it possible to give priority to one of the two levels.

This analysis can be compared to multicriterion games, in which two competing actors each regard several criteria.

7. Description of the results

7.1 Results at an aggregated level

With a growing population and a continuous increase in mobility, the total mobility demand of the Dutch population will increase. This is shown in the resulting mobility demand in figure 5. The direct energy requirements to meet this demand are shown in figure 6.

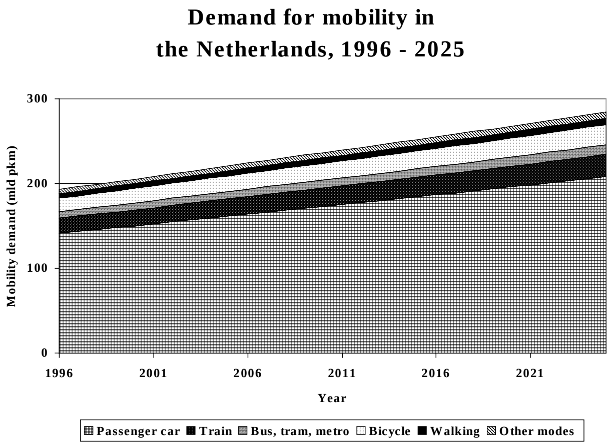


Figure 5. Projected development of mobility demand

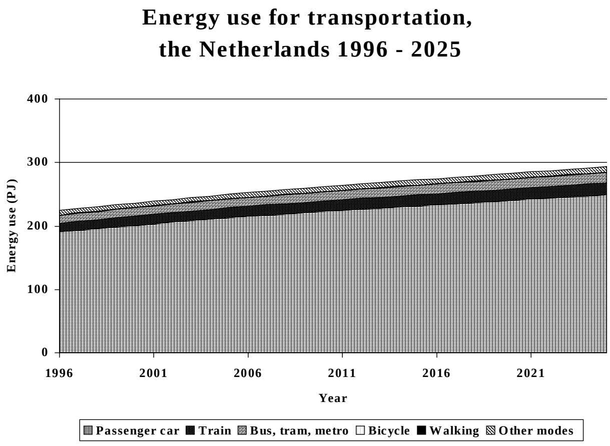


Figure 6. Projected development of energy use

The two figures show that the increase in mobility demand is bigger than the increase in energy use for transportation. This results from an increase of efficiency of the various transportation modes. The passenger car has a major share both in energy use and in the mobility demand.

With the increasing mobility demand per person per day and a given speed distribution of the various modes, the average daily travel time increases, as figure 7 shows. The picture shows that the share of the passenger car in the total travel time is a lot smaller than its share in the total distance. Both travelling by bike and walking have also a big contribution to the total travel time.

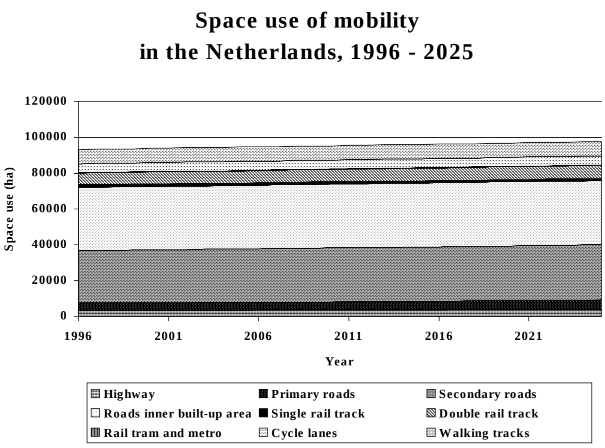
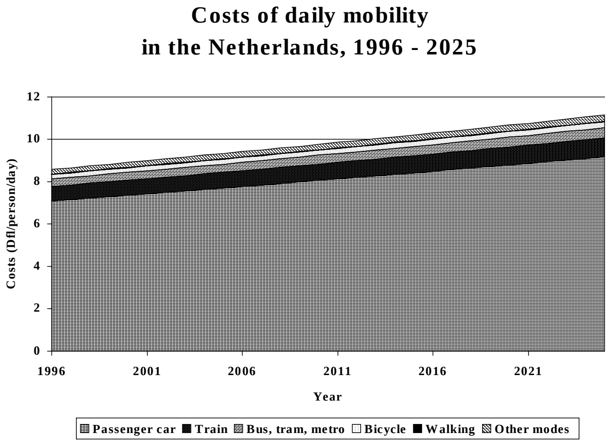


Figure 7. Projected development of space use for passenger transportation



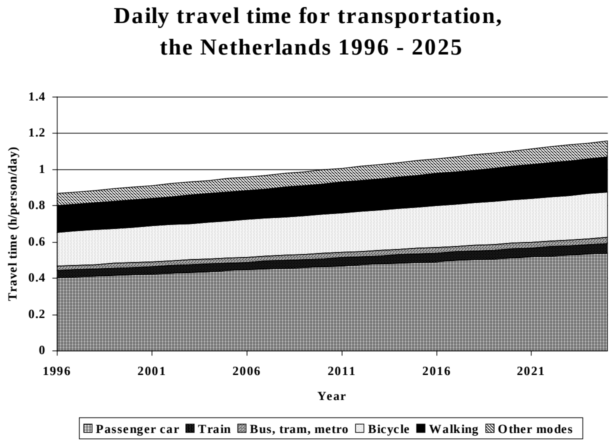


Figure 8. Projected development of daily costs of mobility, 1996 - 2025

Figure 9. Projected development of travel time per inhabitant per day, 1996 - 2025

The costs of mobility, shown in figure 8, are again dominated by the passenger car. Transportation by car is relatively expensive per kilometre, and the car has a big share in the total mobility. The costs of public transportation (both the travel by train or by bus, tram and metro) form the second largest costs in figure 8.

The space use of transportation consists of the direct space needed for the infrastructure. Not all infrastructure should be allocated to passenger transportation however, therefore the values in figure 9 are smaller than the totals presented by the Dutch Central Bureau of Statistics (CBS, 1997b). The roads within the built up area and the secondary roads form the major area. This is not surprisingly, they have by far the biggest total length (see table 3). Although the total length of various infrastructures is increasing, the total increase in space use is limited.

7.2 Comparing the various modes

Next to the results at an aggregated level, the model also generates figures per transportation mode. Energy use, space use, travel time and costs per kilometre by mode are available for all six trip types. This makes it possible to compare the various modes on their scores. Since these results are available for every year between 1996 and 2025, comparisons can be made on an annual basis. The examples shown in this section are limited to the values for the year 2000. While most of the input data are constant in the case discussed in this paper, the results vary only slightly. In cases with more pronounced scenarios, the results will vary more for future years.

The scores of the various modes on the four side effects are for each trip length shown in two graphs. The energy use and the space use are shown in one graph, as these represent the variables at a societal level. The costs and travel time are shown in the graph with the individual relevant variables. Figure 10 shows the costs and travel time of six modes in the year 2000 for the situation in the Netherlands for trips under 2.5

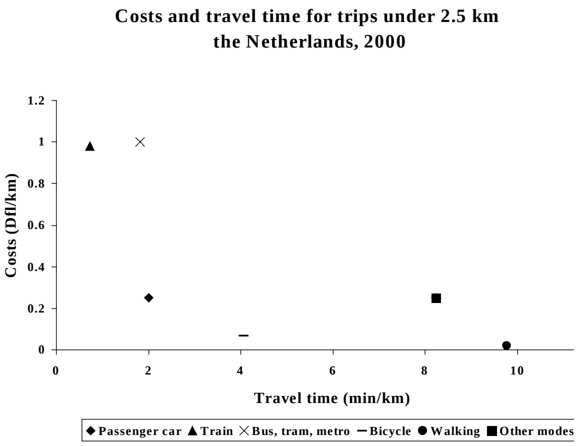


Figure 10. Costs and travel time of various modes

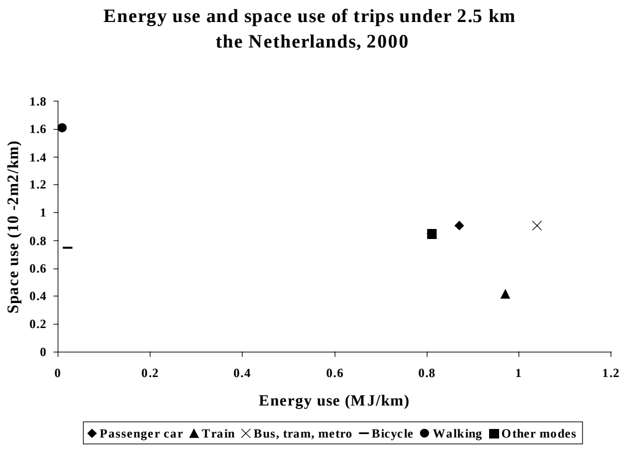


Figure 11. Energy use and space use of various modes

kilometre. All values are for travelling one kilometre. Figure 11 shows the space use and energy use of the trips under 2.5 km.

Remarkably, the space use of walking is the highest of all modes in figure 11. This can be explained by the great number of walking tracks (almost along every kilometre of roads within the built up area) and the small number of kilometres travelled on this type of infrastructure. It is not surprisingly that the train scores low on space use. Energy use for the soft modes (walking and cycling) is considerably smaller than of all other modes.

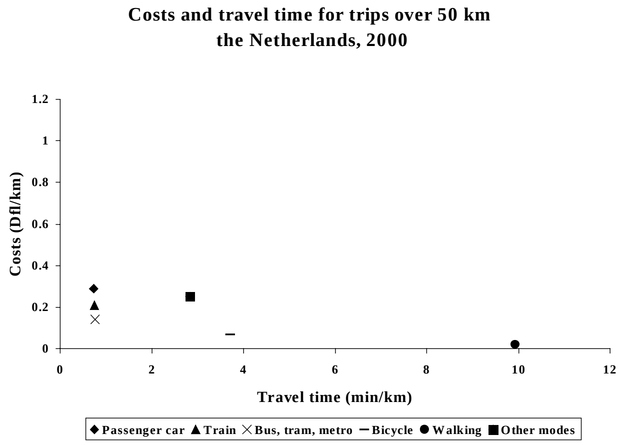
Like the energy use, also the costs for walking and cycling are low. Short distances are relatively expensive for travelling by public transportation.

In the figures 10 and 11, a couple of Pareto optimal transportation modes can be pointed out. From a societal point of view, for trips under 2.5 km, both the train, bicycle and walking are Pareto optimal. From an individual point of view, the train, passenger car, bicycle and walking are Pareto optimal.

In short distances like these, both walking and cycling seem realistic options. Travelling trips under 2.5 km by train is only possible for a very small proportion of the trips (in intensely urbanised areas with train stations close to the departure and arrival points of the trip). The passenger car is also an alternative for almost all trips.

In this specific situation, two transportation modes can be pointed out which are Pareto optimal at both the individual and the societal level: walking and cycling. This situation changes if longer distances are considered. The scores of the modes differ for the various trip lengths and not all modes can be used for each distance (like trains are not a valid option for trips under 2.5 km).

The other extreme case is the trips with a length of over 50 kilometres. The scores on the various side effects of transportation of these trips are displayed in figure 12 and 13. The figures for the other trip lengths are shown in appendix A.



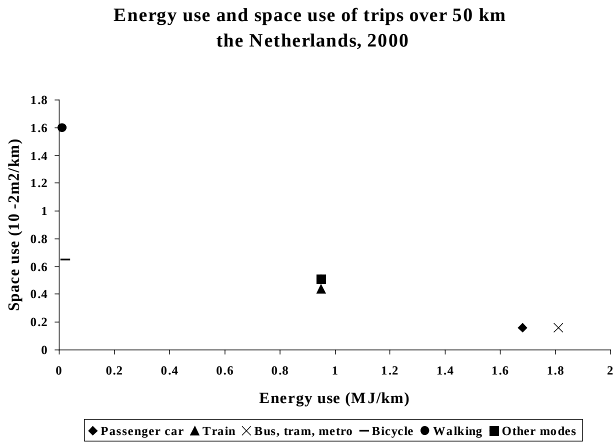


Figure 12. Costs and travel time of trips over 50 km, 2000

Figure 13. Energy use and space use of trips over 50 km, 2000

For trips with a length over 50 kilometre the situation is different. For the costs and travel time, the only mode that is not Pareto optimal is the ‘other modes’. All other modes are Pareto optimal. In the case of energy use and space use, the passenger car, the train and both soft modes are Pareto optimal. This results in four modes that are Pareto optimal on both the individual and the societal level: the train, the passenger car, and the soft modes walking and cycling.

For trips over 50 kilometres, soft modes seem unrealistic options, as their travel speed is too low. This leaves only the passenger car and the train as realistic options. Those two modes are not fully comparable, as the passenger car has a much higher infrastructural network density than the train. Most trips by train should therefore be combined with other modes.

8. Conclusions

The model described in this paper offers possibilities to explore how future changes in mobility demand result in changes in the total energy used for transportation, as well in the space use, travel time and costs of mobility. The model is dynamic on the supply side, implying changes in the supply system (vehicles and infrastructure). Changes on the demand side should be introduced in the scenarios run with the model.

With the model, conclusions can be drawn at an aggregate level. Moreover, Pareto optimal transportation modes can be selected for various trips. The results are not always unambiguously interpretable, as the model does not exclude certain modes for certain trip lengths. So, while selecting the Pareto optimal transportation modes, the range in which the modes can be used should always be taken into account.

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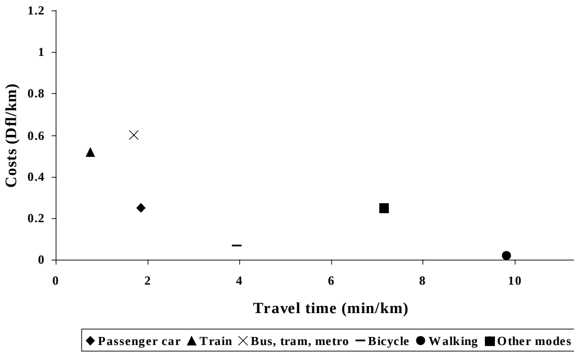
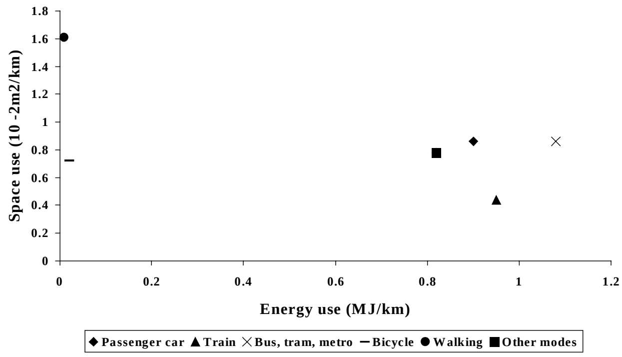
Appendix A. Figures

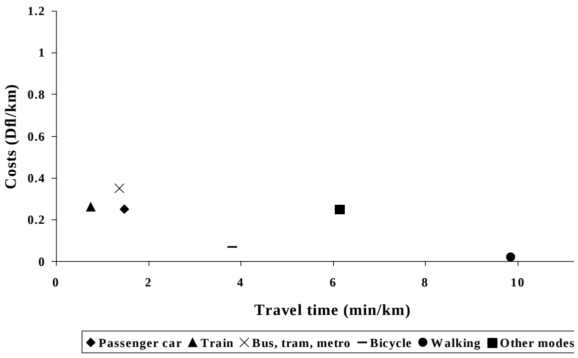
Costs and travel time for trips between 2.5 and 5 km the Netherlands, 2000



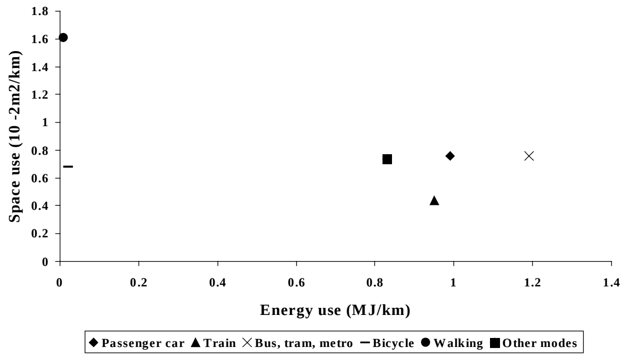
Energy use and space use of trips between 2.5 and 5 km, the Netherlands, 2000



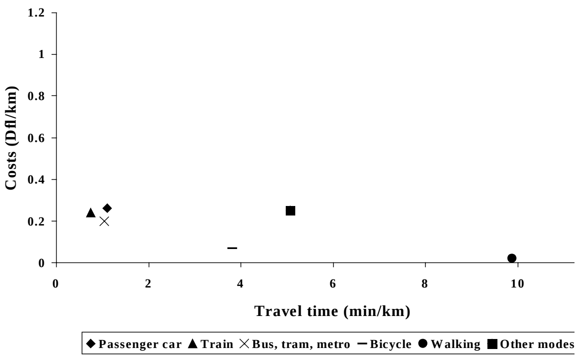
Costs and travel time for trips between 5 and 10 km the Netherlands, 2000



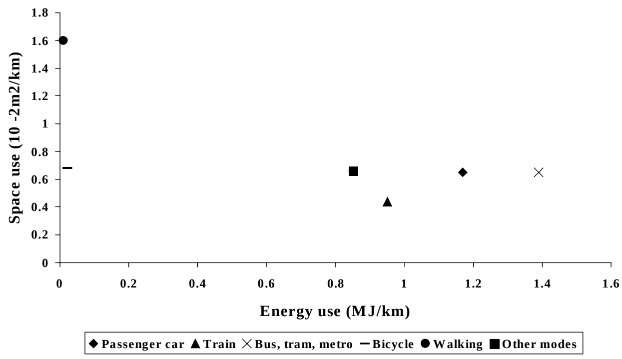
Energy use and space use of trips between 5 and 10 km the Netherlands, 2000



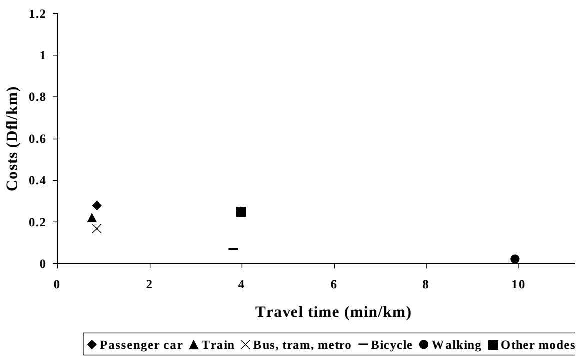
Costs and travel time for trips between 10 and 20 km the Netherlands, 2000



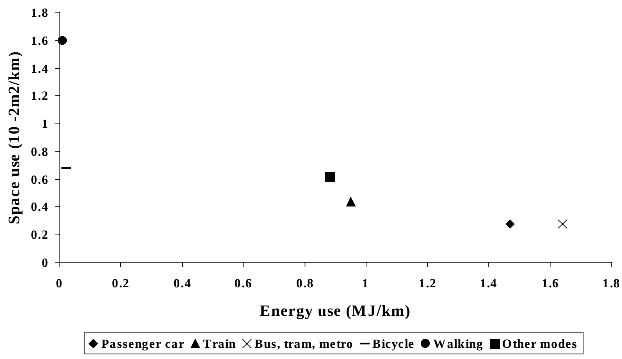
Energy use and space use of trips between 10 and 20 km, the Netherlands, 2000



Costs and travel time for trips between 20 and 50 km the Netherlands, 2000



Energy use and space use of trips between 20 and 50 km, the Netherlands, 2000



Appendix B. Overview of model input and output

Overview of input data

- Mobility demand for the period 1996 – 2025 by mode and trip length
- Subdivision of the mobility demand by mode and trip length over the various types of infrastructure for the period 1996 – 2025
- Speed distribution by mode and type of infrastructure for the period 1996 – 2025
- New sales by mode for the period 1966-1995
- Energy use by mode and construction year for the period 1966-2025
- Fuel prices for the period 1996 – 2025
- Fixed and variable costs by mode for the period 1996 – 2025
- Size of the population for the period 1996 – 2025
- Length and width of various types of infrastructure and the share passenger/freight transportation for the period 1996 – 2025
- Average number of occupants by mode for the period 1996 – 2025

Overview of model output

- Total mobility demand, energy use and space use for the Dutch population by mode and trip length for the period 1996 – 2025
- Mobility demand, energy use, space use, costs and travel time per person per day by mode and trip length for the period 1996 – 2025
- Energy use, space use, costs and travel time of mobility per kilometre by trip length for the period 1996 – 2025

The model distinguishes six modes, six trip lengths, nine types of infrastructure and 21 different speeds. Results are calculated for a period of 30 years.