# Simulating a pay lane within a traffic network using a choice model based on travel time variability

**Masterthesis H. Graaff**


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Deventer, October 2008
Herman Graaff

Twente University
Faculty of Engineering Technology
Centre for Transport Studies

| | |
|---|---|
| Student nr | 0049867 |
| E-mail address | hermangraaff@gmail.com |

<u>Thesis committee:</u>

| | |
|---|---|
| Prof. dr. ir. E.C. van Berkum | Twente University |
| Ir. H.L. Tromp | Goudappel Coffeng B.V. |
| J. Zantema MSc. | Goudappel Coffeng B.V. |
| Dr. T. Thomas | Twente University |

# Preface

This masterthesis is the result of a research about the road user behaviour towards pay lanes. The past months I have worked on this research and with this research I intend to complete my master study Civil Engineering and Management at the University of Twente.

During my research I worked at Goudappel Coffeng. Goudappel Coffeng has a lot of expertise about traffic and transport and a subsidiary of Goudappel Coffeng also developed the software package OmniTrans, that is used to execute the simulations.

I want to thank my thesis committee for their readiness to support my research and invest their time and knowledge during the research process. I want to thank Goudappel Coffeng for the opportunities they offered me to do this research.  I also want to thank Henk Taale for providing the MonicaData and Professor Martin Dijst for his support at the beginning of the research.

Further I want to thank my parents for the opportunities they offered me to complete my study and Eline for her great support during the last months of this research.

# Executive Summary

## Introduction

The road network in the Netherlands will become more and more congested the upcoming years. Although policy is developed and executed to meet the expected congestion problems, it is expected that the accessibility of some important economic regions in the Netherlands will worsen. The introduction of pay lanes could be a measure to guarantee this accessibility for a share of the road users.

Pay lanes are separate lanes at highways that can only be used by road users that pay a certain toll for it. Pay lanes offer road users an extra service, because at pay lanes a low travel time is guaranteed. Road users are free to choose to use the (congested) free lanes or use the pay lane after paying for a guaranteed low travel time. In the United States several pay lanes have been constructed. Evaluation reports about these pay lanes are very positive. As a consequence of the pay lanes the travel times at the free lanes is improved and road users from all income classes use the pay lanes.

The willingness to pay for a pay lane is caused by both the reduction of travel time and the reduction of travel time variability. A reduced travel time variability gives road users a better indication of their arrival time, what seems to be very valuable for road users that have a great need to arrive on time.

To be able to estimate the potential effectivity of pay lanes in the Netherlands, an estimation has to be made about the valuation of this travel time variability by Dutch road users. Because no pay lane situations are available in the Netherlands, these estimations need to be made with a traffic model in which also the travel time variability has to be incorporated. Therefore the following research objective is formulated:

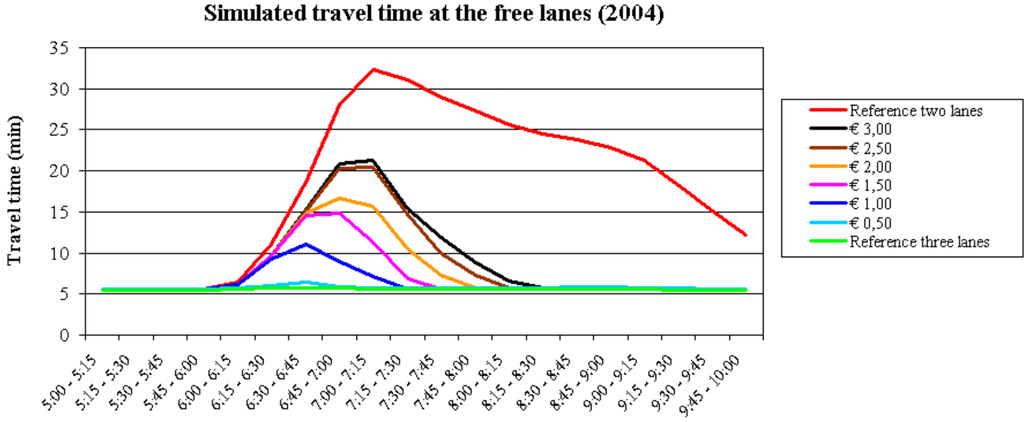
*Research objective:*
*The objective of this research is to develop a travel time variability based choice model and using this model to simulate two concrete pay lane situations in the Netherlands to get an indication of their effectiveness.*

The two concrete pay lane situations are a potential pay lane at the 27 parallel to the Merwede Bridge near Gorinchem and a pay lane at the off-ramp Near Sloten in Amsterdam.

The network model used for the pay lane situations has been taken from the national accessibility model. The national accessibility model is a model developed by Goudappel Coffeng. The road users are divided in the different user classes, which vary in their preferences. The pay lane is added as a separate route in the network. In an iterative procedure the road users are assigned to the road network and subsequently to the pay lane or the free lane.

## Simulation results of the pay lane situation at the A27

At the Merwede Bridge the road capacity is lower than at the other road sections at the A27. A pay lane is simulated along the bridge and the congested road section upstream. This pay lane situation is simulated for different toll levels, and two reference situations. The references consist of the old situation (only two free lanes) and a regular road capacity enlargement (three free lanes). The simulation of the road network in 2004 results in the travel times at the free lane as shown in the figure below.



The congestion that occurs in the old situation is strongly reduced by the pay lane. The congestion effects are fully taken away in the reference situation with three lanes (In the 2020 network this reference situation leads to small congestion effects).

A comparison of the travel costs as a sum of the travel time costs, the schedule delay costs and the toll costs, is shown in the table below. In the individual travel costs the toll costs are included. In the social travel costs, the toll costs are excluded because they are benefited by society as a whole. The pay lane strongly reduces travel costs in comparison with the old situation. At the same time the travel costs for the pay lane are much higher than the reference situation with three lanes, despite the benefits of a guaranteed low travel time.

| | **Travel time costs** | **Schedule delay costs** | **Toll costs** | **Individual travel costs** | **Social travel costs** |
|---|---|---|---|---|---|
| 2004 – Reference three lanes | 29760.49 | 11122.5 | 0 | 40882.99 | 40882.99 |
| 2004 - Pay lane (toll 2,00) | 36501.16 | 10647.9 | 13385.74 | 60534.81 | 47149.06 |
| % - effect | 23% | -4% | | 48% | 15% |
| | | | | | |
| 2020 – Reference three lanes | 54824.66 | 23357.25 | 0 | 78181.92 | 78181.92 |
| 2020 - Pay lane (toll 3,00) | 73772.16 | 20763.71 | 30507.66 | 125043.5 | 94535.86 |
| % - effect | 35% | -11% | | 60% | 21% |
| | | | | | |
| 2004 - Reference two lanes | 97221.53 | 18537.5 | 0 | 115759 | 115759 |
| 2004 - Pay lane | 36501.16 | 10647.9 | 13385.74 | 60534.81 | 47149.06 |
| % - effect | -62% | -43% | | -48% | -59% |

In comparison with the pay lane locations in the United States, these pay lane simulations result in a quite low monetary valuation of schedule delay. This can be partly explained by the fact that the used valuation parameters are based on the monetary valuation of a regular schedule delay and not on a stochastic distributed schedule delay. Also the travel time variability is not included as a traffic flow dependent variable within the simulation procedure.

The simulation results show that the addition of a pay lane can reduce the congestion effects at the free lane. In contrary to a regular capacity enlargement, private exploitation of a pay lane can offer a private company return on investment. From this perspective a pay lane seems be an interesting measure to reduce congestion.

It is recommended to investigate the valuation of a stochastic distributed schedule delay in order to be able to make a good comparison between a pay lane situation and a reference situation with a regular capacity enlargement.

## Simulation results of the off-ramp near Sloten in Amsterdam

The off-ramp near Sloten has sometimes insufficient road capacity. This results in a queue at the off-ramp and even at the main lanes of the highway. As a consequence on-going traffic is hindered. A pay lane alternative is simulated where a longer off-ramp is constructed that forms a buffer where road users can wait. The old off-ramp is used as a fast pay lane alternative.

A first test of the pay lane situation results in a total gridlock at the network. This gridlock is the result of a changed route choice by almost all road users that use the off-ramp. Other off-ramps are more attractive than the long new off-ramp or the old off-ramp where toll is charged. This massive changed route choice (which leads to a worse situation for everyone) can also be explained by the modelling structure of OmniTrans. Because route choice is determined in a static traffic assignment and the traffic conditions are determined in a dynamic traffic assignment, road users make the route choice is not based on the occurring traffic situations, but on a much smaller congestion effect that is estimated by the static traffic assignment.

For this reason no further simulations are executed for this pay lane situation. A conclusion that can be drawn from this simulation is that road users at the off-ramp do not have a benefit from the changed situation. The road users that benefit from this situation are the on-going road users that are no longer hindered. Because the toll is charged for road users that are not the problem owners, the probability that the road user decides to avoid the pay lane and change his route choice is much larger. In this case this has a strong negative effect for the traffic conditions at the Amsterdam road network.

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# 1. Introduction

## Congestion problems in the Netherlands

The last decennia the car has gained a central position in modern life. The massive introduction of the car has increased individual travel opportunities, but also made people more dependent on their car. In the Netherlands the car ownership and the average distance travelled have increased non-stop during the last sixty years. As a consequence, the number of roads with daily congestion is increasing.

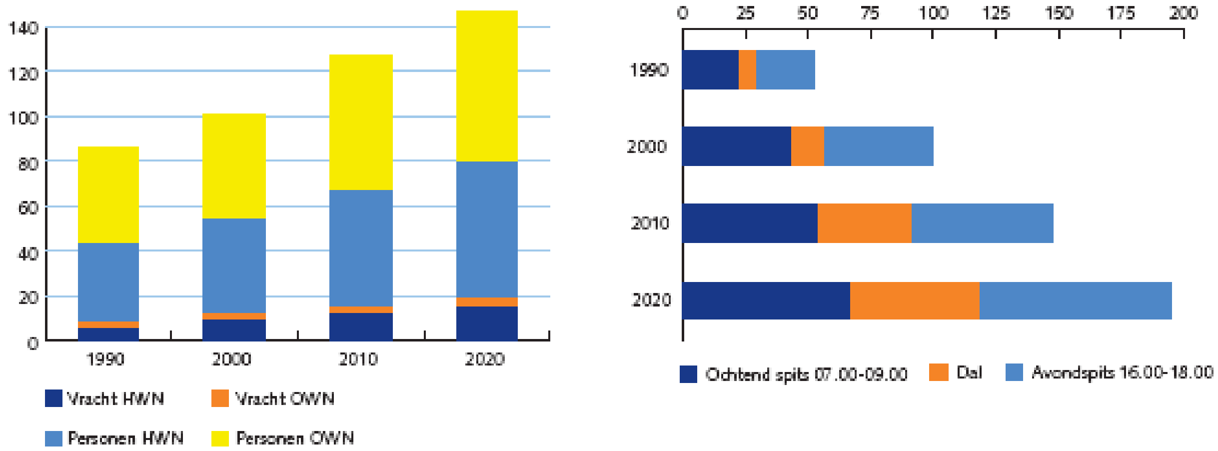



**Figure 1: Development of vehicle kilometres (left) and vehicle loss hours (right) on working days, index 2000 = 100 (source: Ministerie van Verkeer en Waterstaat, 2006,II)**

The size of this development is shown in figure 1. The left figure shows the (estimated) number of vehicle kilometres for person cars (yellow and light blue) and freight. The right figure shows the number of vehicle loss hours during the morning peak, evening peak and the period between both peaks. Both figures come from a Dutch mobility policy document written in 2006. As can be seen the growth of vehicle kilometres has a more than proportional effect on the congestion size. Also the reliability of travel times decreases. The same Dutch document estimates that the economical loss because of congestion effects will be 2.4 billion euro.

## Problems in maintaining the accessibility

The same disproportional effect can be seen in figure 2. The left figure shows the travel time to Schiphol from a certain place in the Netherlands during the morning peak in 2005. The right figure shows the travel times for the year 2020. The area from which Schiphol can be reached within two hours greatly decreases.  The figure supports the political concern that a growing congestion has a strong negative impact on the accessibility of important economic regions in the Netherlands, especially the Randstad Area.

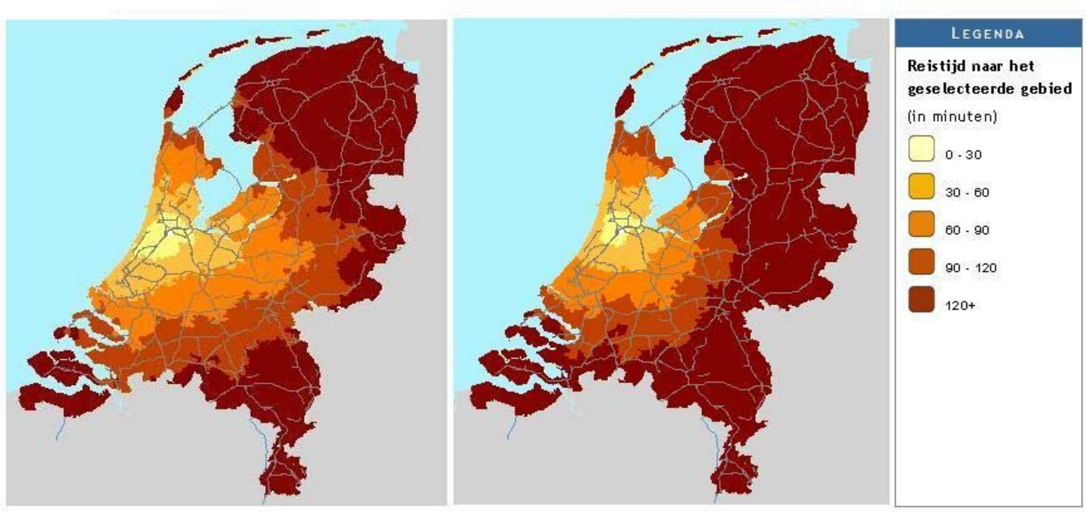



**Figure 2: Travel time to Schiphol during morning peak, 2005 (left) and 2020 prognosis (right), (source Bereikbaarheidskaart.nl)**

## Complex policy issue

The congestion problems have created a complex policy issue. The past decennia the enlargement of road capacity led to an increased traffic demand. As a consequence of this, the further enlargement of road capacity is no longer seen as an accurate solution for the expected problems. Also the limited space available near congested roads makes it difficult to make further road improvements. Moreover the negative environmental effects of car mobility were a reason to consider a further growth of mobility as a negative development (Pahaut et al., 2006).

For these reasons the past two decades political initiatives are made to introduce a form of road pricing in addition to investments in road infrastructure and public transport. Such taxation can introduce an effective incentive for road users to avoid road use during peak hours. Until 2005 these initiatives did not gain general support for realisation, as a consequence of a lack of confidence in the technical opportunities and the fact that many people interpreted the plans as an extra resource for public funds.

In the year 2005 a group of involved organizations including the government formulated an advice to introduce a general variant of time- and place-dependent road pricing (Nouwen et al., 2005). These new taxes should be compensated by reducing the existing taxes on car ownership. The advice was received positively by the parliament, but several postponements were made the last year in the planning process of the implementation. Even so, during the last year several concrete decisions about the introduction of road pricing were made and during the upcoming years the realization can be expected.

## Pay lane: introduction and definition

The road taxation as described in the previous paragraph can be seen as a type of road pricing that deals with all road users. An alternative type of road pricing is the application of pay lanes. In the United States pay lanes have been realized at several places. In pay lane situations a part of the road capacity is allocated to those road users that are willing to pay a certain amount in order to have a guaranteed low travel time.

Scholten et al. (2000) define the following two road pricing mechanisms:

***Congestion pricing:*** Uses road pricing to discourage traffic use during peak hours for all road users.

***Value pricing:*** Uses road pricing to offer road users an additional service that is only available for those road users that are willing to pay toll.

The intended road pricing in the Netherlands can be seen as a form of congestion pricing. Pay lanes are based on the principle of value pricing. Pay lanes intend to guarantee a low travel time for a part of the road users. An additional possibility is to give high occupancy vehicles free access to pay lanes. This can encourage carpooling. The following objective of pay lanes is formulated in an exploring study of the Dutch government:

*Presumed that the congestion problems are partially unsolvable, the objective of pay lanes is not to solve all congestion problems, but to maintain the accessibility of certain regions for those road users who are dependent of a good accessibility. Price is therefore the driving decision criterion (Ministerie van Verkeer en Waterstaat, 1999).*

In this thesis a distinction is made between pay lanes and free lanes, which can be defined as following:

***Pay lane:*** Highway lane that offers a guaranteed travel time and which is only accessible for road users who are willing to pay a toll or eventually have free access because they meet other conditions.

***Free lane:*** Highway lane that is situated parallel to a pay lane and that is used by those road users that are not willing to pay a toll and don’t meet necessary other conditions.

## Research subject and outline of the report

The subject of this research is the introduction of pay lanes in the Netherlands. As stated in the first paragraph, the congestion problems in the Netherlands are increasing and the provision of a reliable travel time seems to be crucial to maintain a good accessibility of the important Randstad Area. For this reason the introduction of pay lanes in the Netherlands could have a positive impact on the economical position. Because of the complex political context it is necessary to have good insight in the likely congestion effects before the realization.

Therefore this research focuses on the application of pay lanes within a traffic simulation model. The next chapter gives an overview of earlier research that is the basis for the background of this thesis. The background also describes the most influential factors that determine if road users decide to use the pay lane or the free lane. The third chapter defines the research structure.

Chapter 4 describes the analysis that is applied on the available travel time data. Chapter 5 and 6 describe the applied choice model. Chapter 7 and 8 show the simulation results and chapter 9 states the conclusions and also makes some recommendations about the improvement of the modelling accuracy.

# 2. Background

This background chapter gives an overview of earlier research about pay lanes or related issues. A distinction is made between the policy, economical and modelling context. All these contexts together create the context in which the thesis is executed. Because the thesis focuses on the choice model and not on the physical implementation of the pay lanes, the technical and physical context of pay lanes is only marginally described in this chapter.

## 2.1 Policy context

This paragraph considers the policy context of pay lanes. It shows both the situation in the Netherlands, where on a small scale policy initiatives for pay lanes have been started, and the situation in the United States, where pay lanes have been realized.

### History of pay lanes in the United States

In the United States most pay lanes are upgraded carpool lanes. These High Occupancy Vehicles (HOV)-lanes were only accessible for cars with two or more occupants. In practice the roads remained almost empty most of the time. As a consequence the social support for maintaining these lanes decreased drastically, the so-called empty-lane syndrome (Scholten et al., 2000). Although in the Netherlands soon after the introduction of the carpool lanes the whole idea was totally cancelled, in California some HOV-lanes were transformed to High Occupancy Toll (HOT)-lanes or Express Toll Lanes (ETL's). HOT-lanes are both accessible for toll payers and cars with two or more (in some cases three or more) occupants. ETL's are only accessible for toll payers.

### The fairness of pay lanes

The decision to transform the HOV-lanes to pay lanes was not self-evident. At some places the plans failed as a consequence of a negative public opinion. There are several objections towards pay lanes. The first group of objections considers road pricing in general. There is already paid for roads via other taxes, so it is unfair to introduce another tax for the use of it. The second group of objections considers the fact that most pay lane users come from high income classes. By introducing pay lanes these groups gain the most advantages, while for low income classes no measures are taken to reduce their congestion disadvantages. The introduction of the soundbite "Lexus Lanes" seemed to be effective in strengthening the negative public opinion.

To these objections, Litman (1999) makes a clear distinction between horizontal and vertical equity. Horizontal equity considers the extent to which the advantages of a measure are experienced by the one that paid for it. Vertical equity considers the question if people who naturally form the weak groups in society experience an advantage or at least not a disadvantage by a measure.

Baker et al. (1998) have analyzed both aspects for the case of the Californian pay lanes. The article also refers to a stated condition for transport policy by the U.S. government that vertical equity may not worsen by a certain policy measure. In the case of pay lanes the impact on vertical equity depends on the distribution of the pay lane users over the different income classes and the way the toll income subsequently are spent. The pay lane use depends on the valuation of travel time and travel time reliability and for these valuations income is not the most influential variable. The article states that a strong improvement of travel time reliability will make a pay lane attractive for road users spread over all income classes. The connotation of a Lexus Lane is therewith not founded.

The horizontal equity of pay lanes is very strong, because road users have a free choice to pay for the lanes and they directly experience an advantage from it. From this viewpoint value pricing is far more attractive than congestion pricing, where toll payment is unavoidable and no direct visible advantages can be experienced.

### Effectiveness of pay lanes in the United States

*California State Route (SR) 91*

One of the most congested corridors of California was the SR-91. Two pay lanes were created in both directions, which are separated from the free lanes by yellow pylons (Poole et al., 1999). The pay lanes were opened in 1995 and are exploited by a private company. Users have to register themselves as a client to get a transponder with which they can enter the pay lanes. The toll level depends on the occurring traffic flow. Higher travel times at the free lanes lead to a higher toll level, to prevent too much road users switch to the pay lanes during times of large congestion. For each time interval a maximum toll level is determined.

Sullivan et al. (1998) show the results of an evaluation of the effects of the introduction of the pay lanes. An important part of this study is a survey of road user opinions. The most important conclusions:

- Travel times: As a consequence of the extra road capacity of the pay lanes, the travel delay decreased in the first year from 30-40 minutes to less than 10 minutes. The second year the total traffic flow grew and the travel delay increased to 12-13 minutes.
- Vertical Equity: A substantial part of the road users (between 7% and 35% at working days) uses the pay lanes. This percentage is higher for high income groups, but the differences are limited. 25% of the lowest group (< $25.000) versus 50% of the highest group (> $100.000) frequently uses the pay lanes. There is also a significant difference between men (28%) and women (42%).
- Social support: The paylanes can count on a broad social support. Pay lanes as a measure to reduce congestion is supported by 60 – 80% of the respondents. This percentage is 5-10% higher for pay lane users in comparison to non pay lane users. 50-75% supports the private character of the exploitation.
- Carpooling: Although carpooling is no longer the only condition to use the pay lanes, the number of carpooling people at the corridor increased. Baker et al. (2008) suggest this is a consequence of the so-called insurance effect, what means that people are no longer dependent on a co-driver to gain access what makes it possible to maintain the same departure times during the week. This makes carpooling a more attractive alternative.

*The I-15 Congestion Pricing Project in San Diego*
Another highway road where pay lanes have been successfully realialized is the I-15 near San Diego. Here two physical separated pay lanes are situated that in the morning are accessible in one direction and in the afternoon in the other direction. In this case the toll level is also flexible with a predefined maximum.

Van Amelsfort (1999) studied the occurring travel time and travel time variation at the free lanes of the I-15. At the most congested moment the difference between the median travel time at the free lane and at the pay lane is 6 minutes in the morning and 3,5 minutes in the afternoon. Also the travel time corresponding to the $90^{th}$ percentile is calculated as an indicator of travel time variability. Here the difference at the heaviest peak moment is 10 minutes in the morning and 16 minutes in the evening. Van Amelsfort also reports that the traffic flow is increased as a consequence of the addition of the pay lanes with a yearly 20% during the first two years. An analysis of the pay lane users shows that the total travel time and the gender of the road user have a strong relationship with the share of pay lane use.

Another interesting finding of the study is the impact of the flexible toll level. When the travel time at the free lane is relative high, the toll level is set high in order to prevent too many people use the pay lane. When the travel time at the free lane is relative low, the toll level is set lower so that more people use the pay lane and the lane does not stay empty. When the assumption is made that road users compare the costs and the benefits of using the pay lane, it is expected that a lower toll level encourages more people to use the pay lane. But in practice this flexible toll is seen by road users as an indicator of the travel conditions at the free lane. So a high toll level means that it is necessary to use the toll to arrive on time, while a low toll level shows that the free lane can be used without congestion. This effect emphasizes the problem of keeping the pay lane an attractive service in different situations. The flexible toll level seems not to be an accurate solution for this problem.

## Potential social support in the Netherlands

The evaluation results of the pay lanes in the United States nuance the view that pay lane use is mostly related to income. Pay lane use is higher for high-income groups, but pay lanes are used by all income classes, especially to reduce travel time variability. In The Netherlands this perception of pay lanes within political debate and public opinion usually lacks this nuance. In the previous decade several studies are made about the possibilities of pay lanes in the Netherlands. The broadly supported advice to introduce general road taxation (see also the previous chapter) did not include pay lanes and as a consequence the discussion about pay lanes was only marginally continued. Despite it is interesting to state the most important findings of these studies.

NIPO, a large Dutch interview company, has studied the public opinion about the concepts of congestion pricing and value pricing in 1997 (Akerboom, 1997). The results show that 42% considers pay lanes to be unacceptable. Only 28% considers pay lanes to be a positive measure and 13% would use the pay lanes if these were realised.

This negative consideration can be partly explained by the failure of carpool lanes, that were introduced some years earlier and offered carpoolers the possibility to pass a queue. After several months the carpool lanes were closed as a consequence of a strong negative public opinion, that was mainly caused by a feeling of unfairness about the fact that the lanes that were financed by public funds were used by just a few of the road users. Also the occupancy of the carpool lane was most of the time at such low level, that the investment in the lanes was seen as wasted money (Feenstra et al., 2001).

In 1998 a study is made about the opinion of several involved organizations towards pay lanes (Ministerie van Verkeer en Waterstaat, 1999). The study shows that consumer organisations and the Dutch Chamber of Commerce prefer pay lanes above congestion pricing. Other organisations consider pay lanes as a good supplement to other pricing measures. Aarnink (1998) confirms this view that many involved organizations have a positive view towards pay lanes. Also a broad consensus exists about the criterions for these pay lanes:

- Choice freedom for the road user
- No exclusion of road users (e.g. carpoolers) from payment
- Guaranteed low travel time at pay lane
- Pay lanes are created as extra lanes
- Toll level is variable
- Pay lanes can be exploited by a private organization

Other studies show the influence of the destination of toll revenues for the social support towards forms of road use taxation. A study of Verhoef (1996) shows that this aspect is crucial for 83% of the road users in the Netherlands. Small (1992) shows that public and political support increases as the direct effect of a tax payment (e.g. a reduced travel time) is larger. The guaranteed travel time can therefore be seen as the most important advantage of a pay lane in comparison with congestion pricing for the acquiring of social support. Parry and Bento (2001) show that a general welfare gain can be achieved when toll costs are compensated by a reduction of taxes with a disturbing effect on the labour market. Lumpsum compensation towards households seems significantly less effective.

Ubbels (2005) has studied the degree of acceptation of different ways to use toll revenues. At a scale from 1 (very unacceptable) to 7 (very acceptable) the following alternatives are judged by respondents:

- General budget (2,15)
- Lower income taxes (3,86)
- Improvements in public transport (3,99)
- Construction of new roads (5,20)
- Lower fuel taxes (5,58)
- Lower taxes for car ownership (5,84)

Beside the social support also the physical opportunities to create pay lanes in the Dutch road network and the limited space for capacity increasement in the cities are studied. DHV (1997) studied a dual system where in the whole Randstad Area both a free lanes and a pay lanes network are created. The study shows that several bottlenecks have to be solved, including some very complex cases. Another study (Ministerie van Verkeer en Waterstaat, 1999) shows a number of separate potential pay lane locations. The study concludes that in most cases a combination of a general capacity enlargement at a part of the section and a pay lane realisation on the remaining part of the section is desired. This offers as much as possible traffic to use the pay lane and at the same time the pay lane is prevented to get hindred by congestion when the pay lane starts before the point where congestion starts.

Another aspect that can postively influence the opportunities for pay lanes in the Netherlands is the private exploitation of pay lanes. One of the current problems with respect to investments in new road infrastructure is the limited budgettary space for these kinds of investments. Some investments will result in far more economical benefits than costs, but as a consequence of too high costs for building these investments are not made. When the opportunity is offered towards a private organization to acquire the ownership of a pay lane after financing and building it this problem could be tackled. Because the pay lane is an additional alternative for road users, there is no problem of a monopolistic ownership, one of the occurring problems at general forms of private road ownership.

Concluded can be that in long term pay lanes can get a large social support as an additional measure for the reduction of congestion. The public opinion about pay lanes depends on the use of toll revenues. The private exploitation offers additional opportunities with respect to the current infrastructure investment limitations.

## 2.2 Economical context

The second context of this thesis is the economical context. The effects of road pricing measures usually are expressed in economical terms in order to analyse their effectivity. It is important from which perspective this economical analysis is executed. It could for example be possible that a private organisation that exploitates a road gets a great profit out of this exploitation, but at the same time many road users are financially disadvantaged by the high tolls. For that reason economical analyses usually are based on the evaluation of gains and losses for society as a whole. Most of the times, not only real monetary profits and losses are incorporated, but also non-monetary profits and losses like travel time and environmental effects are monetarised. In this paragraph an overview will be given of the economical context of pay lanes as stated in earlier research.

### Marginal cost pricing

The idea of congestion pricing as an effective congestion reducing method is based on the principle of marginal cost pricing. This principle can be shown using an economical model for a situation where one road is available between a certain origin and a certain destination. There is an amount of car travellers that like to use the road to travel from the origin to the destination.

The costs to use the road depend on the number of road users at the road. As this number increases, the travel time also increases as a consequence of congestion effects. In general, these costs as a function of the number of road users $v_a$ can be estimated using the following formula (Small et al., 2000):

$$c_a(v_a) = \beta \cdot L + \alpha \cdot t_a(v_a) \qquad (1)$$

Where further $L$ is the length of the road and $t_a(v_a)$ the travel time corresponding to the number of road users. $\alpha$ and $\beta$ are parameters for the monetary valuation of distance and time. Usually congestion effects become stronger as the number of road users nears or exceeds the road capacity. Figure 3 shows a possible cost function for the road as a function of the number of road users.

At the same time all road users have a certain welfare gain for making the trip. This welfare gain differs for each road user. Road users only make a trip when this welfare gain is larger than the trip costs. When trip costs are larger than the welfare gain, road users could better stay home. As a consequence the demand for using the road decreases as the costs for using the road increase. This leads to the demand line in Figure 3.

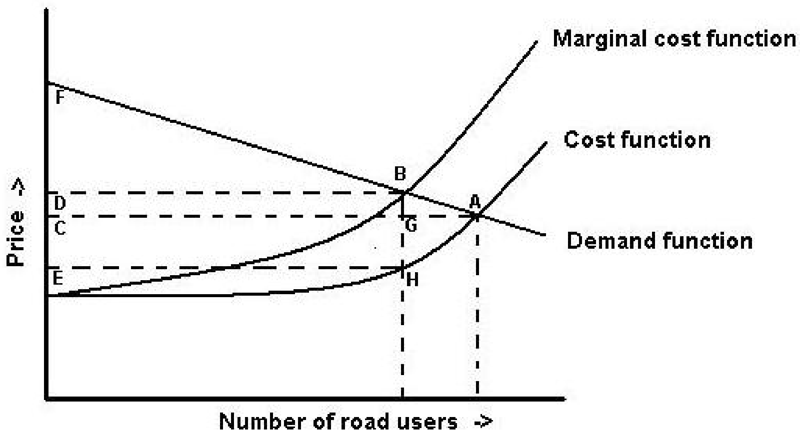



**Figure 3: Economical model for a road (source: Yang et al., 1998)**

Following the economical principles this situation leads to the equilibrium situation that has been marked with A in the figure. Despite the reached equilibrium, this is not an optimal situation. The first reason is that external effects towards the environment are not incorporated by the cost function. The incorporation of these costs is usually aimed by fuel taxes or general road taxation (Mankiw, 2001).

The second reason for the suboptimal situation can be explained by the difference between the marginal social costs and the marginal private costs. The marginal private costs are the costs that are experienced by the last added road user (i.e. the road user at which the equilibrium is reached). These marginal costs are equal to the cost function at that point. The marginal social costs are the costs that are experienced by all road users together. These costs are not only the costs experienced by this new user, but also the extra costs as a consequence of the congestion effects of this user towards all other road users. These marginal social costs can be described using the following formula (Yang et al., 1998):

$$\bar{c}_a(v_a) = c_a(v_a) + v_a \frac{dc_a(v_a)}{dv_a} \qquad (2)$$

Where the first term represents the costs experienced by the new road user and the second term represents the changed road costs by this adding of a road user towards all other road users. The optimal equilibrium situation would be the situation in which these marginal social costs are equal to the marginal welfare gain (point B in the figure). This could be reached by introducing a toll with a price equal to the line HB in the figure. This makes the cost function move upwards and intersect the demand function in point B. This toll can be estimated using the following formula:

$$\tau = v_a \frac{dc_a(v_a)}{dv_a} \qquad (3)$$

## Optimal tolls within a network

Within a traffic network usually more than one route is available between two places. As a consequence it could be possible that when a toll based on the marginal cost pricing principle has been introduced at one of the routes, road users will switch route and use a road where marginal costs are not priced. This situation could be less optimal than the old situation. To really reach an optimal situation in which all marginal social costs are incorporated in the costs a road user experiences, it is therefore necessary that on all routes in a network a toll is charged to incorporate the marginal costs. When this situation is realised, this is called the first best (FB) optimum (Williams et al., 2001).

In practice it is quite difficult to apply marginal cost pricing on all roads in a network. Usually toll charging is limited to highways. The situation that road users switch to local roads to avoid toll charging is strongly undesirable.  In such a case it is better to charge a much lower toll. This lower toll optimum is called the second best (SB) optimum, because the optimum is constrained by a number of no-toll routes in the network.

Next to the first best and second best optimum, there is also a third best (TB) optimum. This optimum is not only limitated by a number of no-toll routes at the network, but also by the condition that the number of vehicles at the toll road must be lower than for example 80% of its capacity, in order to guarantee a certain level of service. This second condition leads to a less efficient use of road capacity at the pay lane and this leads to a situation that is less optimal than the second best optimum. The principle of pay lanes can be seen as a TB optimum.

Small et al. (2000) have simulated a FB, SB and TB optimum for a network with one origin, one destination and two possible routes. The simulation is based on two user groups with each a different value of time. The difference between the values of time of both groups is varied between 0 and 70 cents per minute. For each situation the welfare gain under no toll conditions is determined. Subsequently the welfare gains under FB, SB and TB conditions are determined and these are related to the no toll situation.

Figure 4 shows the results of this procedure. The welfare gain increases as the difference of the value of time increases. In other words, price differentiation is more effective when the variance of travel time valuation is larger. First Best pricing seems to be very effective, while the effect of second best pricing is much smaller and third best pricing leads to a worsening of the welfare gain compared to a no-toll situation. This result seems to indicate that in terms of the total welfare gain as a function of travel time and toll costs, the application of pay lanes is less effective than a no-toll situation.

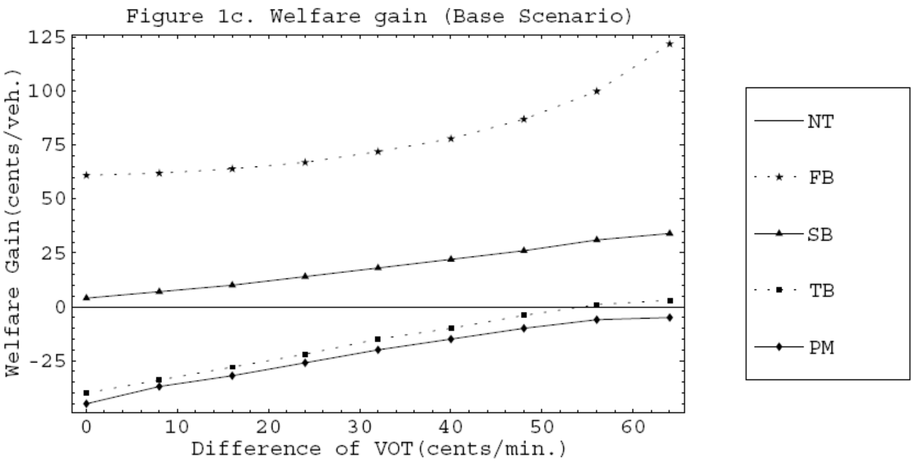



**Figure 4: Results of a two route simulation for two user classes and several value of time differences**

## The effectivity of pay lanes in relationship to congestion pricing

The results shown in the previous paragraph indicate that the condition of a guaranteed low travel time leads to a welfare loss. Based on these findings, the conclusion could be drawn that a general variant of congestion pricing is a better measure than the creation of pay lanes. Despite these results, pay lanes have other advantages that can improve the welfare gain, but are not incorporated in this analysis.

The most important advantage of TB-pricing is that travel time uncertainty is reduced for pay lane users. As a consequence costs resulting from arriving too early or too late will be much smaller than when a road user uses a free road or a toll road under SB conditions. The next paragraph describes the valuation of these travel time reliability.

Another advantage of TB-pricing is that there could be a substantial external valuation for a guaranteed accessibility of certain places. The opportunity to have a guaranteed low travel time to reach mainports and other economical relevant areas improves the concurrention position of the Netherlands and as a consequence the Dutch economy experiences a large gain, which is experienced by both toll road users and free road users.

It is important to incorporate these advantages before evaluating the economical effectivity of a TB-pricing application.

## 2.3 Modelling context

The third context is the modelling context. As described in the previous paragraphs, a pay lane can offer a reduction in travel time and also a reduction in travel time variability for those road users that are willing to pay a certain toll. This paragraph gives an overview of earlier research about the measurement and valuation of travel time variability.

### Travel time variability and schedule delay

A reduction of travel time variability is seen as a significant advantage offered by a pay lane. This means that a disutility is experienced by a road user as a consequence of travel time variability. But what are the causes of these costs? And how can these costs be related to the other occurring costs?

Noland et al. (1997) give an overview of different ways in which travel time variability costs are incorporated in cost functions. There is a main distinction between two aspects that lead to these travel time variability costs:

- Disutility due to congestion:
  Travel time variability usually is a consequence of congestion. Congestion leads to a larger travel time and also to a larger discomfort in comparison to free flow conditions. Both aspects lead to a certain disutility.
- Disutility due to schedule delay:
  As a consequence of travel time variability there is a strong probability that a road user arrives too early or too late at the destination location. When a road user has an important appointment, he can reduce his probability on arriving too late by choosing an earlier departure time. Usually this safety margin leads to an ineffective period spent at the destination location. Arriving too early and arriving too late almost always result in a disutility which is defined as schedule delay costs early (SDE) or schedule delay costs late (SDL).

For both aspects the size of the disutility is related to the level of travel time variability. An important difference is that the first aspect considers costs that are related to the characteristics of the trip itself, while the second aspect considers costs that are related to the purpose of the trip.

When the travel time variability is assumed to be a certain stochastical distribution, the occurring travel time can be estimated for different probabilities. For example the 80% travel time is the travel time that is higher than 80% of the registrated travel times. The valuation of the disutility due to congestion is mostly based on the difference between the travel time in a congested situation (for example the travel time for which 80% or 90% travel time) and the median or average travel time. This leads to the following cost function:

$$E(C_s) = \alpha \cdot t_{50\%} + \beta \cdot (t_{90\%} - t_{50\%}) + \tau \qquad (4)$$

Where $t_{50\%}$ is the median travel time and $t_{90\%}$ the 90% travel time. $\alpha$ and $\beta$ are valuation parameters for travel time and congestion. $\tau$ is the toll level.

The valuation of the disutility due to schedule delay is based on a similar stochastic distribution, but this first has to be translated to an expected schedule delay early and late. This leads to the following cost function:

$$E(C_s) = \alpha \cdot E(T) + \beta \cdot E(SDE) + \gamma \cdot E(SDL) + \tau \qquad (5)$$

Where $E(T)$ is the average travel time, $E(SDE)$ and $E(SDL)$ are the expected schedule delay early and late and $\alpha, \beta$ and $\gamma$ are valuation parameters for travel time and schedule delay. It is also possible to add a penalty to the cost function that is calculated once when a road user arrives too late. This describes a disutility that is a consequence of arriving too late, but that does not depend on the size of the delay.

Although the first formula incorporates only the first aspect and the second formula only the second aspect, in many studies one of both formulas is applied to describe both cases. A reason to use only the first formula is that in many studies no data are available about the size and valuation of schedule delay. A reason to use only the second formula is that the use of the average travel time already incorporates additional travel time in congestion situations (this is not directly the case using the median travel time in the first formula!) and the disutility of comfort is assumed to be similar related to the travel time variability as the disutility of schedule delay late.

This means that in the first formula the valuation of the schedule delay disutility is incorporated in the parameter $\beta$ and in the second formula the valuation of the congestion disutility is incorporated in the parameters $\beta$ and $\gamma$.

## The underlying principle of schedule delay

Tseng et al. (2007) show the underlying principle of schedule delay. In figure 5 the utility experienced at work $W(t)$ and at home $H(t)$ are described during the morning. Because first the utility at home is larger than the utility at work and later vice versa, a road user plans his trip around the switch moment and in such a way that the missed utility during the trip is as small as possible.

Suppose a trip has a duration of $T$ as shown in the figure. The chosen departure time $t_b$ is the most optimal, because during the period between $t_b$ and $t_2$ the available potential utility is smaller than before and after this period. The total disutility is the same as area I till VI in the figure.

When the occurring travel time is lower (for example $t_b$ to $t^*$) the total disutility is lower (area I, II, III and IV). The occurring utility is increased with area V and VI, but as can be logically deduced from the figure, this utility would be larger when a later departure time is chosen and less utility at home would be lost. For a situation with a larger travel time the figure similar shows that an additional disutility occurs, that would be smaller when an earlier departure time is chosen. The relative utility at home during the early morning $\beta(t)$ and the relative utility at work during the late morning $\gamma(t)$ determine this lost utility due to schedule delay.

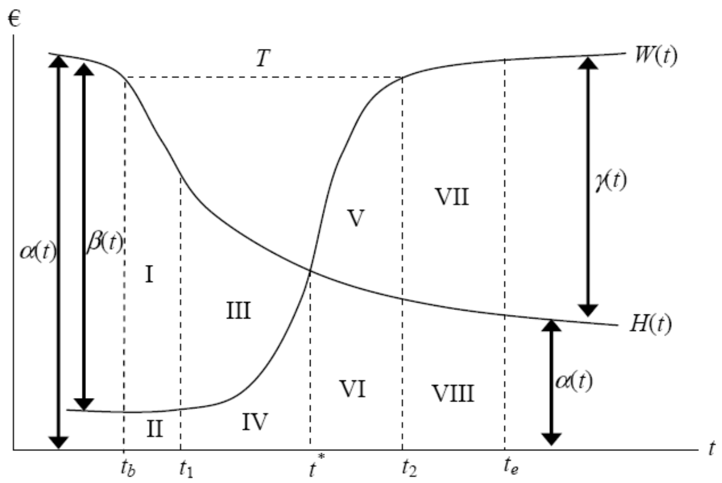



**Figure 5: Underlying principle of schedule delay (source Tseng et al., 2007)**

## Estimation of parameters

The parameters in the cost functions described in the previous paragraphs determine the influence of the different elements on the resulting costs. Different studies are made about these parameters and the influence of socio economic factors on them. For these studies there is a main distinction between Revealed Preference (RP) studies and Stated Preference (SP) or stated choice studies. Both studies will be described separately in the next paragraphs.

Usually both studies have been based on a logit model. Within a logit model for each user *i* and alternative *j* the systematic utility or disutility $V_{ij}$ is estimated based on all $K$ relevant attributes $X_{ik}$ and the (unknown) parameters $\beta_{ik}$ using the following formula (Tseng et al., 2005):

$$V_{ij} = \sum_{k=1}^{K} \beta_{ik} X_{ik} \qquad (6)$$

Assumed there is a stochastic variation $\varepsilon_{ij}$ between this systematic utility for the different users, the utility $U_{ij}$ is estimated using the formula:

$$U_{ij} = V_{ij} + \varepsilon_{ij}, \quad j = 1...J \qquad (7)$$

Based on this stochastic variated utility function, the probability a traveller *i* chooses to use alternative *j* can be described as:

$$P(Y_i = j) = \frac{\exp(V_{ij})}{\sum_{j=1}^{J} \exp(V_{ij})} \qquad (8)$$

When data are available about the resulting distribution of users between the different alternatives and the corresponding values of the attributes, the parameters $\beta_{ik}$ can be found for which the resulting distribution of users from the logit model correspond to the distribution found in the data. This is done by maximising the likelihood, which is described by the following formula:

$$\log L = \sum_{i=1}^{n} \sum_{j=1}^{J} d_{ij} \log P(Y_i = j) \qquad (9)$$

Where $d_{ij}$ is the proportion of the road users that chose for alternative *j*. When the most likely parameters $\beta_{ik}$ have been determined, the monetary valuation of each attribute can be calculated by dividing this parameter by the parameter that corresponds to the monetary costs (for example toll). The value of time for example is calculated by the following formula:

$$VOT = \frac{dU / dT}{dU / dC} = \frac{\beta_T}{\beta_C} \qquad (10)$$

The value of reliability (for example expressed as the difference between $t_{90\%}$ and $t_{50\%}$) can in a similar way be calculated by the following formula:

$$VOR = \frac{dU / dR}{dU / dC} = \frac{\beta_R}{\beta_C} \qquad (11)$$

## Revealed Preference

Revealed Preference studies are based on data available from an existing mobility situation. Interviews or loop detector data are used to determine the occurring distribution of travellers between the different alternatives. Based on this distribution the most likely parameters are estimated with which the choice distribution resulting from the choice model corresponds to the occurring distribution.

Lam and Small (2001) studied the preference at the SR-91. 389 respondents were asked during what share of their trips they use the pay lane. Also some socio economic characteristics like gender and income are registrated. The Value of Time and Value of Reliability have been estimated using different choice models. The resulting Value of Time is $ 19.22 / hr. The resulting Value of Reliability (with reliability expressed as the difference between $t_{90\%}$ and $t_{50\%}$) is $ 11.90 / hr for men and $ 28.72 / hr for women. This significant difference is explained by the fact that women seem to have more time restrictions and are more willing to pay for saving time. The results further show that the Value of Time is dependent on the total trip length (variations between $5 / hr and $26 / hr).

Brownstone et al. (2003) made a similar study about the pay lane use at the I-15 using an interview among 684 respondents. A share of this group is FasTrak user, another share is carpool driver and the remaining respondents are free lane users. Because the toll level at the I-15 is flexible, the expected toll and its variance is determined. Based on these a logit model is constructed with a large number of attributes. Using this logit model the Value of Time is estimated to be $ 30.98 / hr for commuters and $ 71.07 / hr for non-commuters.

In another article Brownstone and Small (2005) compare different studies about the Value of Time and the Value of Reliability at both pay lane locations with each other. The different results show an average Value of Time between $ 20 / hr and $ 30 / hr. Further the estimation is done that two third of the quality difference between the pay lanes and the free lanes can be declared by the reduction of travel time and one third of the quality difference by the reduction of travel time variability.

The article also remarks that for the case of the I-15 the flexible toll is a complicating factor. Because this toll is higher when more traffic is at the freeway, the toll level is an indicator for the unreliability of the travel time. For this reason in some studies the interaction between the actual toll level and the travel time variability is included during the determination of the Value of Time. As a consequence it becomes very difficult to make an accurate estimation of the Value of Reliability. The article therefor considers all estimations that have been made about the VOR of the I-15 unreliable.

An alternative method for the determination of the Value of Time and Value of Reliability is described by Liu et al. (2007). In this method loop detector data are used. A consequence of this method is that segmentation of the measurements based on socio economical data is not possible. With these data an estimation is made of the travel times during morning time intervals of 5 minutes at the SR91. For each time interval the median travel time and the 80% travel time is determined. For the same time intervals the distribution of vehicles between the pay lanes and the free lanes is determined. These data are applied together in a simple logit model containing the attributes travel time, travel time variation and costs. For each 30 minutes the Value of Time and the Value of Reliability is estimated using the most likely parameters. Further the Degree Of Risk Aversion (DORA) is calculated as the Value of Reliability divided by the Value of Time. The resulting values are shown in figure 6.

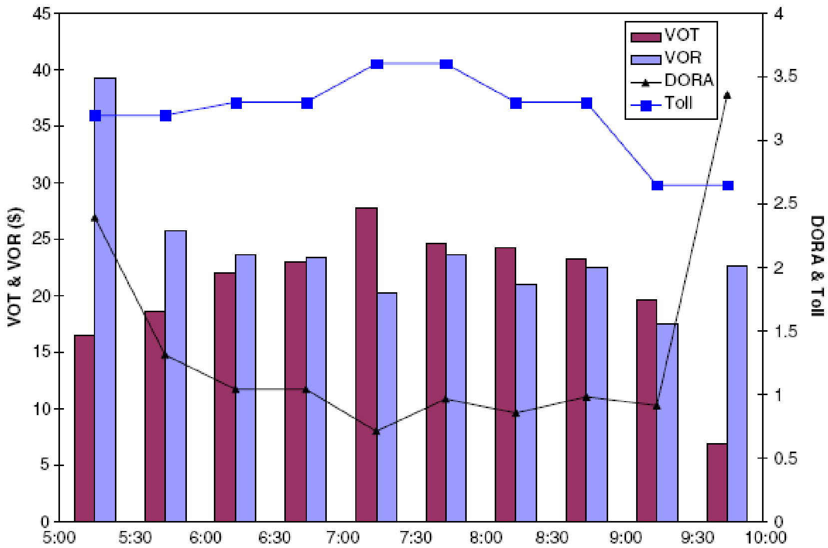



**Figure 6: Estimation of Value of Time and Reliability SR91 based on loop detector data (Liu et al., 2007)**

## Stated Preference

In Stated Preference studies a fictive travel situation is used to determine the parameters for the different attributes. Respondents are asked to select their favourite travel alternative out of different options and based on this choice the valuation of the attributes is estimated.

The most important difference between Stated Preference and Revealed Preference is that SP studies are based on fictive situations, while RP studies are based on real situations. An important advantage of SP is that it is very easy to vary the travel situation for which the preferred travel alternative has to be selected between different respondents. This makes it possible to make a more clear distinction between the influences of the different attributes. RP studies are usually based on one occurring (average) travel situation and this makes it more difficult to determine what part of the valuation of an alternative can be explained by for example travel time reduction, what part by travel time reliability and what part by a reduction of expected schedule delay (Liu et al., 2007).

An important disadvantage of SP is that it estimates the valuation based on a fictive situation. Respondents could make other choices in real situations. This is related to the fact that in real situations no full information is available about the (expected) trip characteristics. If a traveller has little time or a traveller has adjusted his daily schedule pattern, he could have a significantly different valuation for different attributes. Another disadvantage is explained by the perception of travel time reliability. Noland and Polak (2001) state that this perception could be different from the occurring travel time reliability.

For pay lane situations no RP studies are available, because there are no pay lanes in The Netherlands. It is likely that Dutch travellers have other characteristics than travellers from The United States. This makes it difficult to apply the RP result from the United States for a Dutch pay lane case.

For Dutch travellers several SP studies have been executed. Van Amelsfort and Bliemer (2005) have studied the valuation of travel time variability in terms of schedule delay. They have also added an uncertainty term to equation 5. This is done because in some situations the median travel time is almost the same as the free flow travel time, while the occurrence of incidents ans sometimes congestion result in very high travel times. These irregular high travel times lead to a large extra travel time, but this travel time is not incorporated in the expected travel time or expected schedule delay.

Tseng et al. (2005) have studied the valuation of time and schedule delay for Dutch commuters. This SP study has been used to estimate valuation parameters within this study. This study is described in chapter 5.

## Incorporation of travel time variability in a traffic simulation procedure

Within a traffic simulation procedure, traffic is assigned based on a certain assignment logarithm. Within this logarithm all relevant attributes are incorporated. When these attributes depend on the assignment results, usually these logarithms have an iterative structure in which the relation between assigned traffic and the attribute is incorporated.

A frequently used relationship between traffic flow and travel time at a road is the so-called BPR-function. This function describes the travel time $t_a$ as a function of the traffic flow $v_a$ with the following formula (De Dios Ortúzar et al., 2001):

$$t_a(v_a) = t_0 \cdot \left[ 1 + \gamma \cdot \left( \frac{v_a}{C} \right)^k \right] \qquad (12)$$

Where $t_0$ is the travel time under free flow conditions, $C$ is the capacity of the road and $\gamma$ and $k$ are roadtype specific parameters. This function is able to estimate the average travel time at a road under certain circumstances, but does not describe the travel time variation that occurs.

Therefore Tu et al. (2008) have described a method to estimate travel time variability. In the article the assumption is made that above a certain occurring traffic inflow there is a probability that a traffic breakdown occurs. This makes the travel time instable. For this reason the travel time unreliability ($TTUR$) can be described as a function of the travel time variability under normal conditions ($TTV^f$) and under breakdown conditions ($TTV^j$) using the following formula:

$$TTUR = (1 - P_r^{br}) \cdot TTV^f + P_r^{br} \cdot TTV^j \qquad (13)$$

Where $P_r^{br}$ is the probability a traffic breakdown occurs. When sufficient data are available, all elements in the formula can be made dependent on the traffic inflow $q_{in}$:

$$TTUR(q_{in}) = (TT90th^f(q_{in}) - TT10th^f(q_{in})) \cdot (1 - P_r^{br}(q_{in})) + (TT90th^j(q_{in}) - TT10th^j(q_{in})) \cdot P_r^{br}(q_{in}) \qquad (14)$$

Where $TT90th$ and $TT10th$ are the travel times with a 90% and 10% cumulative probability.

Although this method gives a procedure to describe travel time variation as a function of traffic inflow, a strong inconsistency of the method is that it uses two separate differences. Suppose under normal condition the difference between the 90% and 10% cumulative probability for normal situations is 5 minutes and the difference between the 90% and 10% cumulative probability for breakdown situations is also 5 minutes, but the average here is 15 minutes larger. Then the TTUR would be 5 minutes according to the formula. This result seems to a very bad indicator of TTUR, because the real difference between the !0% lowest and 10% highest travel times is more than 15 minutes.

## The influence of accidents

Incidents usually have a small probability to occur, but when they occur, travel times could be very high. Cohen and Southword (1999) describe a method to estimate the delay after incidents as a function of the V/C ratio, the share of road capacity that is used.

The assumption is made that as a consequence of an incident een queue Q originates corresponding to the following formula:

$$Q = (V - rC) \cdot T_i \qquad (15)$$

Where $V$ is the traffic flow, $rC$ is the reduced road capacity that is available after the incident and $T_i$ the duration of the blockade at the incident location. After the blockade is taken away, the queue dissolves after time period $T_g$ that is calculated using the following formula:

$$T_g = Q/(gC - V) \qquad (16)$$

Where $gC$ is the getaway road capacity. After some mathematical operations this leads to the following formula for the total delaytime:

$$D = D_i + D_g = (1/2) \cdot C \cdot T_i^2 \cdot (V/C - r)(g - r)/(g - V/C) \qquad (17)$$

The different types of incidents that can occur are classified in the article. The assumptions are made that the probability of an incident can be described by a Poisson distribution and the duration of an accident by a γ-distribution. With these classifications and assumptions general equations are made for the mean and variation of the incidence delay as a function of the V/C-ratio. For example for a freeway with two lanes in each direction the following mean $\mu_d$ and variation $\sigma_d^2$ of delay $d$ are estimated:

$$\begin{aligned} \mu_d &= 0.0154 \cdot (V/C)^{18.7} + 0.00446 \cdot (V/C)^{3.93} \\ \sigma_d{}^2 &= 0.00408 \cdot (V/C)^{21.2} + 0.00199 \cdot (V/C)^{4.07} \end{aligned} \qquad (18)$$

The method is useful bacause it is based on a microscopic analysis of incident delays and translates these delay to a mean and variation of travel time. But before applying the method the importance of incidents towards the congestion problem has to be evaluated. Mostly incidents lead to such a high travel time and they occur such little that it is nearly impossible to incorporate the potential incident delay in a schedule time margin.

## Applying travel time reliability in cost functions

Shao et al. (2006) describe a model in which the user equilibrium is not based on travel time but on travel time variability. This equilibrium is called the Demand driven travel time reliability-based user equilibrium (DRUE). Within this DRUE all road users make their route choice by minimising the costs $c_a$ as the sum of travel time $t_a$ and a safety margin $s_a$:

$$c_a(v_a) = t_a(v_a) + s_a(v_a) \qquad (19)$$

Where both the travel time as the safety margin are dependent on the traffic flow at a certain road $v_a$. In the article this safety margin is chosen in such a way that there is a 95% probability on arriving on time and the assumption is made that the traffic inflow can be described by a normal distribution. The travel time $t_a$ as a function of the traffic inflow $v_a$ is described by the following formula:

$$t_a(V_a) = t_0^a + \frac{V_a}{C_a} \qquad (20)$$

Where $t_0^a$ is the travel time under free flow conditions and $C_a$ the road capacity.

Using these assumptions formula 19 can be rewritten as:

$$c_a(v_a) = t_a + 1.65 \cdot \sigma_t^a = t_0^a + \frac{V_a}{C_a} + 1.65 \cdot \frac{\mathrm{cov} \cdot V_a}{C_a} \qquad (21)$$

And the covariance can be calculated using traffic inflow $q$ and variation $\sigma_q$:

$$\mathrm{cov} = \frac{\sigma_q}{q} \qquad (22)$$

For a two road network with a highway and a local road the normal user equilibirum (UE), the probit stochastic equilibrium (Probit SUE) and the DRUE have been estimated. The conditions of these equilibriums are shown in Table 1.

| | **UE** | | | **Probit-SUE** | | | **DRUE** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Highway | | Local road | Highway | | Local road | Highway | | Local road |
| Average traffic inflow | 100,00 | < | 175,00 | 116,04 | < | 158,96 | 154,21 | > | 120,79 |
| Average travel time | 2,25 | = | 2,25 | 2,29 | > | 2,09 | 2,39 | > | 1,71 |
| Reistijd SD | 0,13 | < | 0,87 | 0,15 | < | 0,79 | 0,19 | < | 0,61 |
| Veiligheidsmarge | 0,21 | < | 1,44 | 0,24 | < | 1,31 | 0,32 | < | 1,00 |
| Effectieve reistijd | 2,46 | < | 3,70 | 2,53 | < | 3,40 | 2,71 | = | 2,71 |

**Table 1: Simulation results of three different user equilibriums (Shao et al., 2006)**

Because the travel time at the local road increases much faster as traffic flow increases, the necessary safety margin at the local road is larger than at the highway. For this reason in the DRUE more traffic inflow is assigned to the highway in comparison to the UE and the probit-SUE.

The method offers a logic and easily applicable procedure for the incorporation of travel time variability within a traffic assignment. An important disadvantage is that the results are very sensitive to the assumed probability distribution of traffic inflow. Also the assumption that all road users would incorporate a 95% safety margin is not realistic.

# 3. Research questions & methodology

In the previous chapter the background of pay lanes from different perspectives is described. This chapter describes the research structure. First the main problem is defined as a summary of the first two chapters. Secondly the research questions and objectives are stated. Finally the research methodology is described.

## Problem definition

The road network in the Netherlands will become more and more congested the upcoming years. To meet the rising problems, policy is developed to increase road capacity at several places and to introduce a general congestion charge to discourage road use during peak hours.

An alternative or complementary policy instrument is the introduction of pay lanes. This introduction was considered at the end of the last decade, but is not implemented in the transport plans, due to a lack of political support. In the United States several examples of pay lanes are available. In most situations the pay lanes provide a valuable alternative for the free lanes. Pay lanes possess broad social support and increase the accessibility of congested areas for those users that are highly dependent on this.

Pay lanes could also be a valuable policy instrument to maintain the current level of accessibility in the Netherlands. To create social and political support for pay lanes in spite of the current negative opinions it is essential to have a good insight in the likely congestion effects before. Therefore accurate traffic simulations are necessary.

At this moment there is very limited experience with the simulation of pay lanes in traffic models. The choice behaviour that occurs differs strongly in comparison to regular freeways, because not only travel time, but also travel time variability varies very strong. Based on this lack of experience, the following problem statement can be defined:

*Problem statement:*
The monetary valuation of pay lanes in the United States is for an important part based on the valuation of travel time reliability. There is a strong uncertainty about this valuation of Dutch road users and the way this aspect can be incorporated within a choice model. This makes it difficult to accurately forecast the congestion effects of pay lanes.

## Research questions

In addition to the problem statement, the following two research questions are formulated:

1. How can a travel time variability based choice model for a pay lane be composed and integrated in a traffic network simulation procedure?
2. What indicative conclusions can be derived from the simulation of two concrete pay lane situations with respect to the opportunities for introducing pay lanes in the Netherlands?

Because both questions are quite generally formulated, there are also stated several sub-questions. The following sub-questions correspond to the first research question:

1.1 What Travel time variability can be deduced from available loop detector data for the present situation and is it possible to estimate the relationship between traffic inflow and travel time variability based on these loop detector data?
1.2 How can the travel time variability be integrated in a cost function of a pay lane choice model?
1.3 How can this pay lane choice model be implemented in a simulation procedure for a traffic network?
1.4 What limitations has the used software for executing an accurate pay lane simulation?

And the following sub-questions correspond to the second research question:

2.1 What are the congestion effects of adding a pay lane?
2.2 How are the users of the pay lane expected to be distributed between the different income classes?
2.3 To what extent is the pay lane able to guarantee a high level of service under different traffic conditions in the road network?
2.4 How effective is the adding of the pay lane in comparison to a regular capacity enlargement in reducing the congestion costs?

## Research objective
The objective of the research is to develop a travel time variability based choice model and simulating this model within two concrete pay lane situations in the Netherlands to get an indication of their effectiveness.

## Research methodology
Based on these research questions and the corresponding research objective, a research model is constructed. This model is shown in figure 7. The structure of this thesis corresponds to the different elements of the research model.

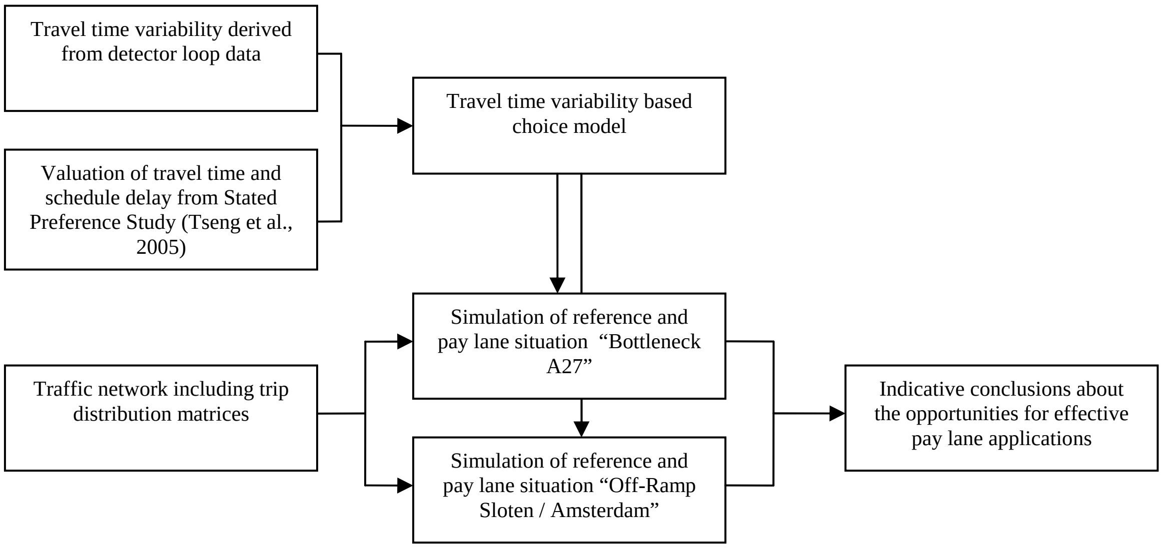



**Figure 7: Research Model**

## Input elements
The research model contains three input elements. Each element will now be shortly described. With these input elements two main methods have been applied. These two methods will be described afterwards.

*Travel time variability*
The travel time variability is an important component of the developed choice model. For this reason an analysis of the occurring travel time variability at the A27 bottleneck (one of the two pay lane situations) is executed. This analysis is described in chapter 4. The results of this analysis are used in the choice model.

*Valuation of travel time and schedule delay*
As described in chapter 2, Stated Preference studies are useful to estimate the valuation of travel time and schedule delay for different road users. The results of the Dutch research described by Tseng et al. (2005) are considered and translated to the modelling context in order to get proper valuation parameters in the choice model. This is described in chapter 5.

*Traffic network and trip distribution matrices*
The two case studies are simulated with a representative traffic network. For both simulations this network is deduced from an existing national accessibility model and a corresponding number of trip distribution matrices. This model is described in chapter 6.

## Method 1: constructing a choice model
One of the current main problems in simulating a pay lane situation is the estimation of the pay lane use. The proportion of the road users that decide to use the pay lane determines the level of service on both the free lanes and the pay lane. As stated in the introduction, price is the most important criterion for people to decide to use the pay lane. Therefore in this research a choice model is constructed that expresses the experienced advantages of the pay lane use in terms of money.

As stated in chapter two, a pay lane with a guaranteed travel time not only offers an improved travel time, but also significantly reduces the risk for road users to arrive too late or too early because the travel time variation is very small. This effect is much smaller within regular traffic simulations. For this reason in this research these pay lanes are not simulated by a regular link-cost (travel time) optimization procedure, but a separate choice model is applied to estimate the proportion of pay lane users. The expected schedule delay depends on the occurring travel time variation. For an accurate estimation of this variation, an analysis of detector loop data is executed.

Because the monetary valuation of travel time and schedule delay also differs for each road user, there is also made a distinction between different income groups and within these income groups between road users with high schedule delay costs and users with low schedule delay costs. And because the schedule delay also depends on the real travel time before and after passing the pay lane section, there is made distinction between small trips and long trips.

This leads to the following components of the choice model:

- Toll
- Expected travel time pay lane / free lane section
- Expected schedule delay early
- Expected schedule delay late
- Expected travel time before and after pay lane / free lane section

For the application of the choice model the following differentiations will be made:

- Time of day
- Income class
- Sensitivity for schedule delay
- Possible compensation for pay lane usage by employer
- Trip length
- Toll level

The construction of the choice model is described in chapter 4.

## Method 2: Simulation of two possible pay lane situations

After the construction of the choice model two possible pay lane situations are simulated. These simulations are considering a traffic network where for one section a pay lane is provided as an alternative. For this simulation the developed choice model is implemented in the traffic simulation procedures. Chapter 5 and 6 describe this procedural implementation. Chapter 7 and 8 show the concrete construction of the pay lane and the simulation results of both situations. Now the both situations are shortly described.

## Situation "Bottleneck A27"

The first situation is the bottleneck at the A27. This bottleneck is a consequence of the Merwedebridge that crosses the Waal River near Gorinchem. The capacity of the road at the bridge is smaller than the capacity of the highway track elsewhere. The main reasons for this difference are the absence of a shoulder lane and the smaller width of the two lanes. Although there is no reduction in the number of lanes, there are great congestion effects at the bridge during peak hours. In the morning peak congestion occurs for the traffic travelling to the north and in the afternoon peak congestion occurs for the traffic travelling to the south.

Figure 8 shows the current situation. The simulation of the pay lane is executed for the morning peak. This means that for the traffic crossing the river from the south an alternative pay lane is created that offers road users the possibility to pass the bottleneck without congestion. This pay lane situation is compared with two reference situations. The first reference situation considers the current situation, in which tha bottleneck contains only two free lanes. The second reference situation considers the situation in which the added lane is also a free lane and all road users have a similar benefit from this capacity extend.

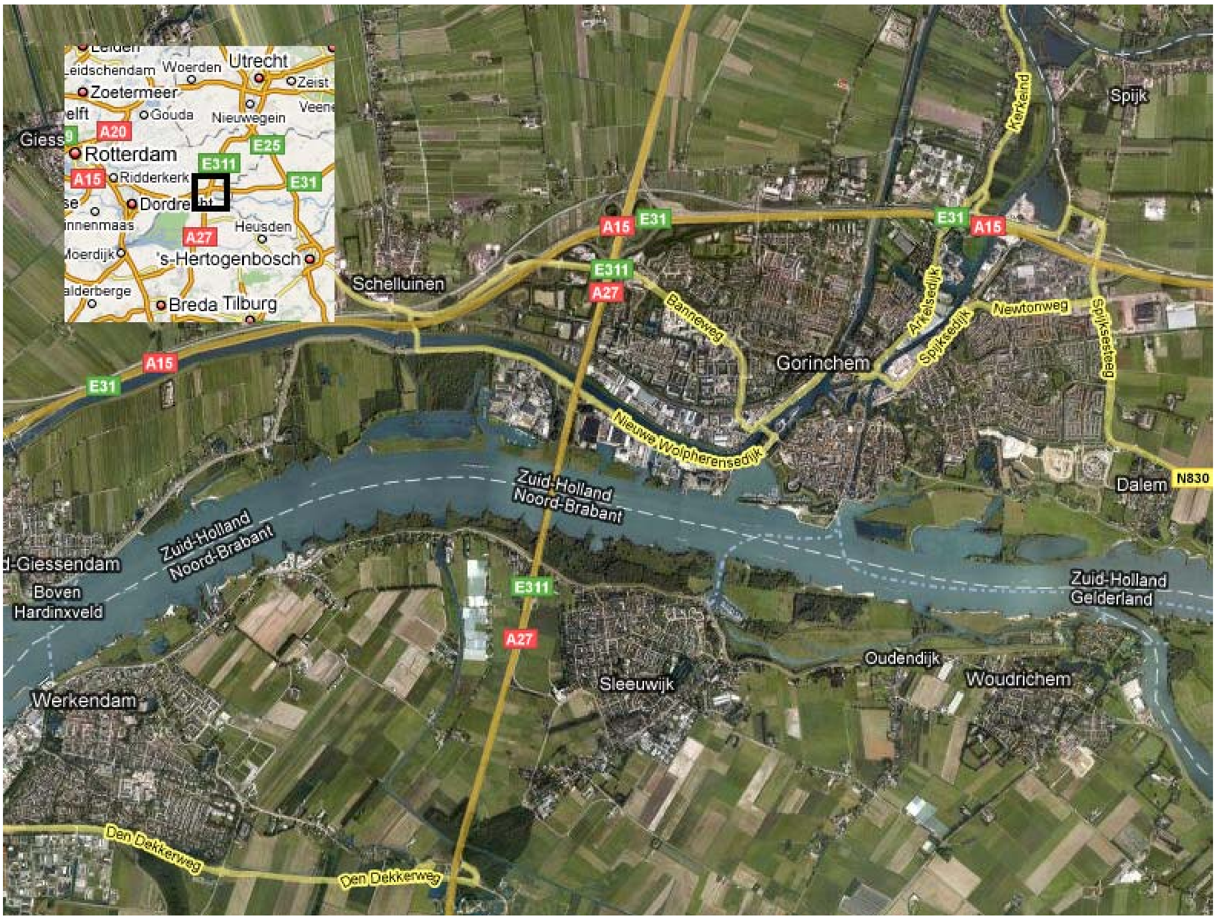


**Figure 8: Situation Bottleneck A27 (source: GoogleMaps)**

## Situation "Off-Ramp Sloten / Amsterdam"

The second situation is the off-ramp near Sloten in Amsterdam. During the morning peak congestion occurs at this off-ramp as a consequence of the waiting time at the junction at the end of the off-ramp. At some times the resulting queue is longer than the off-ramp. This means that also the on-going traffic at the Ring of Amsterdam has an impedance by the off-ramp. As traffic flows grow the upcoming years, it is possible that on several places at the Ring junctions at the end of off-ramps negatively influence the traffic conditions at the highways.

A potential solution for this problem is the creation of extra road length at the off-ramp. As a consequence the waiting times at these off-ramps could increase further, but the negative effects for the on-going traffic are taken away. In this situation a pay lane is created as a fast alternative for the extra long off-ramp. On this pay lane road users can leave the Ring at a high speed and don't have to wait at the off-ramp.

This pay lane variant is simulated for the off-ramp near Sloten. Figure 9 shows the current situation. The red line is the off-ramp for which the adapted situation is simulated. The reference situation considers only the enlargement or the off-ramp length.

**Figure 9: Situation Off-Ramp Sloten / Amsterdam (source: GoogleMaps)**

## Evaluation of simulation results

The last step in the research model is the evaluation of the simulation results. Corresponding to the research sub-questions, several aspects of the simulation results are analysed:

- Social distribution of pay lane users (high / low income classes)
- Travel time of the pay lane for different circumstances
- Congestion costs in comparison to reference situation

Another part of the evaluation of the results considers the applied method. An overview is given of the improvements that can be made or are necessary in order to make the simulation procedure more reliable. And also an overview is given of the opportunities to implement the choice model within regular traffic modelling procedures so the simulation can be made more practicable. These conclusions and recommendations can be found in chapter 9.

# 4. Analysis of travel time variability

In this chapter the results are shown of the analysis of the current traffic conditions at the A27. This analysis is made in order to be able to describe travel time variability in such a way that it can be implemented in a choice model. This analysis is made with detector loop data and is concentrated on the travel times that occur. In the first paragraph these data are described. In the second paragraph the current variation in travel time is analysed. In the third paragraph the relationship between traffic inflow and travel time is studied.

## 4.1 General description of the used data

### The MonicaNet

The data analysis is based on measurements made with the MonicaNet. MonicaNet is a system that is developed by the *Adviesdienst Verkeer en Vervoer,* a former division of the Dutch ministry for Transport and Waterworks. The system is connected to detector loops that are placed on the road surface at a large number of places in the Dutch road network and it analyses the measurements coming from these detector loops.

The detector loops are able to record vehicles that pass the loops. Because at all places two loops are combined, the speed of the vehicle can be deduced from the time difference between passing the first loop and passing the second loop. The system continuously records these vehicles passing and each minute the traffic flow (vehicles per hour) and average speed (kilometres per hour) are registered (Ministerie van Verkeer en Waterstaat, 1996).

The MonicaNet registers data for each detector loop, but these data can also be used to create information about the traffic situation at a certain road track. When this track contains more than one detector loop, the average speed that occurs and the travel time that is needed to pass the track can be estimated. The software programme MoniGraph has been developed to execute this estimation. MoniGraph applies the Piecewise Linear Speed Based (PLSB-) method. With this method the travel times for a road section can be deduced very accurate from a number of loop detectors (Ministerie van Verkeer en Waterstaat, 2006, III). In Appendix A the PLSB-method is described.

### Selected data

The available data from the MonicaNet are very extensive and therefore a selection is made of the time periods and detector loops for which the measured traffic flow and average speed are collected and the corresponding travel times are estimated.

A total of 18 detector loops is selected to analyse the traffic situation at the A27. All these detector loops record the passing traffic coming from the south and moving towards the Merwede Bridge. The total length of the section is 9 kilometres. Inside the section there are two junctions where traffic enters and leaves the A27. The other traffic enters the section at the beginning, near the village Hank and leaves the section at the end, just past the Merwede Bridge. In figure 10 the section is shown as a green line. The blue points show the detector loop locations. Also the beginning and end of the track and the two on- and off-ramps within the track are indicated.

Because the modelling of the express lane is concentrated on the morning peak, the collecting of data from these detector loops is limited to the time periods between 5:00 and 10:00 in the morning. The first dataset that is generated contains all Tuesdays of the year 2007, except those in the months July and August and Dutch holidays (Christmas, carnival and Labour Day). Without these the dataset contains 39 Tuesdays. This dataset can be used to describe the current variation in travel time. For all days and for each 5 minutes the traffic flow and the average speed are collected from all detector loops. Based on these data also the travel time at the track is estimated for each 5 minutes.

The second dataset that is generated contains next to the Tuesdays from the first dataset the other Tuesdays and the other workdays of the months March, April, October and November. These months are considered to be the most representative, because in these months weather conditions are the most regular and the number of holidays is limited. Including the Tuesdays, this results in a total of 110 workdays. This dataset can be used to analyse the influence of traffic inflow on the travel time.

**Figure 10: Illustration of the A27 section (source: GoogleMaps)**

## 4.2 Statistical analysis of the variation in travel time

In the previous paragraph a description is given of the selected track and the two datasets that are composed. The first dataset containing 39 regular Tuesdays is used to analyse the current travel times at the track in order to describe the occurring travel time variability. For all these Tuesdays the travel time is estimated for each 5 minutes. This paragraph gives an overview of the results of this analysis.

### Travel time profiles

For every Tuesday a travel time profile can be drawn. This profile shows how the travel time evolves during the morning peak. Firstly these 39 profiles are sorted based on the average travel time during the morning $\bar{t}$ , which is calculated using the following formula:

$$\bar{t} = \frac{\sum_{i=1}^{P} t(p_i)}{P} \qquad (23)$$

Where P is the number of time intervals during each time travel time profile (60) and $t(p_i)$ is the estimated travel time during time interval i. In figure 11 a selection of these sorted profiles is shown.

As can be seen, the profile with the lowest average travel time barely exceeds the uncongested travel time of approximately 5 minutes. Contrary the profile with the highest average travel time reaches a maximum value of more than 20 minutes. The median profile shows that between 6:00 and 9:30 there is a regularly delay at the track between 5 and 10 minutes. Even the 10% profile has a significant delay of more than 5 minutes at a certain point. The profiles also show that after the moment congestion occurs the travel times remain mostly high until the end of the morning peak. These impressions confirm the supposition that there is a very frequently congestion at the track and that this congestion has a great impact on the travel time.

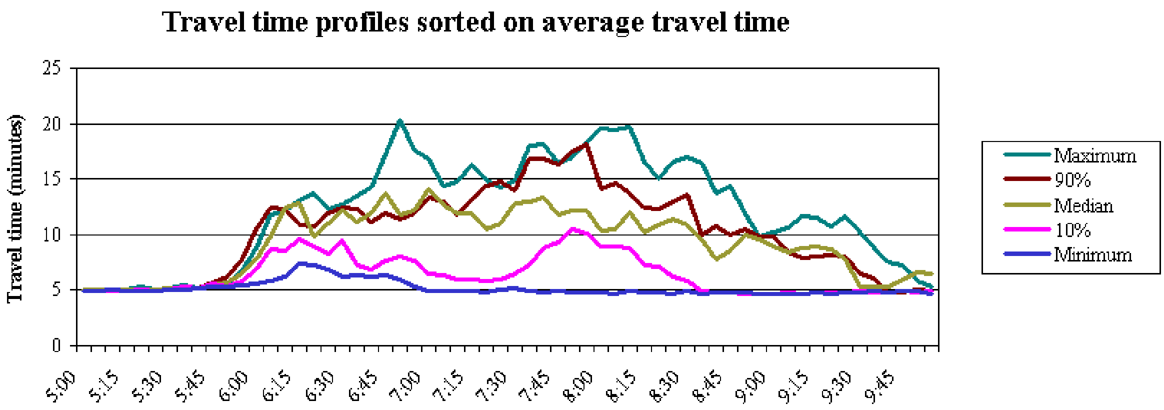



**Figure 11: Travel time profiles sorted by the average travel time during the whole morning**

To get a better impression of the overall variation of the travel time at different times the travel times of the different Tuesdays are separately sorted for each 15 minutes period. Per time period three travel times have been collected for each Tuesday, what results in 117 travel times for each time period.

Sorting these 117 travel times for all 15 minutes periods results in 20 collections of 117 travel times. For each collection the characteristic values (10%, median, 80% and 90%) are selected. This results in the profiles shown in figure 12. These profiles also indicate a large variation in the travel time during almost the whole morning peak. Another interesting aspect is the small difference between the median and the mean profile. If there would be a small number of extremely high travel times the mean profile should be higher than the median. The small difference between both indicates that the high travel times form no exception within the travel time variation, but correspond with a gradually distribution.

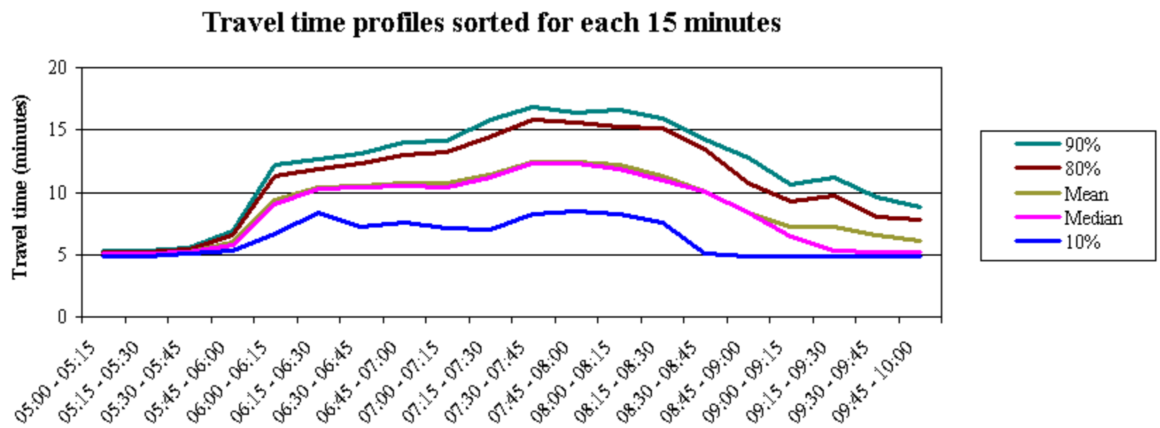



**Figure 12: Characteristics of sorted travel times for each 15 minutes time period**

## Travel time distribution per time period

The profiles in figure 12 show that the variation in travel time varies between the different time periods. This variation represents the travel times that road users expect and the risks for delay that road users take into account. For that reason it is important to get insight in these different distributions.

In figure 13 the probability density of the different travel times is shown for the time period 8:00 – 8:15. This time period is here taken as an example. The now described process is applied on all time periods. Based on the 117 sorted travel times a probability of 1/117 is assigned to every occurred travel time. For every travel time between 0 and 25 minutes (step size 0.1 minute) the occurring travel times are bundled and their probabilities are counted up. This results in the dotted line (not aggregated travel times).

This line contains many peaks and does not show a gradually function. To improve its quality there is made an aggregation of the data. For the same travel times between 0 and 25 minutes now the occurring travel times within a margin of 1 minute are bundled. The counting up of these probabilities results in the solid line in figure 13.

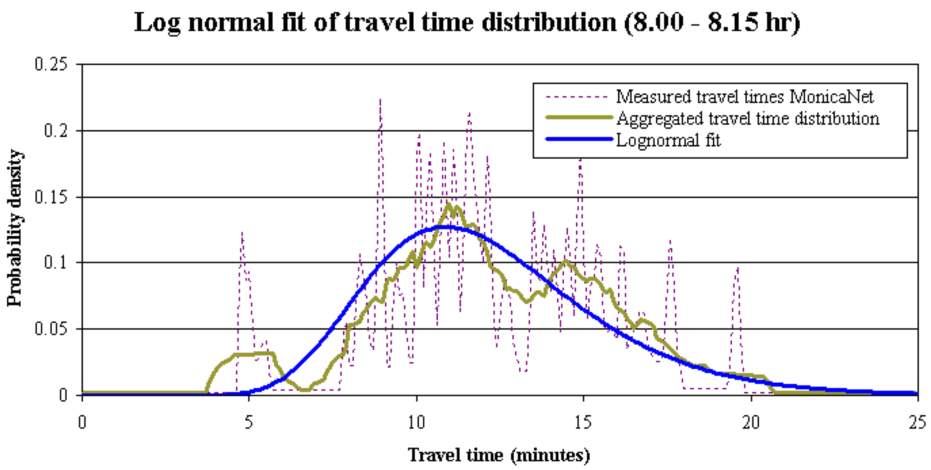



**Figure 13: Probability density of the measured travel times and the lognormal fit**

## Log normal fit

The next step is to make a statistical fit with this aggregated probability density. Earlier research shows that the lognormal distribution gives the best results for approaching the occurring distribution. A lognormal distribution has a relative small density to the left of the top (the travel time with the highest probability density) and a relative large and widespread density at the right of the top. This corresponds to the travel time distribution that mostly occurs. Very low travel times (lower than uncongested) do not occur, while there are sometimes situations where the delay rises very fast. The lognormal distribution is described by the formula:

$$f(x,\mu,\sigma)=\frac{1}{x\cdot\sigma\cdot\sqrt{2\pi}}\cdot e^{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}} \qquad (24)$$

Opposite to a normal distribution function, the parameters $\mu$ and $\sigma$ are not the same as the mean and standard deviation. Instead the mean and variation of a lognormal function can be calculated with the formulas:

$$E(X)=e^{\mu+\sigma^2/2} \qquad (25)$$

$$Var(X)=\left(e^{\sigma^2}-1\right)\cdot e^{2\mu+\sigma} \qquad (26)$$

Because $E(X)$ and $Var(X)$ can be determined from the available travel time measurements, the parameters of the lognormal fit will be based on these values. Rewriting the formulas above results in:

$$\mu=\ln(E(X))-\frac{1}{2}\ln\left(1+\frac{Var(X)}{(E(X))^2}\right) \qquad (27)$$

$$\sigma^2=\ln\left(\frac{Var(X)}{(E(X))^2}+1\right) \qquad (28)$$

Using these functions to determine $\mu$ and $\sigma$ results in the lognormal fit shown in figure 13. As can be seen, this lognormal distribution fits quite well with the aggregated probability density.

In figure 14 the cumulative distribution is shown for the aggregated measurements and the lognormal fit. The lognormal fit has a characteristic shape. As a consequence of this, the approached minimum and maximum travel times can differ from the measured travel times which are a consequence of the travel time in a non congested situation at the one hand and an incidental travel time on the other hand. It’s always difficult to fit these extremes, but it could be valuable to include these extremes well because they influence the perceived travel time variability the most strongly. Despite no procedure has been developed for this thesis to include these extremes. The lognormal fit makes it possible to describe the cumulative travel time distribution with only two parameters. That makes it more suitable to apply in a modelling environment than the aggregated probability density or the raw data.

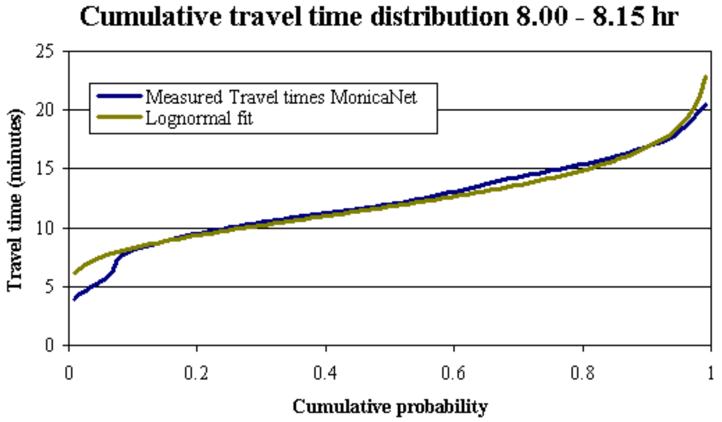



**Figure 14: Cumulative distribution of travel time**

Table 2 shows the resulting parameters for all time periods. In the first two columns the calculated mean and variance of the measured data are shown. The third and fourth columns show the parameters of the lognormal fit. The last column shows the value or $R^2$, the variance in the measured cumulative travel time that is explained by the lognormal distribution. This explained variance mostly turns out to be quite high. These parameter values can therefore be a suitable starting point for the modelling of travel time variability.

| Time | mean | variance | μ | σ | $R^2$ |
|---|---|---|---|---|---|
| 05:00 - 05:15 | 5,1 | 0,04 | 1,63 | 0,040 | 0,70 |
| 05:15 - 05:30 | 5,1 | 0,02 | 1,62 | 0,030 | 0,65 |
| 05:30 - 05:45 | 5,2 | 0,03 | 1,65 | 0,035 | 0,69 |
| 05:45 - 06:00 | 6,0 | 0,80 | 1,78 | 0,148 | 0,91 |
| 06:00 - 06:15 | 9,4 | 4,02 | 2,21 | 0,212 | 0,99 |
| 06:15 - 06:30 | 10,4 | 3,18 | 2,33 | 0,170 | 0,99 |
| 06:30 - 06:45 | 10,5 | 4,83 | 2,33 | 0,208 | 0,98 |
| 06:45 - 07:00 | 10,8 | 7,43 | 2,35 | 0,249 | 0,99 |
| 07:00 - 07:15 | 10,7 | 7,68 | 2,34 | 0,254 | 0,97 |
| 07:15 - 07:30 | 11,4 | 10,57 | 2,39 | 0,280 | 0,96 |
| 07:30 - 07:45 | 12,4 | 12,05 | 2,48 | 0,275 | 0,94 |
| 07:45 - 08:00 | 12,4 | 10,96 | 2,49 | 0,261 | 0,94 |
| 08:00 - 08:15 | 12,2 | 11,94 | 2,46 | 0,278 | 0,96 |
| 08:15 - 08:30 | 11,3 | 11,03 | 2,39 | 0,287 | 0,95 |
| 08:30 - 08:45 | 10,0 | 12,02 | 2,25 | 0,336 | 0,96 |
| 08:45 - 09:00 | 8,4 | 8,81 | 2,06 | 0,345 | 0,97 |
| 09:00 - 09:15 | 7,3 | 6,16 | 1,93 | 0,332 | 0,98 |
| 09:15 - 09:30 | 7,2 | 6,98 | 1,91 | 0,355 | 0,96 |
| 09:30 - 09:45 | 6,5 | 5,19 | 1,82 | 0,338 | 0,96 |
| 09:45 - 10:00 | 6,1 | 2,50 | 1,77 | 0,256 | 0,96 |

**Table 2: lognormal parameters for all 15 minute periods**

## 4.3 Analysis of the influence of traffic inflow on travel time

The results of the previous paragraph describe the variability of the travel time in the current situation. The expected travel times and the risks for delay that are taken into account by road users could be deduced for a similar situation from the statistical fit that is made. At the same time it could be possible that a part of this variability could be explained by other factors. Perhaps the extreme high travel times profiles correspond to bad weather situations. Or the large travel time profiles correspond to morning peaks where more vehicles were using the track than during the morning peaks with small travel time profiles.

If this kind of circumstances can explain a part of the variability, the variability that road users are unable to predict when they leave home would be smaller. In a modelling environment this can be important. On the other hand it could be possible that in a prospective situation the circumstances are changed, because there is more or less traffic at the track or the capacity of the track has changed. For these reasons it can be interesting to analyse the influence of various factors on the travel time.

This paragraph shows the results of the analysis of the influence of traffic inflow. Tu et al. (2008, see also chapter 2) show there is a positive relationship between the traffic inflow at a track and the variability of the travel time. Because the probability for a traffic breakdown increases as the inflow becomes larger, also the probability for high travel times becomes larger.

## The difference between traffic flow and traffic inflow

The used data from the MonicaNet contain the measured traffic flows, but not the traffic inflow. For several reasons this is a not negligible difference. The first reason is that the inflow at the track does not come from one origin. Most of the traffic enters the section at the beginning and comes from the section upstream the A27. But another part of the traffic is coming from one of the two junctions halfway the track, near Nieuwendijk and near Werkendam (see also figure 10, page 29). In figure 15 the distribution between these three origins is shown. This distribution is estimated by calculating the difference between the traffic flows at the different detector loops. Unfortunately no traffic flow is measured at the crossing roads or the onramps at the junction, what makes the results less accurate. The inflow from the junction near Werkendam seems to be quite high and also varies strongly during the morning peak.

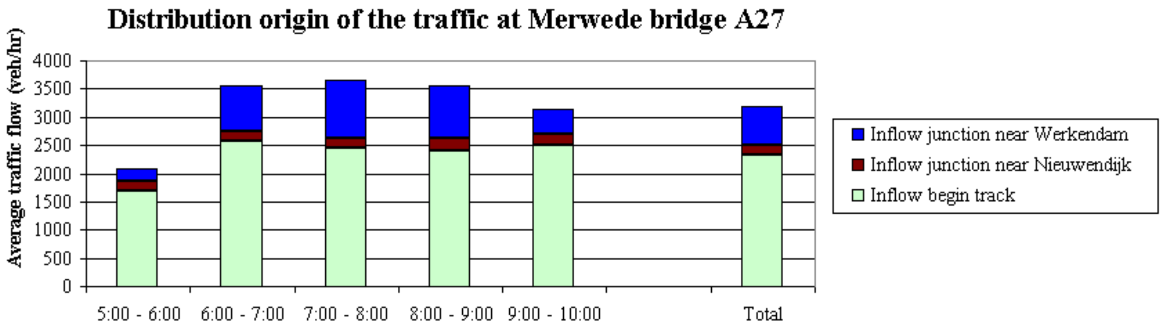



**Figure 15: Distribution origin of the traffic at the Merwede bridge**

Another aspect is the occurrence of congestion. When a queue is becoming larger or smaller, this is the result of more respectively less vehicles entering the congestion track than leaving it. When a queue starts before the beginning of the section, it is possible that more vehicles are entering the queue than there are entering the section. As a consequence of this the measured traffic flow is an underestimation of the traffic inflow. When the traffic flow is measured during the whole morning peak, the total inflow will equal the total outflow. But when the flow is measured for smaller time intervals, large differences can occur as a consequence of this aspect.

Figure 16 and 17 show the variation of the traffic flow upstream and downstream the road section. This variation is based on the collected traffic flows from the 39 regular Tuesdays for the first and the latest detector loop. The rightest column shows the average flow during the whole morning.

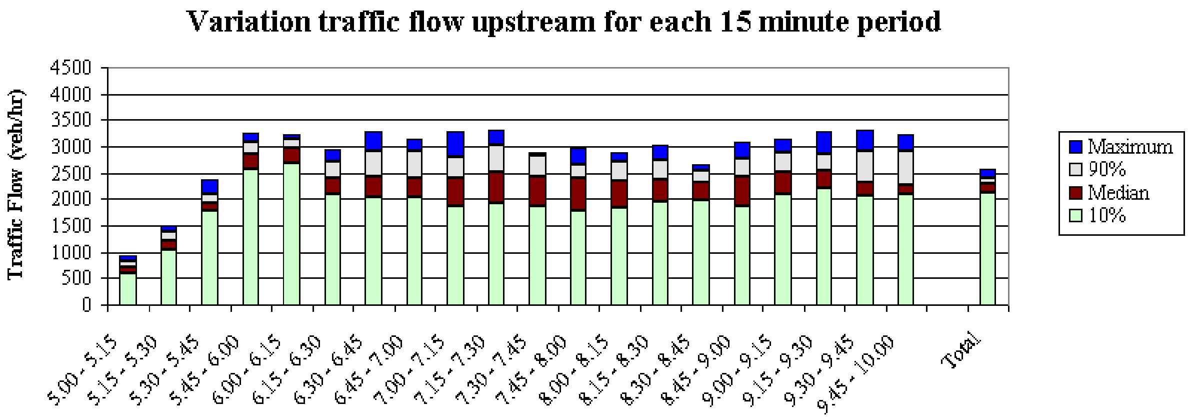



**Figure 16: Variation of the traffic flow at the beginning of the section for each time period**

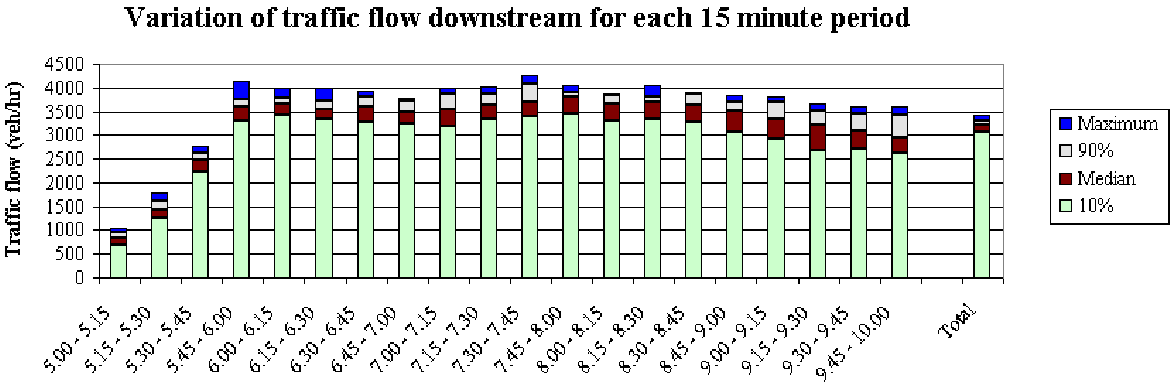



**Figure 17: Variation of the traffic flow at the end of the section for each time period**

As can be seen the variation in the first figure is much larger than the variation in the second figure. This difference can be explained by the fact that at the end of the section the road capacity is reached. This means that the traffic flow here does not represent the traffic inflow at the bridge, but describes the number of vehicles that just passed the queue at the Merwede Bridge. This queue forms a sort of buffer for the traffic inflow and creates a constant traffic outflow.

This leads to the conclusion that the traffic flow downstream is not a suitable indicator for the traffic inflow. At the same time the traffic flow upstream is also not a suitable indicator because the inflow from the two on- and off-ramps is not incorporated in these traffic flows. Another complexity is the fact that the number of vehicles entering at the on-ramps cannot be determined because the flow difference between a detector upstream an on-ramp and a detector downstream an on-ramp can also be caused by congestion effects.

## Relating inflow to travel time

The second dataset is used for a further investigation of the relationship between the inflow and the travel time. This dataset contains 110 workdays and for these workdays the travel times at the road section are collected for every 5 minutes. The dataset also contains the traffic flows and the measured average speed at all detector loops for every 5 minutes.

With these data it is possible to collect more than 6000 combinations of a travel time and a traffic flow at the entrance of the track. The largest problem with this procedure is that the registered inflow is sometimes influenced by the congestion, what makes the traffic flow lower than the real traffic inflow. Another problem is that traffic flow is based on a period of 5 minutes. During this short period there can be a large variation in the measured traffic flow, because the random passing of 10 additional vehicles results in an overestimation of the traffic flow by 120 vehicles. Also the time periods before and after these 5 minutes have a large influence on the travel time. As shown earlier (see Figure 11, page 30) travel time profiles do not have a couple of high and narrow peaks, but they mostly have a gradually changing line. Time periods at the end of the morning peaks often have travel time delay because of the congestion from earlier time periods and not because of the large traffic inflow at the moment.

As a consequence of this relationship between the different time periods and in order to avoid the large errors that occur for 5 minute time intervals, the travel times and traffic flows are averaged for periods of an hour and for the whole morning peak. The average travel time $\bar{t}$ is calculated using the following formula:

$$\bar{t} = \frac{\sum_{i=1}^{P} t(p_i)}{P} \qquad (29)$$

Where P is the number of 5 minutes time intervals (12 for an hour, 60 for the whole morning) and $t(p_i)$ is the collected travel time for time period i. The average traffic flow $\bar{q}$ is calculated in a similar way, using the following formula:

$$\bar{q} = \frac{\sum_{i=1}^{P} q(p_i)}{P} \qquad (30)$$

Where $q(p_i)$ is the collected traffic flow for time period i. Applying this procedure results in a total of six series of 110 combinations of an average travel time and an average traffic flow at the beginning of the track. These are plotted in figure 18.

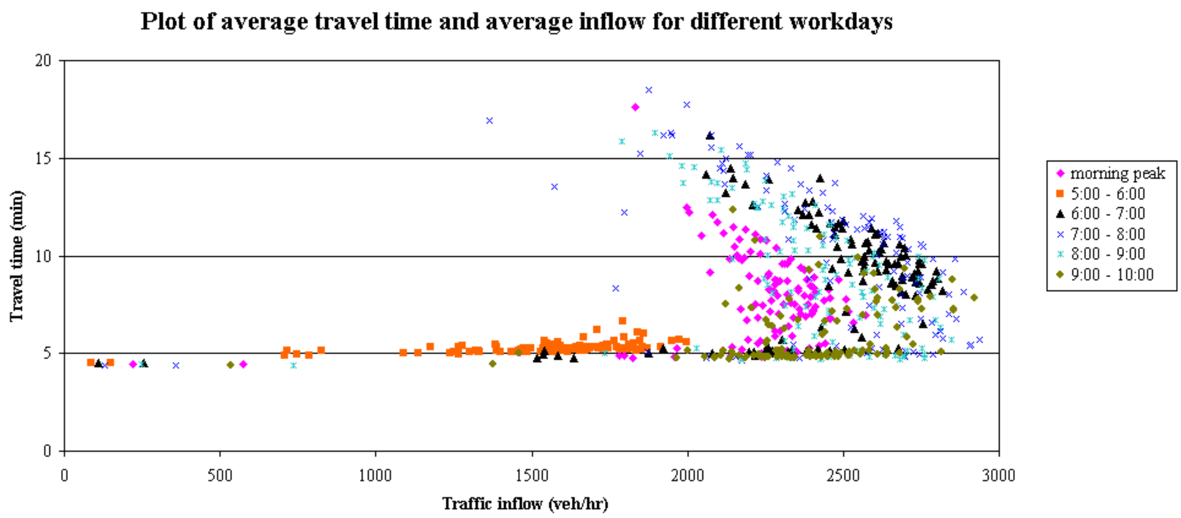



**Figure 18: Plot of the average travel time and average traffic flow for all collected workdays**

Figure 18 shows that for an inflow smaller than 1800 vehicles per hour almost all travel times remain low, what means that there are no traffic breakdowns. Above 1800 vehicles per hour the number of large travel times increases very fast and for high values of the inflow the travel time variation decreases. This corresponds to the common relationship between travel time and *traffic flow* (when capacity is reached or exceeded this can lead to a traffic breakdown with a higher travel time and a lower traffic flow). On the contrary this result does not correspond to the expected relationship between travel time and *traffic inflow*. According to the described method of Tu et al. (2008) the probability on traffic breakdowns increases as the inflow is larger and as a consequence the occurring travel times should be spread over a wider range. Figure 18 shows a decreasing range as the inflow increases.

In figure 19 bins are made for the average traffic flow during the morning peak. As can be seen far most of the flows are between 2100 and 2500. The calculated mean and standard deviation for each bin also show that the average travel time and the variation within the bin are decreasing for high values. Further the traffic flows of the available data are too much concentrated around capacity what makes it difficult to measure the variation for small traffic inflows. The results of both figures seem to indicate that even the average traffic flow does not represent the traffic inflow very well especially in the situations when a traffic breakdown occurs.

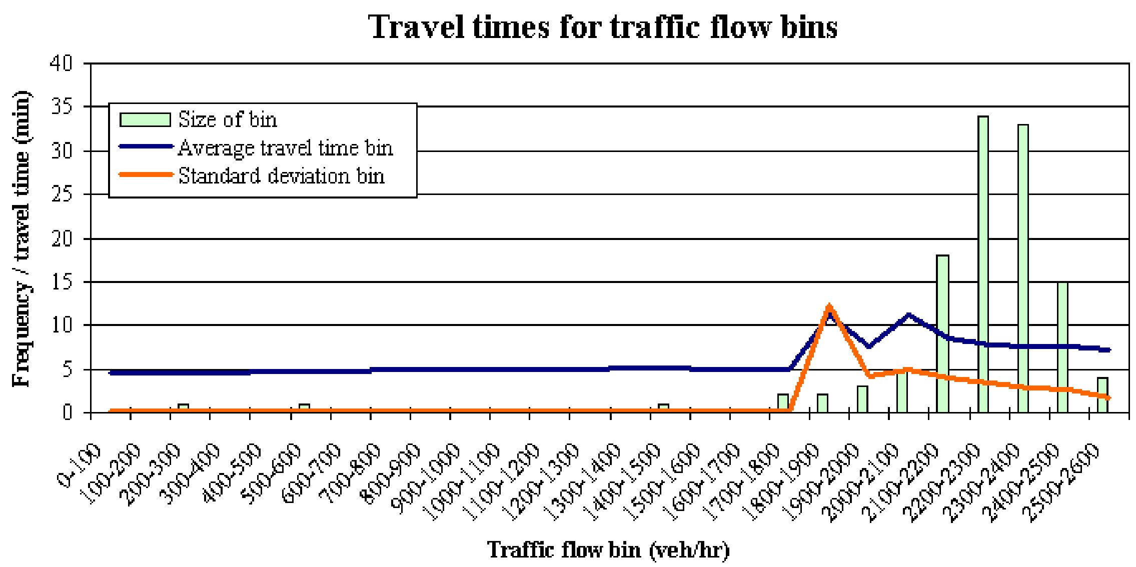



**Figure 19: Travel time variability for traffic flow bins**

## Conclusion

In this chapter detector loop data are used to describe the current travel time variability at the A27 road section. For almost all Tuesdays in 2007 travel time profiles show a lengthy period of delay and larger travel times. Using a log normal fit to approach the travel time variability for 15 minutes time intervals gives high R-squared values, as shown in table 2.

With the available data it seemed not possible to describe a relationship between the traffic inflow and the travel time variability. This is caused by the following reaons:

- No data are available about the traffic flow at the on-ramps. This makes it difficult to determine the traffic inflow from the on-ramps.
- Congestion effects make traffic flow patterns more constant. This makes it difficult to determine the real traffic inflow from the traffic flow shown by the detector loops.
- The variation of the total traffic flow during a morning within the selected days is relatively small. This makes it difficult to determine the influence of traffic flow on the travel time variability.
- The variaton of the traffic flow during 15 minutes time intervals is much larger. Unfortunately the traffic conditions usually are strongly influenced by the road conditions during the time intervals before the current time interval. For this reason it is not desirable to relate the traffic inflow during one time interval to the travel time variability that occurs.

These aspects have to be taken away before this relationship can be determined. This can be done by collecting data from more road sections and from more different days (also data on which the traffic flow is much lower). Within this thesis unfortunately no more time was available to execute this new data analysis.

# 5. The pay lane choice model

This chapter describes the choice model that is developed to estimate the distribution between the pay lane and free lane within a traffic simulation model. In the first paragraph a description is given of the ideal kind of model. The second paragraph describes the assumptions that are made to be able to perform this model within the context of this thesis. The third paragraph describes the different user classes that are used within the choice model. The last paragraph describes the resulting (mathematical) procedure that forms the choice model including travel time variability that is applied.

## 5.1 The ideal choice model

As described in chapter 2 the choice road users make to use a pay lane or a free lane depends mostly on the following three factors:

- Toll level
- Difference in expected travel time
- Difference in expected schedule delay

In an ideal choice model for each road user the values of these three factors can be determined. Based on these values the costs using the pay lane and the costs using the free lane are estimated and subsequently the lowest cost alternative is determined.

The difference in expected schedule delay depends on the probability on arriving too early or too late. This probability not only depends on the occurring variation at the free lane, but also on the departure time and the occurring travel times before and after the pay lane. As a consequence, this ideal model not only considers the traffic conditions at the pay lane and free lane, but the whole traffic network.

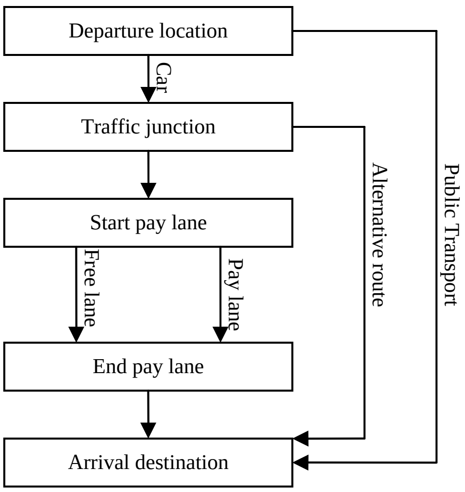



**Figure 20: Alternatives and choice places for an ideal choice model**

Figure 20 shows the route alternatives and the corresponding choice moments for a possible trip that passes a pay lane. At the departure place the road user intends to use the most optimal route. In combination with this most optimal route choice an optimal departure time is chosen, for which the expected schedule delay is minimised.

If this route is a route by car, it is possible that the road user arrives after a while at a road junction where route information is given. When this route information advices an alternative route than the intended route (because of congestion or an accident) the road user changes route and won’t pass the pay lane location.

When the road user arrives at the start of the paylane, he already passed a share of the trip. Therefore it is possible that he has more information about the expected travel time of the free lane and the trip after the free lane. This information reduces the uncertainty and makes it possible to make a better estimation of the expected arrival time. This new information could have the consequence that an intended free lane user decides to use the pay lane or vice versa.

These possibilities lead to the following aspects that have to be considered within an ideal choice model:

- Expected travel time and variation before and after pay lane location
- Degree of information of actual travel times
- Expected travel time and variation of alternative routes
- Expected travel time and variation of public transport

## 5.2 Assumptions regarding the ideal choice model

To execute the described ideal choice model it is necessary to implement much information about the characteristics of the road network and the choice alternatives in the model. Therefore much data should be collected and next to this, the modelling structure of the available software should be changed.

The focus of this research is to describe travel time variability within a traffic model. For this reason several asumptions are made towards some aspects of the ideal model, in order to make the simulations for this research. These assumptions are categorized and wil now be shortly described.

### Choice alternatives

In the ideal choice model there are several alternatives for pay lane use that are taken into account. The assumption is made that the choice model only has to estimate the distribution between pay lane and free lane. This means that the underlying assumption is made that the choice between pay lane and free lane is subordinar to the choice between public transport or road use and the choice between different alternative routes.

The choice model does not consider mode choice and route choice. These aspects are modelled within another part of the traffic model or are assumed to stay unchanged after the creation of the pay lane.

### Expected travel time and variation at the pay lane location

In the ideal choice model there is plenty information about the expected travel time and variation. In this case the only available information is the current travel time variability at the A27 section expressed as a lognormal distribution with the parameters $\mu$ and $\sigma$. In the situation with a pay lane or roadcapacity enlargement, this travel time variability will change. Because no quantative conclusions could be drawn about the relationship between traffic flow and travel time variability, it is very difficult to quantify the new travel time variability.

For this reason some assumptions are made to be able to estimate the travel time variability under different circumstances. The first assumpton is that the travel time variabilty in the new situation can be described as a lognormal distribution for which the same parameters as listed in table 2 can be used. The resulting distribution can subsequently be split up in two parts. The first part is the average travel time and the remaining part is the variation of the travel time in relation to the average travel time.

The average travel time for the changed situation is assumed to be the result of the traffic assignment that is executed for the traffic model, as will be described in the next chapter. The average travel time for the pay lane is also estimated with this assigment. The variation for the changed situation at the free lane is assumed to be the original travel time variation multiplied with a variation factor that depends on the simulated situation. This variation factor is defined in chapter 7. The variation at the pay lane is assumed to be zero, because the pay lane intends to guarantee a congestion free road.

### Expected travel time and variation at the sections before and after the pay lane location

In the ideal choice model there is plenty information about the travel time and variation of all roads in the network. In this case this information is not available. Travel time variation before and after the pay lane location has an influence on the difference between the expected schedule delay of a pay lane user and the expected schedule delay of a free lane user, but at the same time the variation outside the pay lane location seems to have a relatively small influence. For this reason the assumption is made that the travel time variation at the sections before and after the pay lane is equal to the original travel time variation at the free lane multiplied with a factor that depends on the expected travel times of the section before and after the free lane. This factor will be defined in paragraph 5.4.

### Choice of departure time

The expected schedule delay depends on the departure time road users choose. The assumption is made that all road users choose a departure time witch such a safety margin that their expected schedule delay using the intended route is minimised.

### Availability of actual travel time information
In the ideal choice model information of actual travel time information can lead to a changed route choice or another decision at the start of the pay lane. The assumption is made that available information about future travel times does not influence the choice behaviour. This means that only the travel time of the trip before the pay lane location can influence the choice for the pay lane or free lane, in the case this travel time is smaller or larger than the expected travel time.

At the same time the assumption is made that almost all road users frequently use the road, and as a consequence they have an idea of the expected travel time and its variation.

### Flexibility of toll level
As described in chapter 2 in some pay lane cases the toll level depends on the traffic flow at the free lane. As stated this flexibility aims to encourage more people to use the pay lane when a low occupation is expected, but it also has an opposite effect. Because of the unpredictability of the effects of this flexible toll the toll level is set at a fixed price in this study.

### Variation of user characteristics
In the ideal choice model each road user has its own valuation of travel time and schedule delay. For this study it was undesirable from the viewpoint of simulation time to vary this valuation for each road user. For this reason different user classes are constructed that represent the different valuations of travel time and schedule delay.

## 5.3 Overview of selected user classes
As described in chapter 2 the monetary value that road users assign to a reduction of travel time and an improvement in travel time reliability varies strongly. Therefore several user classes are constructed. In the next chapter the determination of the number of trips for each user class is described. This paragraph describes the road user characteristics that are used to define the user classes.

The Revealed Preference and Stated Choice studies that are cited in chapter 2 show several characteristics that influence the choice behaviour. The characteristic with the most impact on the value of time seems to be the income. The studies also show that the gender has a large influence on the value of reliability, what partly is related by the fact that women have often more time restrictions than men as a consequence of a combination of activities. More in general, Snellen et al. (2007) show that the value of reliability within all income classes varies strong (see also chapter 2).

Tseng et al. (2005) describe the results of a Stated Choice study. This study is made by questioning 1115 Dutch commuters. A couple of choice panels are stated and the respondents are asked to give their preferred travel alternative under the stated conditions (toll, travel time, travel time uncertainty and arrival time). Based on this study the valuation of travel time and schedule delay is deduced for different respondent characteristics. Table 3 shows the resulting values.

| **Characteristic** | **Category** | **%** | **VOT (€ / hr)** | **VSDE** | **VSDL** | **Penalty** |
|---|---|---|---|---|---|---|
| Gender | Men | 76,23% | 8,10 | 10,43 | 15,30 | |
| | Women | 23,77% | 10,26 | 17,36 | 14,74 | |
| Household income | < € 28.500 | 20,72% | 4,88 | 14,29 | 18,74 | |
| | € 28500 - € 45.000 | 26,73% | 6,08 | 11,30 | 16,79 | |
| | € 45000 - € 68.000 | 26,10% | 12,31 | 9,75 | 10,56 | |
| | > € 68.000 | 26,46% | 10,10 | 12,41 | 12,02 | |
| Triplength | < 30 km | 35,16% | 6,31 | 14,82 | 19,80 | |
| | 30 - 60 km | 36,95% | 6,20 | 9,47 | 11,23 | |
| | > 60 km | 27,89% | 10,78 | 11,18 | 9,18 | |
| Restrictions | No restriction | ? | 8,06 | 9,84 | 11,54 | - |
| | Restriction late arrival | 54,71% | 7,14 | 12,67 | 15,66 | 6,42 |
| | Restriction early departure | 15,07% | 9,88 | 18,35 | 11,45 | 1,46 |
| | Restriction late departure | 14,44% | 12,86 | 7,78 | 10,78 | 2,98 |
| Compensation of travel costs | No compensation | ? | -2,31 | 10,94 | 15,77 | |
| | Partially compensation | ? | 7,34 | 8,68 | 11,17 | |
| | Full compensation | ? | 10,15 | 13,12 | 13,25 | |
| **Total** | | 100,00% | 8,47 | 12,07 | 14,88 | |

**Table 3: Results Stated Choice Study Tseng et al. (2005)**

Based on this table the first distinction is made for household income. The four categories and the corresponding values of time form the main characteristics of these groups:

- < € 28.500 (Value of time: € 4,88)
- € 28.500 – € 45.000 (Value of time: € 6,08)
- € 45.000 – € 68.000 (Value of time: € 12,31)
- > 68.000 (Value of time: € 10,10)

The second distinction is made for the different valuations of schedule delay. The different restrictions show that the value of Schedule Delay Early varies at least between € 7,78 and € 18,35 and the value of Schedule Delay Late between € 10,78 and € 15,66 (plus a penalty of € 6,42). It seems also clear that the characteristics household income and restrictions are not independent to each other. The values of schedule delay of the different income classes suggest that the low income classes have a relatively large share of road users with restrictions while this share is relatively small for the high income classes. Because no further information is available about the exact distributon of these restriction classes within the income classes, there are made instead categories purely based on a certain value of Schedule Delay Early and Late. A distinction between a time-dependent Schedule Delay Late and a once charged penalty for arriving too late is not made for the income classes. All costs as a consequence of arriving too late are incorporated by the value of Schedule Delay Late. For this reason the definition of the user class parameters is based on the Schedule Delay Early and Late parameters and no penalty parameter is included. The following parameters are used:

Schedule delay early:

- Low (€ 9,0 / hr)
- High (€ 15,0 / hr)

Schedule delay late:

- Low (€ 10,0 / hr )
- Average (€ 15,0 / hr)
- High (€ 25,0 / hr)

The influence of trip length is assumed to be taken into account by simulating the travel time variation of the trip before and after the pay lane location. As a consequence no specific user classes are constructed. Further it is possible that employees can declare their express lane toll at their employer. The assumption is made that these road users always choose to use the pay lane. As a consequence, these road users are excluded from the choice model and automatically assigned to the pay lane.

Compensation of pay lane costs

- No compensation (choice model)
- Full compensation (automatically assigned to pay lane)

## 5.4 Mathematical procedure of the choice model

The mathematical procedure of the choice model is based on a certain trip which can be divided into three sections as shown in figure 21. The second section is the pay lane location at which a road user can choose for the free lane or the pay lane. In this paragraph the mathematical procedure is described stepwise.

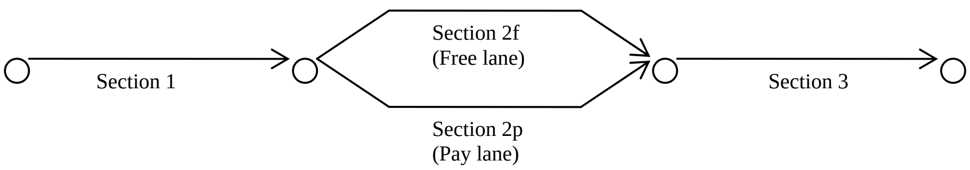



**Figure 21: Schematic overview trip**

An important aspect of the choice model is that it is based on two choice moments. The first choice is concerning the intended choice and the corresponding departure time. This choice is made before the start of the trip. The second choice concerns the real choice and is made as the road user reaches the pay lane and already passed section 1.

In chapter 2 the expected costs are described as the sum of the costs of the expected travel time, the expected schedule delay early and late and the toll. The corresponding formulas for the expected costs of using the free lane $E(C_f)$ and the pay lane $E(C_p)$ are:

$$E(C_f) = \alpha \cdot E(T_f) + \beta \cdot E(SDE_f) + \gamma \cdot E(SDL_f) \quad (31)$$

$$E(C_p) = \alpha \cdot E(T_b) + \beta \cdot E(SDE_p) + \gamma \cdot E(SDL_p) + \theta_{TOLL} \quad (32)$$

In these formulas the parameters $\alpha, \beta$ and $\gamma$ are user class specific parameters.

## The correction of schedule delay parameters

In paragraph 5.3 the valuation parameters of travel time, SDE and SDL are defined for the different user classes. To use these parameters with this cost function, a correction is made to the schedule delay parameters. This correction is made because in the Stated Choice study described by Tseng et al. (2005) the parameters are based on an occurring schedule delay. In this case the parameters are applied to an expected schedule delay.

The travel time variability is described by a log normal travel time variation as shown in figure 22. Assume a travel time of 40 minutes results in arriving just in time. Then the grey area below 40 minutes shows the occurring Schedule Delay Early and the grey area above 40 minutes the occurring Schedule Delay Late. Because the probability that high values of SDE and SDL occur is relatively small, the average SDE and SDL (i.e. the expected SDE and SDL, represented by the dotted line) are much smaller than the highest values of SDE and SDL.

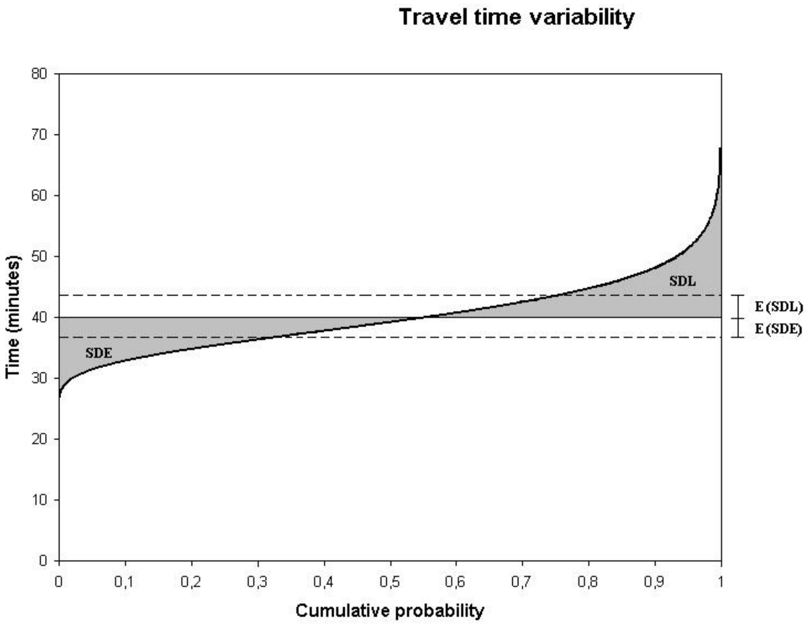



**Figure 22: Relationship between expected schedule delay and maximum schedule delay**

Tseng et al. (2007) show that the disutility people experience from a regular small schedule delay is smaller than the disutility people experience from a high incidental schedule delay. When the valuation parameters from the Stated Preference study would be included without a correction, this would mean that the incidental Schedule Delay Late of 25 minutes as shown in the figure would be valued as a regular expected SDL of 4 minutes.

For this reason the parameters are increased in such a way that the new expected SDL is equal to 40% of the maximum incidental SDL, so a reasonable part of the gap between the average and the peak is taken away. The same is done for the SDE. This results in a factor of 2.0 for the Schedule Delay Late and 1.1 for the Schedule Delay Early. In other words, the valuations of the schedule delay early and late are:

$$\beta = 1{,}1 \cdot VSDE \quad (33)$$

$$\gamma = 2{,}0 \cdot VSDL \quad (34)$$

This 40% norm is quite arbitrary and does not really translate the valuation of an occurring schedule delay towards the valuation of an expected schedule delay. This translation can be improved by defining several schedule delay classes. For example the following classes are possible:

- 0 – 5 minutes: No significant disutility
- 5 – 15 minutes: Small disutility
- > 15 minutes: Large disutility

Applying these classes will result in a higher valuation of an expected schedule delay if this schedule delay contains some large incidental schedule delays, as in a lognormal distribution. These classes are not applied within this research, but as also stated in the recommendations in chapter 9 this application is highly recommended in order to be able to describe the valuation of expected schedule delay properly.

## Stepwise procedure for the estimation of expected travel costs

The size of the expected schedule delays depends on the occurring travel time variability, but also on the time period $\zeta_1$ that lies between the chosen departure time and the preferred arrival time. If this time period is equal to the expected travel time, the probability a road user arrives too late is relatively large. If the road user incorporates an extra time margin, this probability becomes smaller. As a consequence the probability to arrive earlier becomes larger. To estimate the expected costs based on the most optimal value of $\zeta_1$ the following stepwise procedure is applied:

### *Step 1: Estimating the travel time variability of the whole trip*

Figure 23 shows the travel time variability based on the log normal parameters (black line). This travel time variability is described as a function of the cumulative probability $x$ and is defined by $TTV(x)$. Based on the assumption that this variability can be divided in an average travel time and a variation of the travel time, the variation at the free lane section $\tilde{t}_{2f}(x)$ can be deduced from the travel time variability using the following formula:

$$\tilde{t}_{2f}(x) = TTV(x) - \int_0^1 TTV(r)dr \qquad (35)$$

Where the last term is equal to the average travel time. This results in the blue line of the figure.

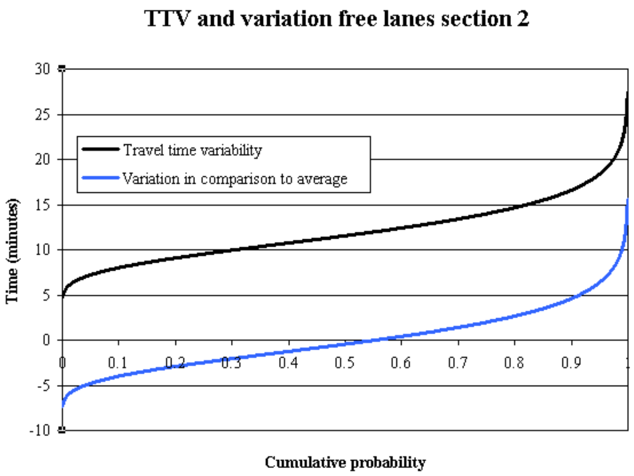



**Figure 23: TTV and variation of free lane section (7.30 – 7.45 hr)**

As described in paragraph 5.2, the variation at the sections 1 and 3 is assumed to be proportionally to this variation. Because the absolute variation has to be larger as the travel time increases, but the relative variation has to be smaller, the assumption is made that the variation at section 1 (and at a similar way the variation on section 3) can be estimated using the formula:

$$\tilde{t}_1(x) = \frac{5}{\tilde{t}_{2f,\max}} \cdot \sqrt{E(t_1)/10} \cdot \tilde{t}_{2f}(x) \qquad (36)$$

Where $\tilde{t}_{2f,\max}$ is the maximum value of the variation at the free lane. It needs to be emphasized that this assumption is made fully arbitrary. Table 4 shows for different values of the expected travel time at section 1 the corresponding travel time variability. The second column shows the maximum travel time that can occur at section 1. The third column shows the proportional factor that is applied to the variation of the free lane at section 2 in order to determine the estimated variation at section 1.

| $E(t_1)$ | $t_{1,\max}$ | $\lambda_1$ |
|---|---|---|
| 5 | 3.54 | 3.54 / $t_{2f,\max}$ |
| 10 | 5.00 | 5.00 / $t_{2f,\max}$ |
| 15 | 6.12 | 6.12 / $t_{2f,\max}$ |
| 20 | 7.07 | 7.07 / $t_{2f,\max}$ |
| 30 | 8.66 | 8.66 / $t_{2f,\max}$ |
| 40 | 10.00 | 10.00 / $t_{2f,\max}$ |
| 50 | 11.18 | 11.18 / $t_{2f,\max}$ |
| 60 | 12.25 | 12.25 / $t_{2f,\max}$ |
| 90 | 15.00 | 15.00 / $t_{2f,\max}$ |

**Table 4: Travel time variability of section 1 for different travel times**

The total travel time variability can be determined by summing the expected travel time and the variation of the three sections. This leads to the following formula for free lane users:

$$t(x) = E(t_1) + E(t_{2f}) + E(t_3) + (\lambda_1 + \lambda_{2f} + \lambda_3) \cdot \tilde{t}_{2f} \quad (37)$$

And the following formula for pay lane users:

$$t(x) = E(t_1) + E(t_{2p}) + E(t_3) + (\lambda_1 + \lambda_{2p} + \lambda_3) \cdot \tilde{t}_{2f} \quad (38)$$

It needs to be remarked that this travel time variability is the maximal travel time variability that can occur. Based on statistical principles the total travel time variability as a function of cumulative probability should have another shape. This is explained by the fact that the variation at section 1 is (partly) independent from the variation at section 2f and section 3. The simplification that is used in these functions is made in order to keep the different travel time variability functions similar to each other what makes the several computations easier.

The values of the proportional factor $\lambda$ for the different sections is shown in table 5. Because the variation at the pay lane is assumed to be zero, the value of $\lambda_{2p}$ is zero.

| Section | $\lambda$ |
|---|---|
| 1 | $\frac{5}{\tilde{t}_{2f,\max}} \cdot \sqrt{E(t_1)/10}$ |
| 2f | 1.0 |
| 2p | 0.0 |
| 3 | $\frac{5}{\tilde{t}_{2f,\max}} \cdot \sqrt{E(t_3)/10}$ |

**Table 5: Values of $\lambda$ for the different sections**

Suppose the expected travel time at section 1 and 3 are 20 and 10 minutes and the travel time at section 2 is 12 minutes (free lane) or 7 minutes (pay lane). Figure 24 shows the resulting variation. As can be seen, there is a significant difference in total variation between the trip using the free lane and the trip using the paylane. The total travel time variability (expected travel time and variation) is shown in figure 25.

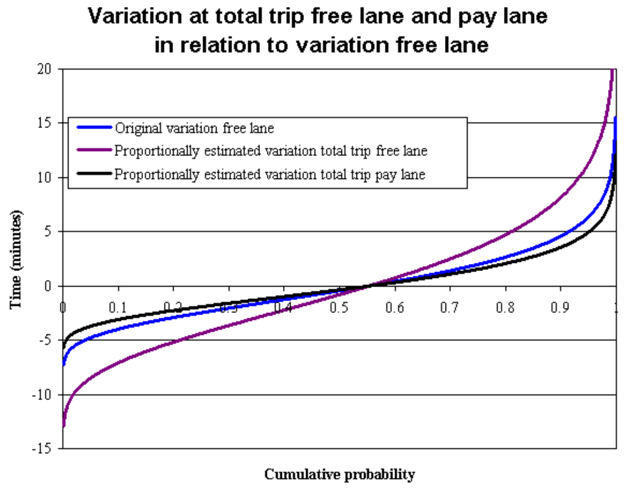



**Figure 24: Proportionally estimated variation for total trip (7.30 – 7.45 hr)**

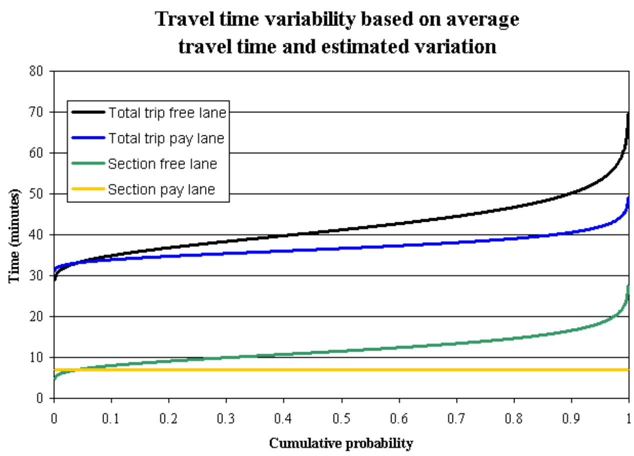



**Figure 25: Estimated travel time variability (7.30 – 7.45 hr)**

### *Step 2: Determining the most optimal departure time*

With the estimated travel time variability of the whole trip the most optimal departure time margin $\zeta_1$ is estimated. Suppose that a trip using the free lane results in an average travel time of approximately 40 minutes and a road user also leaves home 40 minutes before the preferred arrival time (The value of $\zeta_1$ is 40 minutes). The expected SDE and SDL are estimated based on the difference between the travel time variability and the chosen $\zeta_1$, using the formulas:

$$E(SDE) = \int_0^{x0} (\zeta_1 - t(x))dx \qquad (39)$$

$$E(SDL) = \int_{x0}^{1} (t(x) - \zeta_1)dx \qquad (40)$$

Where $x0$ is the probability for which the travel time variability function is equal to the value of $\zeta_1$. Figure 26 shows the areas corresponding to the expected SDE (area IV) and the expected SDL (Area I and II). Because $\zeta_1$ is the same as the average travel time, the expected SDE and SDL have the same size.

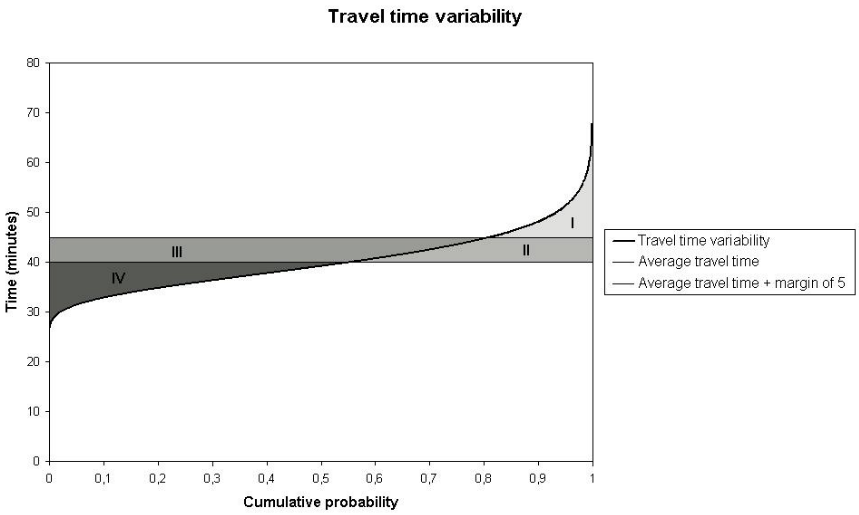



**Figure 26: Expected schedule delay early and late (7.30 – 7.45 hr)**

Now suppose a road user takes an extra margin of 5 minutes and leaves home 45 minutes before the preferred arrival time. The expected SDE increases with area III and the expected SDL decreases with area II. It depends on the values of the parameters $\alpha, \beta$ and $\gamma$ if this time margin results in a decreasment of the expected costs of a trip. To find the unique optimal margin for which the expected schedule delay costs are minimal the following minimization problem has to be solved:

$$Min\ E(C_{SD})(\zeta_1) = \beta \int_0^{x0} (\zeta_1 - t(x))dx + \gamma \int_{x0}^{1} (t_a(x) - \zeta_1)dx \qquad (41)$$

Within the procedure the optimal value of $\zeta_1$ for a certain road user during a certain time period is found by calculating these schedule delay costs for different values of $\zeta_1$ with a small interval step between them.

### *Step 3: Determining the intended choice*

Applying this method for both the free lane as the pay lane situation results in an optimal time margin $\zeta_1$ for both situations. With this margin the expecteds costs of both alternatives are determined, using the following formulas:

$$E_1(C_f) = \alpha \cdot E(t_1 + t_{2f} + t_3) + \beta \cdot E(SDE_f) + \gamma \cdot E(SDL_f) \qquad (42)$$

$$E_1(C_p) = \alpha \cdot E(t_1 + t_{2p} + t_3) + \beta \cdot E(SDE_p) + \gamma \cdot E(SDL_p) + \theta_{TOLL} \qquad (43)$$

The alternative with the lowest costs is assumed to be the intended choice.

### *Step 4: Determining the final choice*

In some cases there is a significant difference between the chosen departure time for the free lane users and the chosen departure time for the pay lane users. Anyhow it is possible that an intended pay lane user with a small value of $\zeta_1$ experiences such a small travel time at section 1, that it is no longer necessary to use the pay lane to arrive in time. At the same way it is possible that an intended free lane user with a large value of $\zeta_1$ experiences such a large travel time at section 1 that the expected schedule delay costs for arriving too late are larger than the toll costs of the pay lane. In these cases it is possible that road users switch their choice.

To incorporate this switched choice in the choice model, the expected costs are also estimated at the moment road users arrive at the beginning of section 2. Based on the intended choice and the corresponding $\zeta_1$ and the experienced travel time $\overline{t_1}$ at section 1, the time between the start of section 2 and the preferred arrival time $\zeta_2$ is equal to:

$$\zeta_2 = \zeta_1 - \overline{t_1} \qquad (44)$$

Based on this value of $\zeta_2$ the expected costs are estimated again for both the free lane and the pay lane, using the formulas:

$$E_2(C_f) = \alpha \cdot E(t_{2f} + t_3) + \beta \cdot E_2(SDE_f) + \gamma \cdot E_2(SDL_f) \qquad (45)$$

$$E_2(C_p) = \alpha \cdot E(t_{2p} + t_3) + \beta \cdot E_2(SDE_p) + \gamma \cdot E_2(SDL_p) + \theta_{TOLL} \qquad (46)$$

In this second cost calculation the variation of section 1 is excluded, because this section is already passed. In case of a large difference between the real travel time and the expected travel time at section 1, the probability of arriving too early or too late is very large what can result in high schedule delay costs.

The road user is expected to choose the alternative the situation with the lowest costs. This means that he will switch his choice when the situation is now opposite to the situation at the beginning of section 1. It is important to emphasize that the intended choice is not meaningless in this model. Although the second definite choice calculation decides the real choice, the intended choice determines the departure time and corresponding time margin. A large time margin results in a much smaller probability that the road user decides to use the pay lane than a small time margin.

## Conclusion

In this chapter the developed choice model is described including the assumptions that are made to make the model applicable with the available data. Because of this, rough assumptions have been made regarding the travel time variation on the free lane and the sections before and after the pay lane location.

The next chapter describes the implementation of the choice model in a traffic simulation model. During this process the strong points and weaknesses of the choice model become visible and at the end of this thesis recommendations are made for further improvement of the model.

# 6. The realisation of the two traffic models

In this chapter the realisation of the two traffic models is described. First a description of the used software and the basic model is given. Then the made assumptions are listed. The third paragraph describes the procedure that is applied to assign all trips to the different user classes and the fourth paragraph is about the procedure that is applied to create the small traffic networks from the original model. Finally the implementation of the pay lane and the pay lane choice model is described.

## 6.1 Description of the used software and the basic model

### OmniTrans

All modelling procedures within this study are executed in OmniTrans, a software package developed by OmniTrans International BV, a subsidiary of Goudappel Coffeng BV. OmniTrans is an Integrated Multi-Modal Transportation Planning Package that combines a graphical network interface with a database environment and extensive programming opportunities.

Networks in OmniTrans are composed by nodes that are connected to eachother by links. Some nodes are so called centroids that represent different zones within the network. Within the network trips can take place from one centroid to another. Socio economic data can be attached to the zones and on this way they can be used to estimate the number of trips between centroids. Subsequently the optimal route choice can be calculated for each trip and these route choices result in a traffic flow on each link. On links with large traffic flows congestion could occur and this will increase the expected travel time at the link. This increased travel time could influence the most optimal route choice and for this reason usually this procedure is iterated a couple of times. There are several methods for these iterations and most of them are integrated in the programming opportunities of OmniTrans.

In OmniTrans also the dynamic assignment method MaDAM is integrated. MaDAM calculates the traffic flow and the traffic speed by executing a large number of small time intervals during which the trips in the network are propagated along the links. As a consequence the congestion effects at a link can be estimated from the context of the traffic network and not only from the link characteristics.

### The basic model

The basic model that is used to make the smaller local models of the A27 corridor and the Amsterdam case is the Dutch National Model that is developed by Goudappel Coffeng within the context of the accessibility map (Bereikbaarheidskaart in Dutch). In the rest of this thesis, this model is defined as the national accessibility model.

Within this model the year 2004 is considered as the base year. The road network contains both the highway network and the most important provincial and local roads. The defined zones correspond to the approximate 4000 Dutch postal codes. The trip distribution matrices for a full workday are estimated using a unimodal gravity model and are expressed in pae (person car equivalent). These matrices are also split up proportionally for time periods of one hour.

Traffic counts during the morning peak and the evening peak are used to calibrate the trip distributions. Next to the 2004 model also a future model is developed for the year 2020. This model is based on expected new road constructions and a scenario for strong economic growth that is developed by the WLO.

### Place of the choice model within the traffic model

The structure of the national accessibility model and the modelling elements in OmniTrans are based on the classical four stage model that is shown in figure 27. The pay lane / free lane choice model as described in the previous chapter is constructed as a separate stage within the model and is implemented after the fourth stage. Because the choice model and the traffic assignment influence each other, both stages are executed several times during an iterative procedure. In the next paragraph the assumptions regarding the different steps are described.

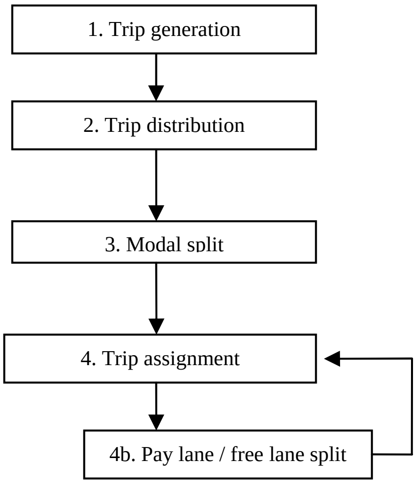



**Figure 27: Position pay lane choice model within four-stage model**

## 6.2 Assumptions in the created traffic models

Within the creation of a traffic simulation model many assumptions are made. First a traffic model is composed by the definition of a road network and a collection of trips. The way this network is created has a big impact on the simulation result. Despite this impact many input data and relationships within this model are based on more or less roughly made assumptions. For this reason this chapter also contains an overview of these assumptions.

### Price elasticity and modal split

It is possible that as a consequence of the available capacity at the pay lane there are people who decide to use the road instead of public transport or staying home. Because no information is available about these effects within the national accessibility model and because the simulation runtime will increase when iterative procedures for this elasticity are implemented, these effects have not been taken into account. Also in the case of a regular capacity enlargement no elasticity effects are taken into account. As a consequence the comparison between pay lane and the regular capacity enlargement remains quite fair.

### Departure time choice

It is also possible that the creation of the paylane leads to a shift of trips from offpeak hours to peak hours because a congestion free alternative is offered. Although this effect seems logical, the assumption is made that this effect does not occur. The main reason for this assumption is again that the simulation runtime would increase. As a consequence the hour matrices remain unchanged.

### Route choice

As will be described in the next paragraphs a small region around the pay lane location is selected from the national traffic network and only this region will be used in the pay lane simulation. It is possible that after the creation of the pay lane road users that don’t pass the pay lane location choose to switch their route because a congestion free alternative is offered. As a consequence of the small regional traffic network no new route choice is calculated for all routes outside the region. All road users within the region could change route if more than one route between two zones is available. This means that an increase or decrease of the traffic at the pay lane location could be possible.

### Distance travelled outside selected region

In the previous chapter is shown that the travel time at the section before and after the pay lane location can influence the pay lane or free lane choice. For this reason it is necessary to implement the travel time road users have outside the selected region. The assumption is made that this can be accomplished by defining a number of distance classes that represent different ranges of travel times. Within the traffic model these travel times are added to the travel times within the traffic network for these trips. The procedure for this adjustment is described in the fourth section of this chapter.

### Using fifteen minutes time periods

The assumption is made that the traffic model can be simulated using time periods of fifteen minutes. Although the trip matrices contain trips for a hour time period, the travel time variability differs significantly for the different fifteen minute periods within the hour. That means that during an hour the same number of trips are assigned every fifteen minutes, but a different travel time variability is used in the choice model and a different travel time is estimated. Subsequently the distribution of road users between the pay lane and the free lane can change every fifteen minutes time period.

Trips that take longer than fifteen minutes *inside the traffic model* correspond to the time period during which the trips started, unless the travel time before the beginning of the pay lane is longer than 15 minutes. In this case the choice model is based on the occurring travel times and travel time variation at a later time period. When for a fifteen minutes period no reliable travel time can be estimated, the travel time of the previous time period is assumed to be applicable.

### Assumptions following from the used software and traffic model

- As a consequence of the absence of junction modelling in the national accessibility model no junction modelling is applied within the traffic models. Especially for the simulation of traffic at the underlying road network this can have negative consequences for the reliability of the simulation results.
- The static traffic assignment within OmniTrans estimates the travel times based on a very generalized formula and does not take into account the effects of congestion at adjacent roads. The dynamic traffic assignment takes these effects into account, but has other weak points. Therefore it is important to keep in mind the assignment methods that are incorporated in the software of OmniTrans. The recommendations in chapter 9 will reflect on these aspects.
- The simulations that are executed for the year 2020 are based on very rough estimation of the trip matrices for this year. Errors in these future traffic estimations always appear to be very significant.

### User classes

Because for the choice model a distinction is made between different user classes, the trip matrices from the national accessibility model are divided in separate trip matrices for all user classes. The assumption is made that a procedure for the division between the different income classes is executed that is based on:

- The number of households of each income class of each area within the network
- The average number of trips of each income class
- The average trip length of each income class
- The total number of trips between each origin-destination combination during each time period according to the calibrated matrices from the national accessibility model

Next to this division procedure the trips of each income class are divided for the different user classes with each a different valuation of Schedule Delay Early and Schedule Delay Late. The assumption is made that these trips are divided in such proportions that the average Schedule Delay Early and Late correspond to the values shown in the Stated Preference study cited in Tseng et al. (2005) for each income class. Both procedures are described in the next section.

### Calibration of the networks

The traffic counts at the pay lane locations in the national accessibility model differ significantly from the traffic counts that can be found in measurement data from the Dutch government. For this reason all trips within the selected region are calibrated based on the small number of available traffic counts within the selected region. In order to keep into account the time effects of trips starting in another time interval than entering the pay lane location, this calibration is executed based on dynamic assignment results.

At a later moment the dynamic calibration results of the whole selected region of the A27 seemed to be plausible, but the dynamic calibration results of the trips passing the pay lane location show an illogical course. For this reason an additional calibration has been executed, as will be described in the fourth section.

### Implementation of the choice model

The choice model is implemented as a separate step in the modelling procedure. This means that the choice model is performed apart from the assignment process and as a consequence the pay lane traffic is assigned to a different mode in the network, as will be described in the last paragraph. This assumption is a consequence of the assumptions made in the development of the choice model, as described in the previous chapter. The impact of this assumption is reflected in chapter 9.

## 6.3 The creation of user class specific trip matrices

As described in the previous chapters the monetary value that road users assign to travel time savings and an improved travel time reliability varies strongly. As a consequence the specific definition of user characteristics has a large influence on the results of a simulation of a pay lane situation. In the previous chapter the selection of user classes and their valuation parameters is described. An even important issue is the determination of the distribution between the different user classes within the traffic model. The way trips are assigned to the different user classes determines the total number of road users that decide to use a pay lane at a certain toll level.

As stated in the previous paragraph, the origin-destination matrices from the national accessibility model are seen as the basic assumption for the total number of trips between the different zones for each separate morning peak hour. These trips are firstly divided for the four income classes. After that, the trips are divided for the different schedule delay parameter values.

The division for the four income classes is based on available data about the number of households within the income classes in each region. Also data from the Dutch Mobility Research (Ministerie van Verkeer en Waterstaat, 2006, I) are used. As shown in table 6 the income has a great influence on the number of trips and the distance a person makes a day as a car driver. For this reason the trip generation (the total number of trips departing from a zone) is for each zone separately adjusted to the number of households and the trip frequency of each income class. Subsequently the trip distribution (the distribution of the generated trips between the available arrival zones) is adjusted to the average travelled distance of each income class. Unfortunately the data from table 6 correspond to the individual income instead of the household income that has been used in the definition of user classes. Also it seems quite complex to adjust the trip distribution without changing the calibrated total trips between the different zones. Appendix B describes the method that is applied to divide the trips for the four income classes in a proper way.

| **Individual income** | **Trip frequency** | **Distance travelled (km)** | **Average trip length (km)** |
|---|---|---|---|
| < € 7.500 | 0,67 | 8,34 | 12,45 |
| € 7.500 - € 15.000 | 0,96 | 11,73 | 12,22 |
| € 15.000 - € 22.500 | 1,48 | 22,84 | 15,43 |
| € 22.500 - € 30.000 | 1,69 | 30,48 | 18,04 |
| > € 30.000 | 1,99 | 44,83 | 22,53 |
| **Totaal** | 0,97 | 16,26 | 16,76 |

**Table 6: Average trip frequency and distance travelled per person per day as a car driver (source: Ministerie van Verkeer en Waterstaat, 2006, I)**

After this division the income class trip matrices are divided for the schedule delay classes. Also a share of the trips is assigned to the group road users that are compensated for pay lane usage. The assumption is made that these road users are only represented in the two highest income classes, with 40% in the highest class and 15% in the other. The division of the trips for the different schedule delay classes is also applied with fixed percentages for each income class. This is done in such a way that the average Schedule Delay Early and Late of the whole income class correspond to the values estimated in the study cited by Tseng et al. (2005) as shown in table 3 (page 39). This results in a distribution in terms of percentage as shown in table 7.

| **Value of SDE** | | **€ 9,00** | | | **€ 15,00** | |
|---|---|---|---|---|---|---|
| **Value of SDL** | **€ 10,00** | **€ 15,00** | **€ 25,00** | **€ 10,00** | **€ 15,00** | **€ 25,00** |
| < € 28.500 | 2% | 6% | 7% | 13% | 34% | 38% |
| € 28.500 – € 45.000 | 9% | 24% | 27% | 6% | 16% | 18% |
| € 45.000 – € 68.000 | 13% | 34% | 38% | 2% | 6% | 7% |
| > 68.000 | 6% | 16% | 18% | 9% | 24% | 27% |

**Table 7: Distribution of schedule delay classes for each income class**

## 6.4 Creation and calibration of the two submodels

After the division of the trip matrices from the national accessibility model into user class specific trip matrices the two submodels are created. The first submodel is created for the region around the A27 Bottleneck and the second submodel for the region around the off-ramp Sloten in Amsterdam. This paragraph describes the applied procedure shortly. The procedure is described in more detail in Appendix C. The creation of the pay lane and the adjustments for the pay lane simulations that have been made have been described in the next two chapters.

Within the national accessibility model all trips are selected with their origin and/or destination in one of the two regions or the trips that cross one of the regions. These trips are copied to the submodels and assigned to the corresponding zones or boundary links where the trips enter or leave the network. Subsequenty the travel times are analysed of all trips that pass the link where the pay lane has to be created. These travel times are divided in the travel time before passing the pay lane location (section 1 in the choice model) and the travel time after passing the pay lane (section 3). Based on these travel times all trips are assigned to one of the travel time classes.

Within the submodels the travel time classes are represented by different extra zones that are created. In the case of the A27 bottleneck the following classes are used for the travel time at section 1 and 3:

- < 15 minutes
- 15 – 30 minutes
- 30 – 60 minutes
- > 60 minutes

Table 8 shows the number of trips during the whole morning peak for the different travel time classes. The trips with their origin or destination within the submodel are classified separately.

| | **Arrival within submodel** | **Arrival time < 15 minutes** | **Arrival time 15 - 30 minutes** | **Arrival time 30 - 60 minutes** | **Arrival time > 60 minutes** | **Total** | **%** |
|---|---|---|---|---|---|---|---|
| **Traffic joined at Werkendam junction** | 949 | 281 | 913 | 382 | 54 | **2.580** | **15%** |
| **Traffic joined at Nieuwendijk junction** | 671 | 179 | 638 | 316 | 40 | **1.845** | **11%** |
| **Time to reach bottleneck < 15 minutes** | 537 | 594 | 720 | 475 | 67 | **2.394** | **14%** |
| **Time to reach bottleneck 15 - 30 minutes** | 1.501 | 1.236 | 1.819 | 1.625 | 398 | **6.579** | **39%** |
| **Time to reach bottleneck 30 - 60 minutes** | 599 | 326 | 707 | 747 | 176 | **2.555** | **15%** |
| **Time to reach bottleneck > 60 minutes** | 185 | 73 | 181 | 250 | 97 | **785** | **5%** |
| **Total** | **4.442** | **2.690** | **4.978** | **3.796** | **832** | **16.737** | |
| **%** | **27%** | **16%** | **30%** | **23%** | **5%** | | |

**Table 8: Distribution of trips passing the Merwede bridge for different travel time classes whole morning peak**

In the case of the off-ramp Sloten in Amsterdam only a classification is made for the travel time before passing the pay lane location, because far most of these trips have their destination within the submodel. Here the following travel time classes are used:

| **Travel time class** | **% of trips** |
|---|---|
| To reach < 15 minutes | 39% |
| To reach 15 - 30 minutes | 25% |
| To reach 30 - 60 minutes | 21% |
| To reach 60 - 90 minutes | 13% |
| To reach > 90 minutes | 2% |

**Table 9: Distribution of trips passing the off-ramp Sloten for different travel time classes**

After this addition of the distance classes a calibration is executed. In the case of the A27 bottleneck this calibration is based on traffic counts at eight links in the submodel that are done by the Dutch road authority. Because not all occurring congestion effects are included within the static assignment this calibration is applied on the dynamic traffic assignment results. For the off-ramp Sloten case in Amsterdam no calibration is executed, as described in chapter 8.

## 6.5 Implementation of the developed choice model within OmniTrans and the submodel structure

In this section the implementation of the developed choice model is described. As shown in the first paragraph this choice model is executed separately from the traffic assignment during an iterative procedure.

### Two mode traffic assigment

Because the choice model and the traffic assignment are executed during different stages, it is necessary that during the traffic assignment stage it is clear which trips have to be assigned to the pay lane and which trips have to be assigned to the free lane. Also it is necessary that within the traffic network it is clear which roads are accessible for pay lane users, which roads are accessible for free lane users and which roads are accessible for all users.

For this reason the implementation of the choice model is based on a traffic assignment at a two mode network. The network uses mode 2 for all free lane users and mode 3 for all pay lane users. Both networks are exactly the same, except the free lane (only accessible for mode 2) and the pay lane (only accessible for mode 3).

Towards the trips that have to be assigned to the links on the network a distinction is made between four groups, each corresponding to a submode:

- Trips for which no pay lane alternative exists, because they don't pass the pay lane location or only a part of it (submode 21).
- Trips that are assigned to the free lane by the choice model (submode 22).
- Trips that are assigned to the pay lane by the choice model (submode 31).
- Trips that are assigned to the pay lane because toll is compensated (submode 32).

Submode 21 and 22 are both assigned to the mode 2 network and submode 31 and 32 are assigned together to the mode 3 network. Because the traffic assignment is executed only in order to calculate the travel times in the network as an input for the choice model, the simulation runtime is strongly reduced by summing first all user classes for each mode. The simulation runtime of the choice model is also reduced by only applying the choice model for the trips of submode 22 and 31, the so-called flexible trips. This is done because the chosen mode fot the other trips does not depend on the estimated travel times. Figure 28 schematically shows the relationship between the different modes and submodes.

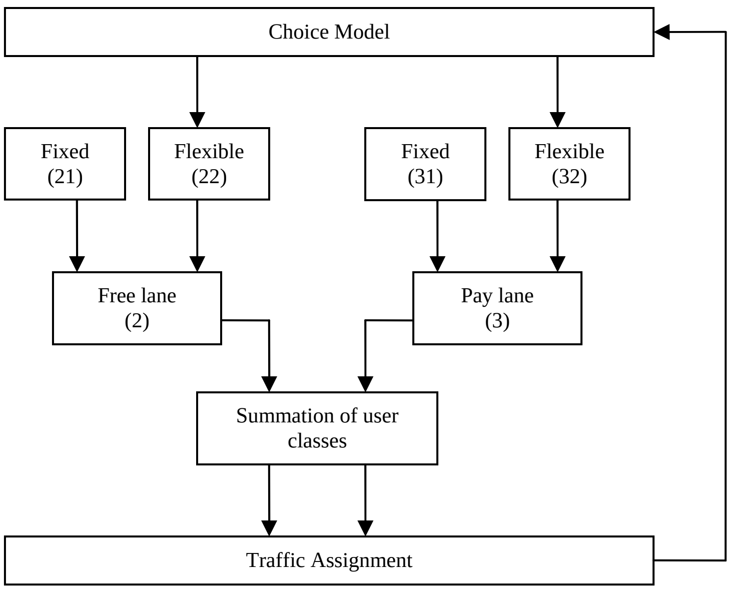



**Figure 28: Relationship between different modes and submodes**

### Iterative simulation procedure

Corresponding to the assumptions that are formulated in the previous chapter the travel times that are used within the choice model are related to the traffic flow that is assigned to the network links. The execution of the choice model results in a certain trip distribution between the pay lane and the free lane. When this trip distribution is different from the trip distribution for which the travel times have been calculated, it is expected that the travel times at the free lane and the pay lane will change as a consequence of the new trip distribution.

This again leads to a different trip distribution, because the attractivity of one of both alternatives has been improved in relation to the other.

As a consequence of these effects an iterative procedure is developed which recalculates the travel times and the choice model several times in order to approach the equilibrium situation in which all road users are assigned to the most optimal mode. This iterative procedure is shown in figure 29 and the different steps in the procedure are described below.

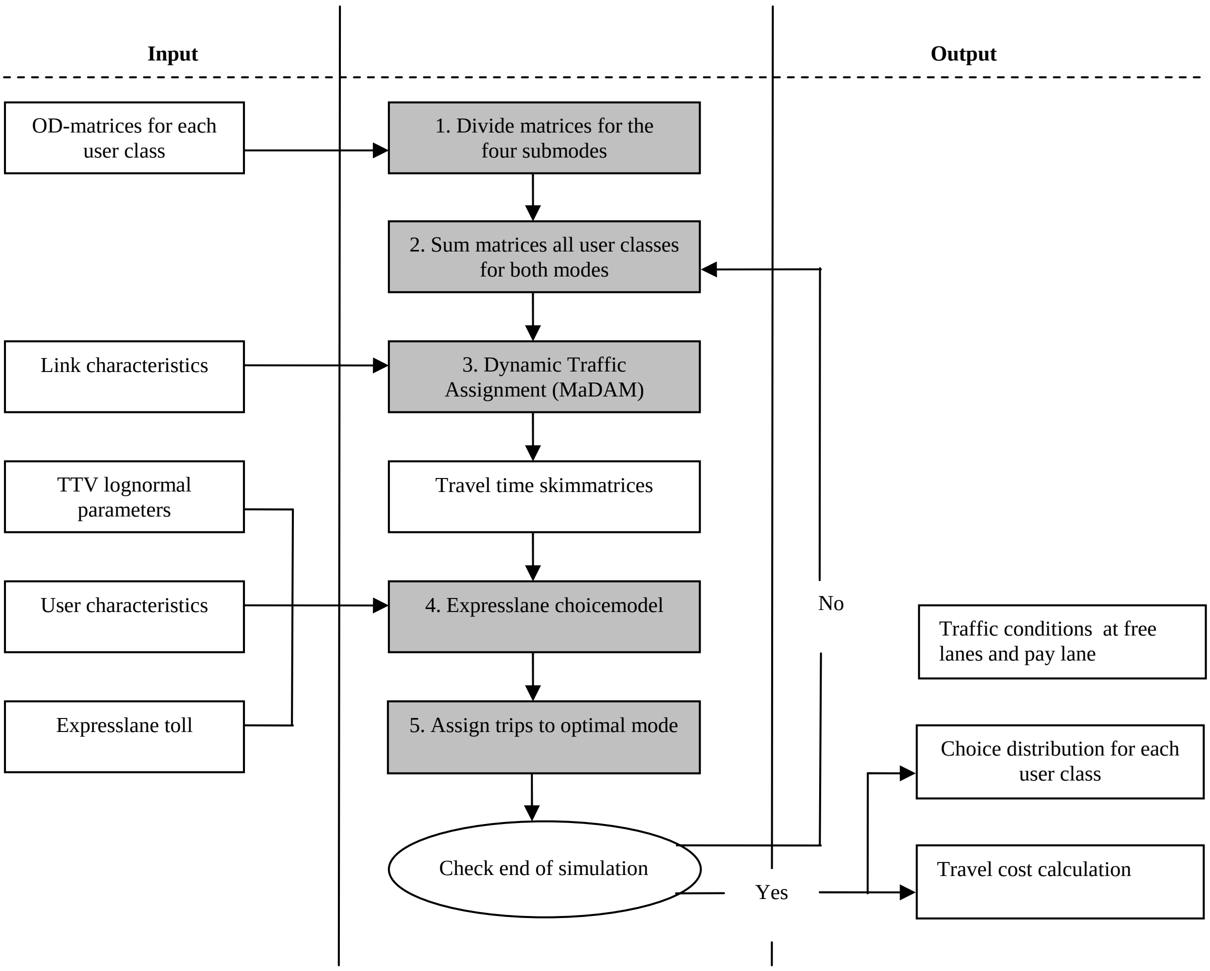



**Figure 29: Iterative procedure for the modelling of a pay lane**

*Step 1: Divide matrices for two modes*

In the first step of the procedure the OD-matrices for the separate user classes are divided for the four submodes. After this division the number of trips for each origin-destination combination can be determined that is assigned definitively to the two modes and the number of trips that is assigned to one of the two modes based on the choice model. In the first iteration all flexible trips are been assigned to the free lane.

*Step 2: Sum matrices all user classes for both modes*

In the second step all user class matrices are summed, in order to make simulation runtime faster. Also the two submodes of each mode are summed. This is done by the following formulas that are applied for all trips from i to j and corresponding to user class u:

$$T_{ij}^{2} = \sum_{u} T_{iju}^{21} + \sum_{u} T_{iju}^{22} \qquad (47)$$

$$T_{ij}^{3} = \sum_{u} T_{iju}^{31} + \sum_{u} T_{iju}^{32} \qquad (48)$$

*Step 3:Dynamic Traffic Assignment (MaDAM)*

In the third step the trip matrices for both modes are assigned to the traffic network. This is done by starting with a static traffic assignment which determines the route choice within the submodel. After this a dynamic traffic assignment is executed in MaDAM. This dynamic traffic assignment simulates the moving of the traffic on the network during the simulated time period with time steps of one second. The procedure makes a distinction between road sections of $> 300$ meters and for each road section the density is estimated based on the traffic flow and density at the section and the section before during the previous second. Based on this density $k$ the speed $V(k)$ at the section is determined using the following formula:

$$V(k) = V_a^0 \cdot \exp\left[ -\frac{1}{\alpha_a} \left( \frac{k}{k_a^c} \right)^{\alpha_a} \right] \tag{49}$$

Where $V_a^0$ is the travel time under free flow conditions, $\alpha_0$ is a link specific parameter and $k_a^c$ is the critical density.

This assignment procedure makes it possible to estimate the congestion effects in the whole network when a bottleneck occurs at a certain moment. MaDAM is also used to estimate the travel times between all different origin-destination combinations within the network for both modes. Subsequently these travel times are splitted up in a travel time at section 1, section 2f or 2p and section 3.

*Step 4: Pay lane choice model*
In this step the choice model as described in the previous chapter is executed. The choice model is executed separately for each origin-destination combination, each user class and each 15 minutes time period. This makes it possible to incorporate for each trip the corresponding user parameters, log normal parameters and travel time input.

*Step 5: Assign-trips to optimal mode*
The choice model determines the optimal mode for each trip. In the fifth step these trips are assigned to one of both modes in order to approach the desired equilibrium situation. Because a large number of user classes are used, it is possible that this step results in a distribution in which some user classes are fully assigned to the pay lane and other user classes are fully assigned to the free lane. In this case only a small number of iterations is necessary to reach this equilibrium situation and this equilibrium is quite solid. As shown in chapter two, the probability for this kind of equilibrium decreases when the differences between the valuations of the pay lane of the different user classes are relatively small. In this case a change in the travel time input can result in a switch of a very large part of the road users to another mode. As a consequence it could be possible that each iteration a large part of the road users is switched from the one mode to the other and in the following iteration the same road users return back to the first mode.

If this situation occurs, no equilibrium situation will be reached. For this reason the assignment of the trips to the two modes is executed similar to the Method of Successive Averages (De Dios Ortúzar, 2001) by assigning a share of the trips to the newest optimal mode and the remaining trips to the old optimal mode. This is done during 10 simulations where the number of assigned trips to the most optimal mode $m$ (which is flexible mode 22 or 32) for iteration n is estimated by the following formula:

$$\left(T_{iij}^{m}\right)_n = (1-\lambda)\cdot\left(T_{iij}^{m}\right)_{n-1} + \lambda \cdot T_{iij}^{22+32} \tag{50}$$

Where $\lambda = 1/n$ and $T_{iju}^{m}$ is the total number of flexible trips for the concerning time, user class $u$ and origin-destination $ij$ .

*Results*
Based on the last iteration (in which the percentage of moved trips is such small that an equilibrium situation is supposed) the trip distribution between both modes for each user class and the traffic conditions at the free lane and the pay lane are determined. These results are shown in the next chapters.

# 7. Situation Bottleneck A27

In this chapter the followed procedure and simulation results are described for the first pay lane case, the bottleneck at the A27 near Gorinchem. In chapter 5 the travel times at this road section in the current situation are analyzed. This current situation (the two-lane reference situation) is changed by adding a pay lane (the pay lane situation) and by adding a regular lane (the three-lane reference situation). Simulations are executed for these three variants in order to answer the following subquestions (see also chapter 3):

2.1 What are the congestion effects of adding a pay lane?
2.2 How are the users of the pay lane expected to be distributed between the different income classes?
2.3 To what extent is the pay lane able to guarantee a high level of service under different traffic conditions in the road network?
2.4 How effective is the adding of the pay lane in comparison to a regular capacity enlargement in reducing the congestion costs?

In the first section a general description of the created traffic network is made. The following sections give an overview of the simulation results. In the last paragraph the simulation results are evaluated.

## 7.1 Properties and assumptions regarding the traffic network

The traffic network is selected from the national accessibility model for the year 2004 as described in chapter 6. Figure 30 shows the traffic network and the location of the bottleneck. At this bottleneck the road capacity is 3400 vehicles per hour, while at other places the road capacity is 4300 vehicles per hour. This is a consequence of the smaller width of the lanes and the absence of a shoulder lane at the bridge. The highway has two lanes during the whole section between the start and end of the pay lane.

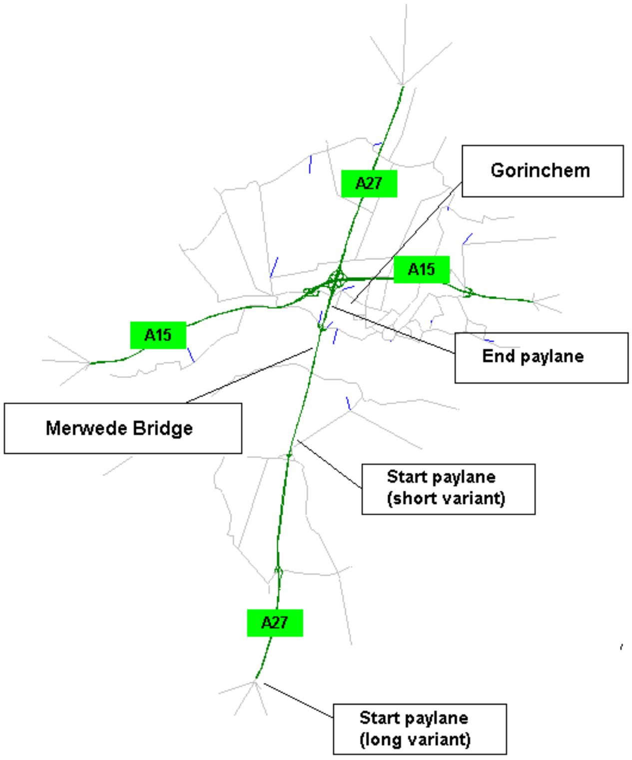



**Figure 30: Traffic network after selecting from national accessibility model**

### Pay lane construction

The pay lane is created by adding an extra link along the bottleneck. There are many possible pay lane locations, but two variants are considered. Both variants end after the bottleneck and just before the junction where the A27 and A15 cross each other, as shown in the figure. When the pay lane would end after this intersection, a large share of the road users is not able to use the pay lane, because they have to leave the A27 at the intersection. Before the pay lane end there is another off-ramp to Avelingen. This off-ramp is passed by the pay lane, because this off-ramp is directly after the bottleneck and could cause additional congestion on both the free lanes and on the pay lane.

For the starting point of the pay lane a short variant and a long variant is made, as shown in the figure. The short variant starts after the on-ramp near Werkendam, where a large share of the road users at the bottleneck enters the A27. An advantage of this variant is that this traffic is able to use the pay lane. A disadvantage is that the pay lane is relatively short. A consequence could be that the queue at the free lane is such long that also the traffic using the pay lane is hindered by this queue.

The long variant starts at the border of the network, where four different links representing the different distance classes enter the traffic network, as shown in the figure. Opposite to the short variant, this long variant is not accessible for the road users entering the A27 at the on-ramp near Werkendam, but the probability that queues occur of such length that pay lane users are hindered is much smaller.

A test simulation of the network shows that the queue that occurs with the short variant are of such length that traffic wanting to use the pay lane is hindered. For this reason the pay lane is created as an uninterrupted link along the “long variant” road section.. The road has one lane and a road capacity of 2150 vehicles per hour. Corresponding to the method described in chapter 6, this pay lane is only accessible for the pay lane mode, while the bottleneck is only accessible for the free lane mode.

## Construction of the three-lane reference network

Next to the pay lane network also a network is constructed for the three-lane reference situation (the old network represents the two-lane reference situation). In this new network at the A27 along the “long variant”-section the number of lanes is upgraded from two to three lanes. The capacity of the bottleneck is upgraded from 3400 to 5550 vehicles per hour, the same as the capacity of the free lane and the pay lane together. The capacity at the other places at the road is similarly upgraded from 4300 to 6450 vehicles per hour.

## The 2020 road network

The pay lane situation and the two reference situations are also simulated for the year 2020. For this year the same road network is used. Within the national accessibility model a selected link analysis showed that the traffic flow at the Merwede Bridge increases with 40% between 2004 and 2020. The assumption is made that all traffic passing the whole “long variant”-road section increases with 40%. Because no network adjustments are made at the other links in the traffic network the other traffic flows remains unchanged. Furthermore the assumption is made that the road capacity at all links has increased with 8% in the year 2020 as a consequence of technical road and car improvements.

## Correction of travel time variation

In chapter 5 the travel time variation at the A27 is described. As a consequence of the creation of the pay lane, a share of the road users switches to the pay lane and the traffic flow at the free lane is than the traffic flow when the total traffic flow remains the same. Although in chapter 5 it seemed not possible to determine a quantitative relation between traffic flow and travel time variation, it is likely that this variation is smaller in the new situation. The assumption is made that the variation for all executed simulations is proportionally to the current variation with a certain variation factor. Table 10 shows the variation factor that is used for the different variants.

| Network | Capacity factor | Calibration factor | Variation factor | Toll level |
|---|---|---|---|---|
| 2004 – Reference (2 lanes) | 1,0 | 1,0 | 1,0 | - |
| 2004 – Reference (3 lanes) | 1,0 | 1,0 | 0,6 | - |
| 2004 – Pay lane | 1,0 | 1,0 | 0,7 | € 3,00 |
| | | | | € 2,50 |
| | | | | € 2,00 |
| | | | | € 1,50 |
| | | | | € 1,00 |
| | | | | € 0,50 |
| 2020 – Reference (2 lanes) | 1,08 | 1,4 | 1,2 | - |
| 2020 – Reference (3 lanes) | 1,08 | 1,4 | 0,9 | - |
| 2020 – Pay lane | 1,08 | 1,4 | 1,0 | € 4,00 |
| | | | | € 3,50 |
| | | | | € 3,00 |
| | | | | € 2,50 |
| | | | | € 2,00 |

**Table 10: Overview of executed simulations**

## Toll levels

Table 10 also gives an overview of the simulations that are executed and the network properties that are used. As described in chapter 2, it is important that the traffic flow at the pay lane is not too high but also not too low. For this reason several toll levels are used in the simulations of the pay lane situations, in order to find the toll level which leads to the most optimal distribution of road users between the free lanes and the pay lane.Because congestion effects at the free lane are larger in 2020 than in 2004, the toll levels are set higher in order to prevent too much road users choose for the pay lane alternative.

## 7.2 Simulated travel times

Figure 31 and 32 show the travel times at the free lane following from the simulation of the reference situations and the pay lane variants in 2004 and 2020.

As can be seen, the congestion that occurs in the two lane reference situation is strongly reduced by the different pay lane variants. In the simulation of the three lane reference situation almost all congestion is taken away in 2004. For 2020 the congestion in the three lane reference situation is still present, but strongly reduced. The two lane reference seems even not capable to let all the traffic pass during the morning hours simulation period.

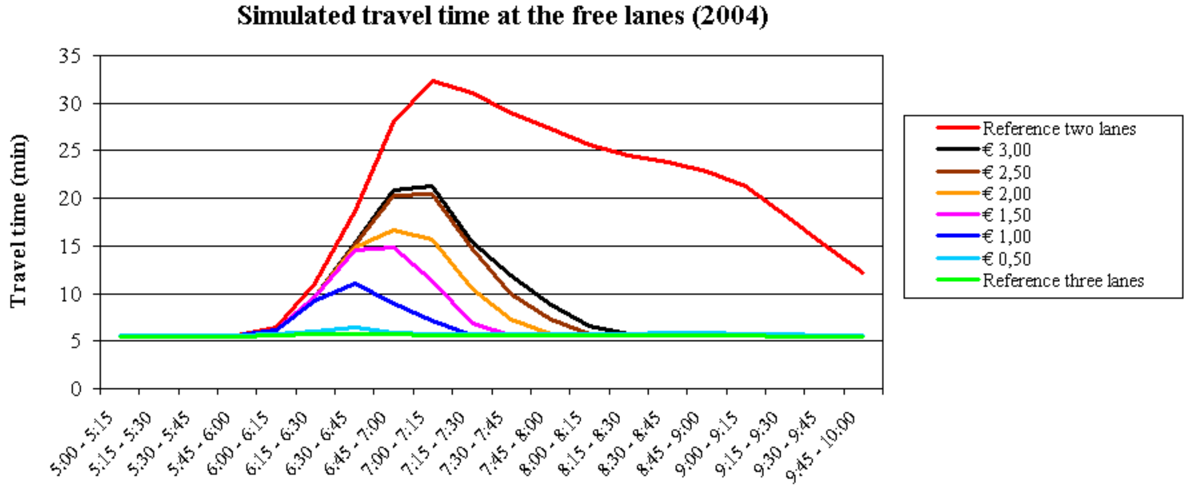



**Figure 31: Simulated travel time at the free lanes for different toll levels and reference situations (2004)**

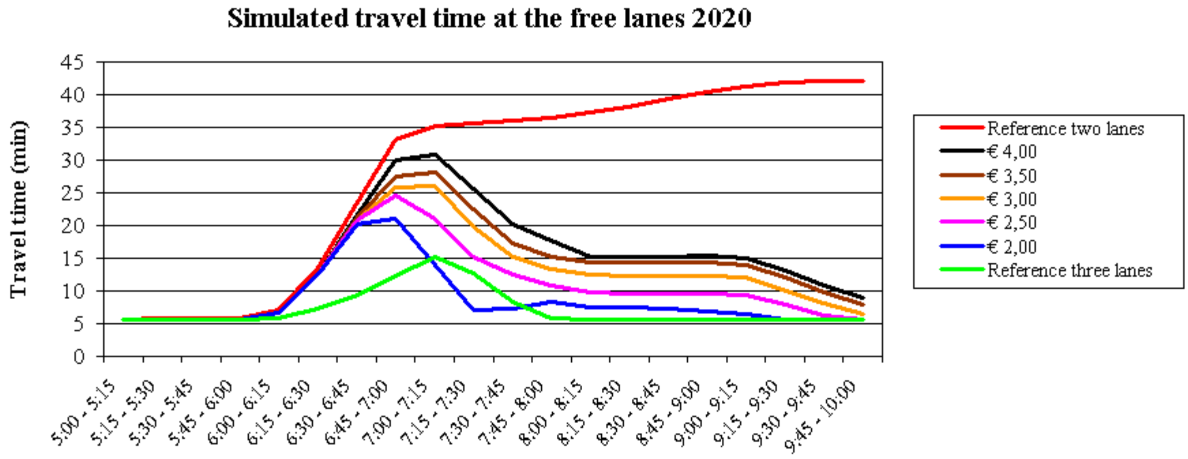



**Figure 32: Simulated travel time at the free lane for different toll levels and reference situation (2020)**

Figure 33 and 34 show the travel time at the pay lane and the travel time at the free lanes including the potential delay according to the 90% cumulative probability. The 2004 figure is based on a toll level of € 2,00 and the 2020 figure is based on a toll level of € 3,00.

As can be seen, the travel time variability is relatively small, because the expected travel time following from the simulation is much higher than the current expected travel time following from the data analysis described in chapter 4. Despite the figures give a good impression about the potential gain in departure time that road users can experience by of a high travel time reliability at the pay lane.

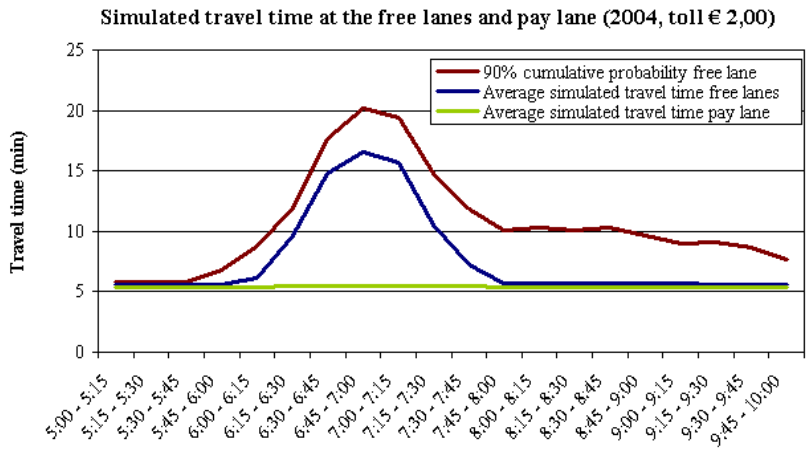



**Figure 33: Simulated travel time at the free lane and pay lane (2004, toll € 2,00)**

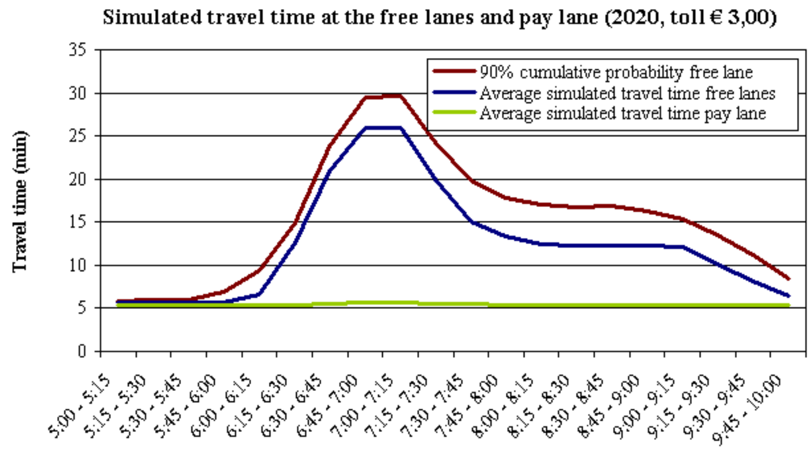



**Figure 34: Travel time profile at the free lane and pay lane (2020, toll € 3,00)**

## 7.3 Pay lane use by different income classes

Within the simulation a total of 24 user classes are simulated corresponding to four different income classes and six difference schedule delay classes. In table 11 and 12 for each income class the number of pay lane users is shown as a percentage of the road users that pass the whole road section during the morning.

| Toll | < € 28.500 | € 28.500 - € 45.000 | € 45.000 - € 68.000 | > € 68.000 |
|---|---|---|---|---|
| € 0,50 | 33% | 16% | 21% | 56% |
| € 1,00 | 0% | 0% | 23% | 46% |
| € 1,50 | 0% | 0% | 28% | 48% |
| € 2,00 | 0% | 0% | 31% | 47% |
| € 2,50 | 0% | 0% | 25% | 47% |
| € 3,00 | 0% | 0% | 25% | 44% |

**Table 11: Average pay lane use for different income classes (2004)**

| Toll | < € 28.500 | € 28500 - € 45.000 | € 45000 - € 68.000 | > € 68.000 |
|---|---|---|---|---|
| € 2,00 | 0% | 2% | 29% | 48% |
| € 2,50 | 0% | 0% | 32% | 51% |
| € 3,00 | 0% | 0% | 35% | 49% |
| € 3,50 | 0% | 0% | 30% | 48% |
| € 4,00 | 0% | 0% | 29% | 47% |

**Table 12: Average pay lane use for different income classes (2020)**

As can be seen all simulations (except the simulation with a toll level of € 0,50 for 2004 and the simulation with a toll level of € 2,00 for 2020) show a 0% pay lane use for the two lowest income classes. This means for these income classes that, although a large number of the road users has a high valuation of schedule delay, the benefits of the guaranteed low travel times remain lower than the toll level. It is important to remark that for the two highest income classes the assumption was made that 15% and 40% of the road users is compensated for pay lane use and is automatically assigned to the pay lane.

This result does not correspond to the pay lane use distribution that was seen at the pay lane locations in the United States, where road users were triggered by a reduction of travel time and a reduction of travel time uncertainty. For this reason an addition analysis is made of the willingness to pay road users have towards the pay lane at the 2020 network.

The willingness to pay is divided in the valuation of the reduction in expected travel time and the valuation of the reduction in schedule delay costs for each user class. Figure 35 shows the valuation of the travel time reduction for a toll level of € 3.00. Figure 36 shows the valuation of the reduction in schedule delay costs.

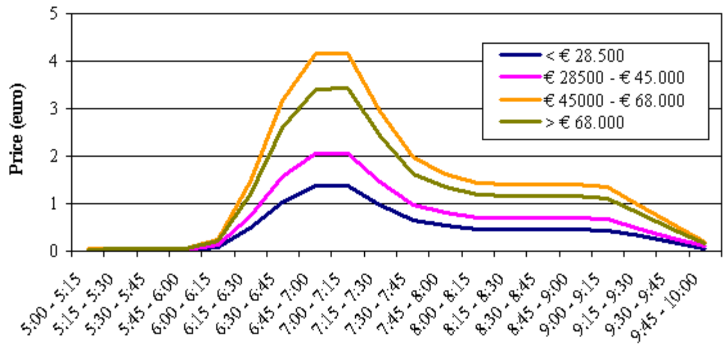



**Figure 35: Monetary valuation of travel time reduction at pay lane for each income class (toll € 3,00, 2020)**

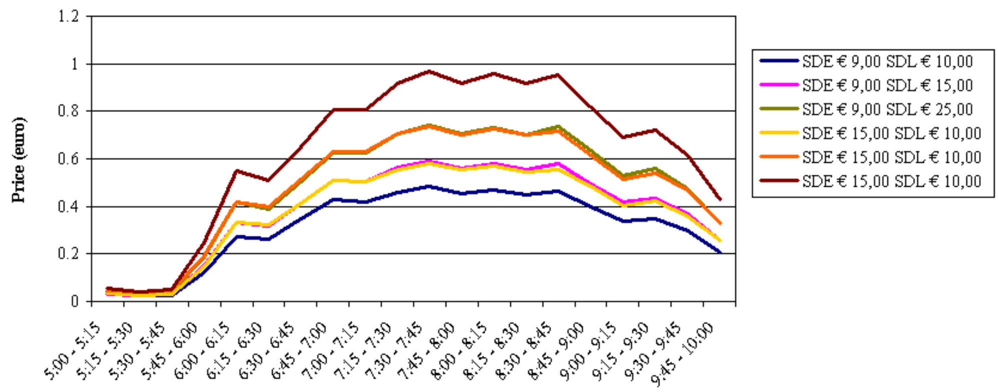



**Figure 36: Monetary valuation of schedule delay costs reduction for each schedule delay class (2020)**

As can be seen the monetary valuation of travel time reliability is much lower than the monetary valuation of travel time reduction. For example when the both valuations are summed for a road user from the lowest income class and the highest schedule delay class, the maximum value is approximate € 2.40, while the two highest income classes have a valuation only for the travel time reduction that is higher.

This low valuation of the reduction in schedule delay costs explains the 0% pay lane use by the low income classes. At the same time these results don't correspond to the situation that appeared in the United States. This could be explained by a potential difference between the valuation of schedule delay by Dutch road users and this valuation by American road users. Another explanation is the fact that in this case the travel time reduction is relatively large, while the travel time variability reduction is relatively small. But the most likely explanation seems to be that the valuation parameters for reliability are too low (as was already mentioned in chapter 5, page 41) or that the level of the travel time variability is underestimated. In the evaluation of the results in the last section of this chapter these aspects are described.

## 7.4 Traffic conditions at the pay lane

When a low travel time at the pay lane has to be guaranteed, it is necessary the traffic flow at the pay lane is not too high. Small (2000) translates this condition to the criterion that the traffic flow as a share of the road capacity (the so-called volume / capacity ratio) needs to be below 0.8.

Figure 37 and 38 show this volume / capacity ratio resulting from the simulations of the different toll levels. As can be seen, the value of 0.8 is exceeded in some results. This means that some toll levels are too low to guarantee a low travel time. Because the results of the previous section showed that a lower toll level leads to a lower congestion level at the free lanes, the optimal toll level can be determined based on these figures. This toll level is € 2.00 for 2004 and € 3,00 for 2020.

The lines shown in the figure have sometimes more than one peak and the places of the peaks seem unlogical. This behaviour can be explained by the fact that the determination of the pay lane use is based on the occurring travel time at the free lane. When in an earlier time interval many road users choose to use the pay lane, the situation at the free lane is improved, which leads in the next time interval to less road users that choose to use the pay lane. This effect is a consequence of the way the choice model is incorporated in the traffic model and in real the effect is expected to be more constant.

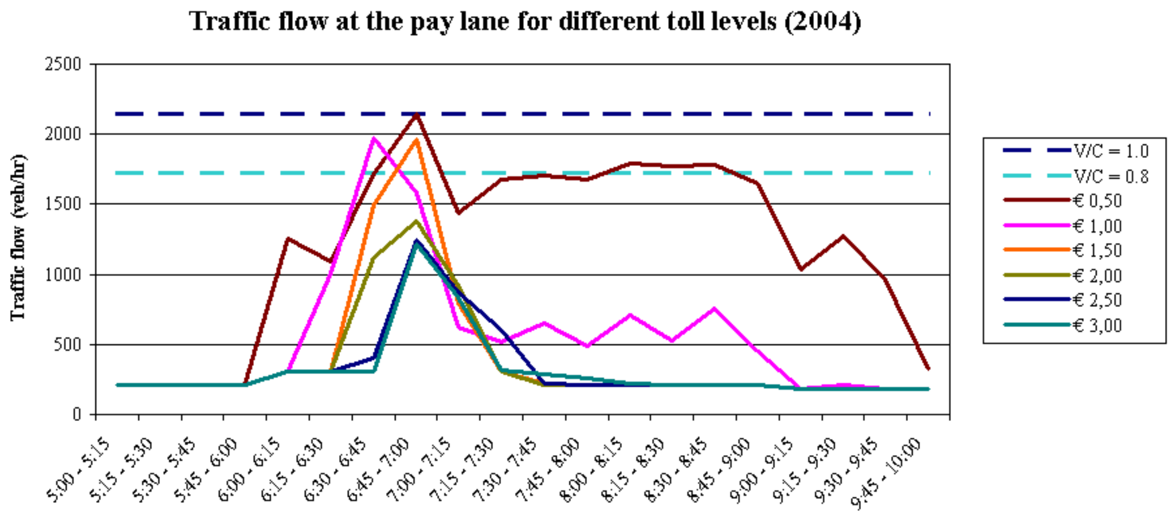



**Figure 37: Traffic flow at the pay lane for different toll levels (2004)**

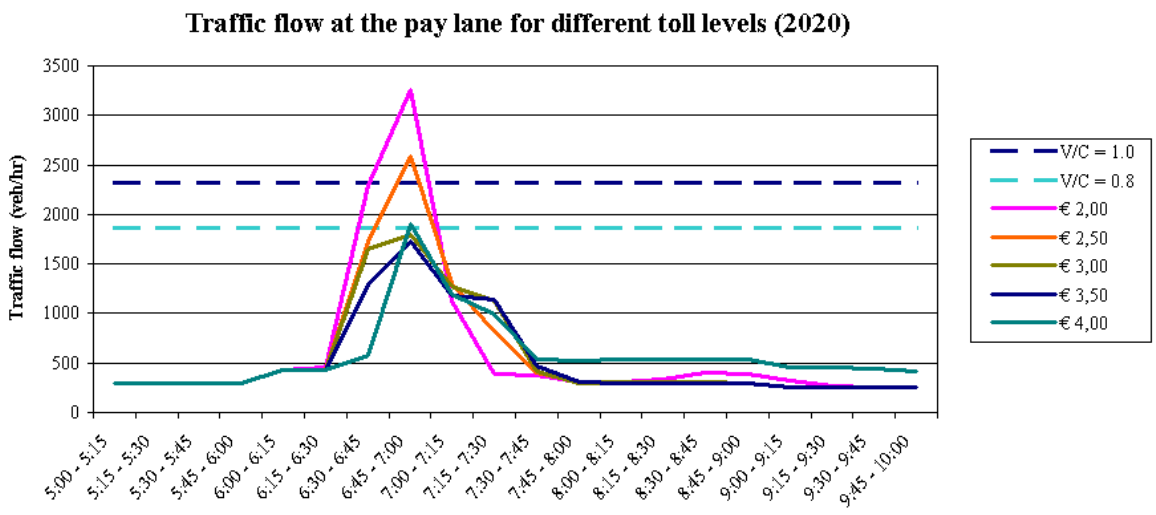



**Figure 38: Traffic flow at the pay lane for different toll levels (2020)**

As described in chapter 5, within the choice model it is possible that road users have a final choice that is opposite to their original choice to use the pay lane or free lane. For the pay lane situation in 2020 with a toll level of € 3.00 this effect is analysed for different situations at the road sections before the pay lane. Because the length of this road section depends on the departure location no absolute travel times are used for this analysis, but different cumulative probabilities in the travel time variability function. As described in chapter 5 the variation at section 1 is assumed to be proportionally to the travel time variation at section 2f according to the following formula:

$$\tilde{t}_1(x) = \frac{5}{\tilde{t}_{2f,\max}} \cdot \sqrt{E(t_1)/10} \cdot \tilde{t}_{2f}(x) \qquad (51)$$

Figure 39 shows the traffic flow at the pay lane resulting from traffic simulations based on different cumulative probability values for the travel time at section 1. As can be seen, the differences between the 5%, median and 95% probability is very small, despite the fact that road users arrive much later or earlier at the beginning of the pay lane than expected.

An explanation for this small effect seems again the fact that the valuation of schedule delay costs is underestimated. This means that larger differences could be expected for these situations that really influence the level of service at the pay lane. As a consequence a higher toll level should be used or a flexible toll level needs to be introduced in order to avoid these incidental congestion effects at the pay lane.

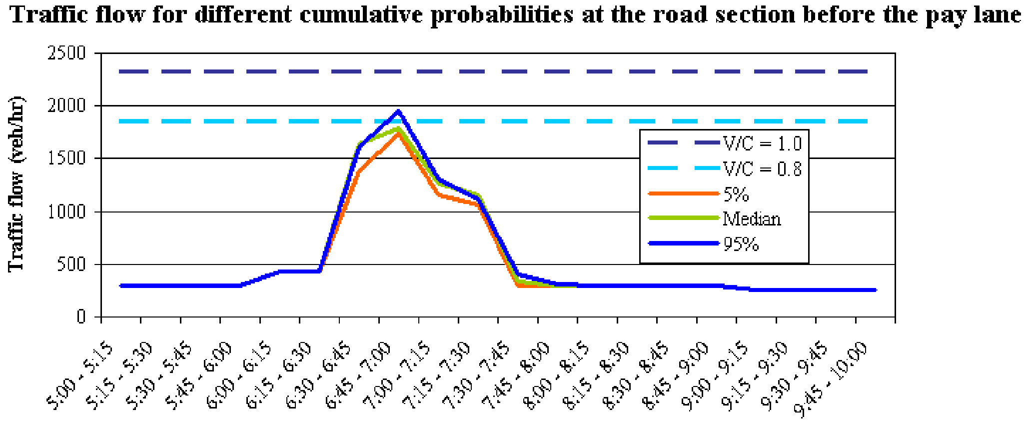



**Figure 39: Traffic flow for different occurring travel times at sectioo before (2020, toll 3,00)**

## 7.5 Comparison of simulation results pay lane and references

In section 7.2 the travel times for the pay lane situation and reference situations are shown. As described in chapter 2, it is also interesting to see which effects these variants have for the accessibility of several economic regions, because a large external valuation for the pay lane is possible.

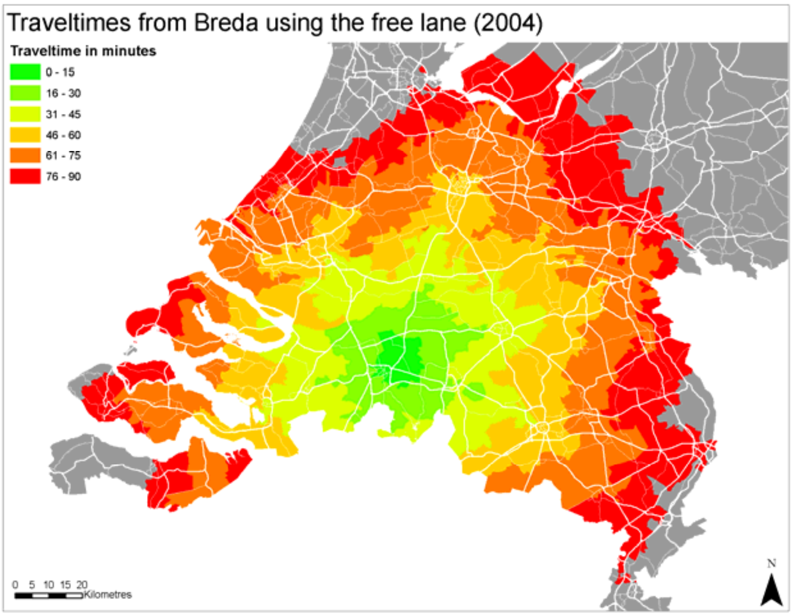
Figure 40 and 41 show the travel times from Breda for the free lanes, pay lane and reference situation. For 2004 the reference situation with two lanes is shown. The reference situation with three lanes is almost the same as the pay lane situation (both have no congestion). For 2020 the reference situation with three lanes is shown. The reference situation with two lanes was not capable to let all the traffic pass.

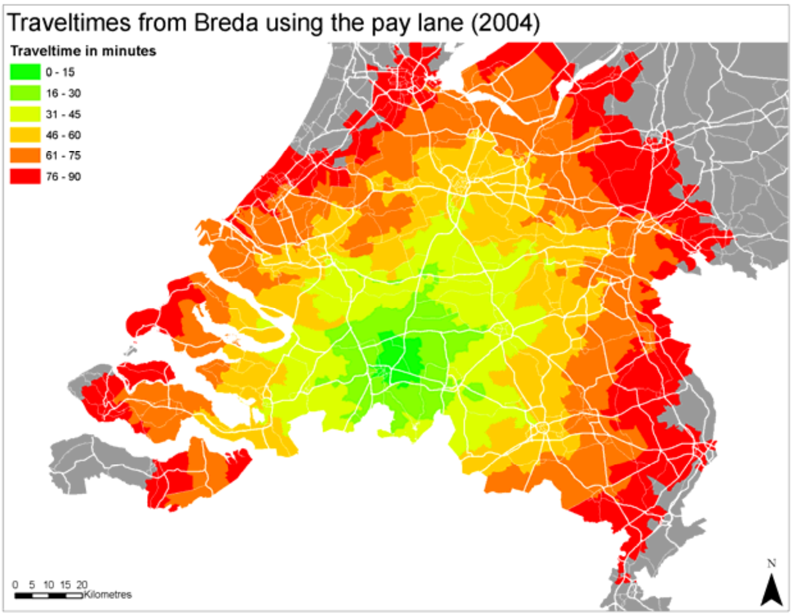
For these figures the highest travel times of the variants are implemented in the national accessibility model. All trips passing the Merwede Bridge are corrected with these travel times. These corrections are shown in table 13. In the national accessibility model the Merwede Bridge has two lanes in the 2004 network and three lanes in the 2020 network. For this reason the corrections are negative for 2004 and mostly positive for 2020.

| | 2004 | 2020 |
|---|---|---|
| Travel time according national accessibility model (minutes) | 19 | 14 |
| Correction for pay lane (minutes) | - 13 | - 8 |
| Correction for free lane (minutes) | - 4 | + 12 |
| Correction for 2-lane reference (minutes) | 0 | + 38 |
| Correction for 3-lane reference (minutes) | - 13 | 0 |

**Table 13: Corrections made within travel time matrices of national accessibility model for different variants**

The figures give more perspective towards the simulation results. It shows how the boundaries of the different travel time isochrones move inwards as a consequence of the congestion effects that occur in the different variants.



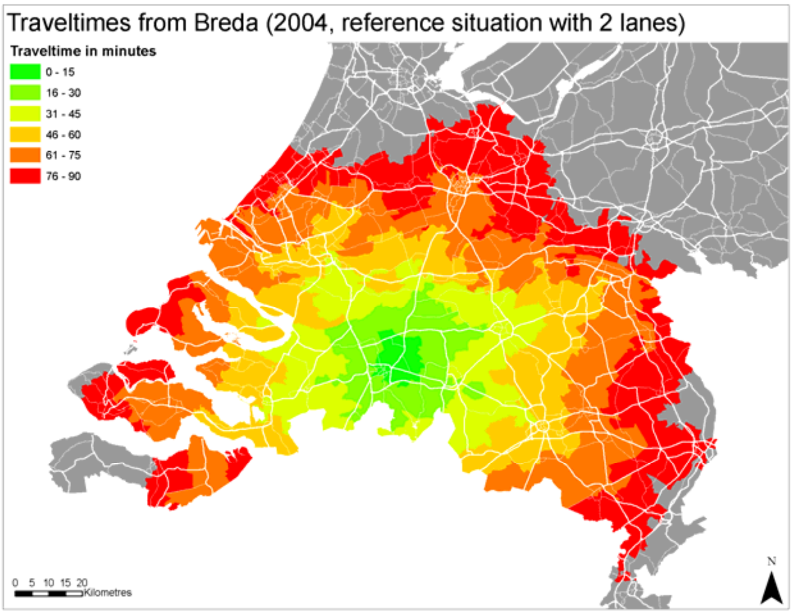
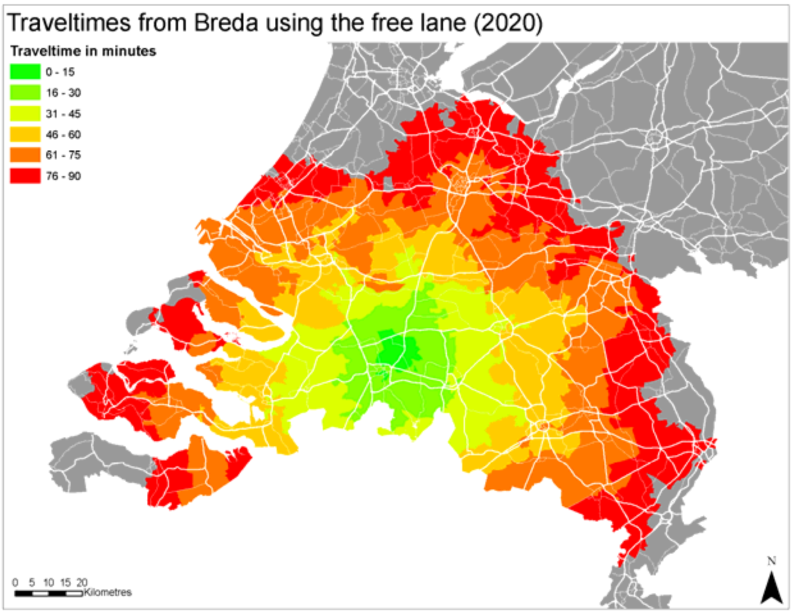
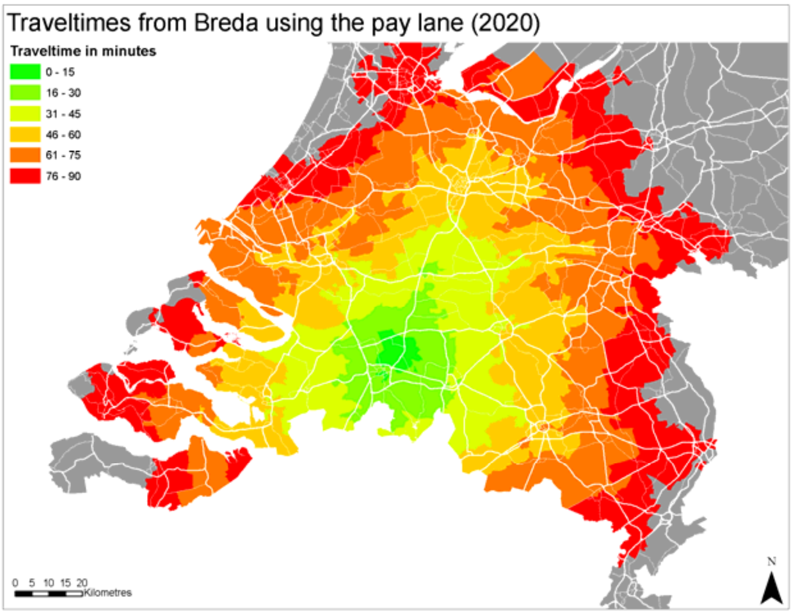




**Figure 40: Accessibility effects of reference, pay lane and free lane (2004)**



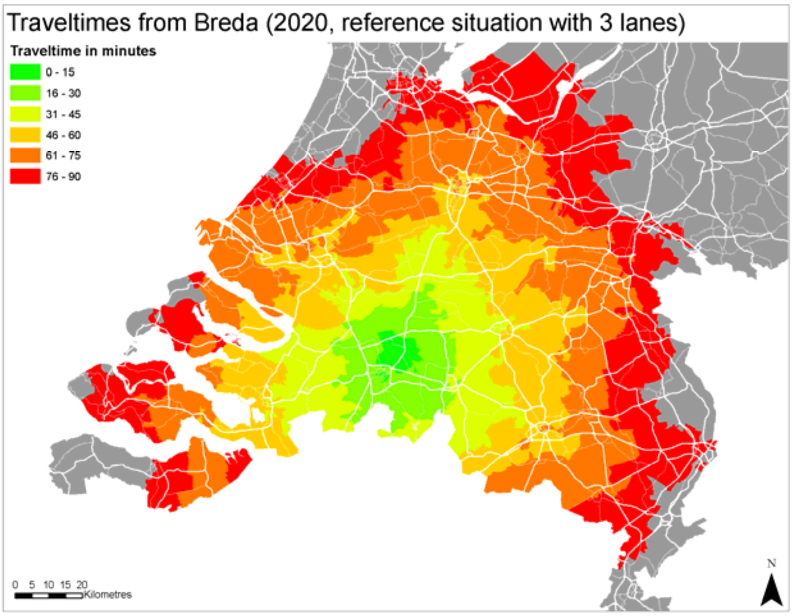




**Figure 41: Accessibility effects of reference, pay lane and free lane (2020)**

The choice model is based on the minimization of travel costs by each road user according to the following formula (see also chapter 5):

$$E(C) = \alpha \cdot E(T) + \beta \cdot E(SDE) + \gamma \cdot E(SDL) + \tau \quad (52)$$

Because the assumption was made that the travel costs are described by these attributes and the total number of trips for the pay lane situation and the reference situations remains the same, an increase of the total welfare gain as described in chapter 2 is equal to the decrease in total travel costs.

The change in total travel costs can be divided in the change in travel time costs, the change in schedule delay costs and the change in toll income. The travel time costs are calculated using the following formula:

$$C_{TT} = \sum_t \sum_m \sum_u \sum_i \sum_j T_{iijut}^m \cdot \alpha_u \cdot E(T)_{ijt}^m \quad (53)$$

In this formula all trips $T_{iijut}^m$ are multiplied with their corresponding value of time $\alpha_u$ and their corresponding travel time $E(T)_{ijt}^m$. In this calculation the flexible modes 22 and 32 and the fixed mode 31 are included. The trips that do not pass the Merwede Bridge are not taken into account. In the case of a pay lane variant, there is a difference between the expected travel time for the pay lane modes and the expected travel time for the free lane mode. Further all time intervals $t$ and all user classes $u$ are included.

In a similar way the schedule delay costs are calculated using the following formula:

$$C_{SD} = \sum_t \sum_m \sum_u \sum_i \sum_j T_{iijut}^m \cdot \left[\beta_u \cdot E(SDE)_{ijt}^m + \gamma_u \cdot E(SDL)_{ijt}^m\right] \quad (54)$$

And the toll income are calculated using the following formula:

$$TI = \sum_t \sum_m \sum_u \sum_i \sum_j T_{iijut}^m \cdot \tau \quad (55)$$

In this formula only the pay lane modes 31 and 32 are incorporated. When the assumption is made that the toll income are benefited by society as a whole, the road users at the Merwede Bridge only marginally benefit from the toll income by government. As a consequence, the total individual costs include the toll costs and are equal to the sum of the three costs elements:

$$C_{individual} = C_{TT} + C_{SD} + TI \quad (56)$$

The total social travel costs do not include the toll costs, because the toll costs are also income for society as a whole. Therefore the total social costs are calculated by the following formula:

$$C_{individual} = C_{TT} + C_{SD} \quad (57)$$

Table 14 shows the travel costs of the different variants, calculated with these formulas the costs of the different variants are calculated.

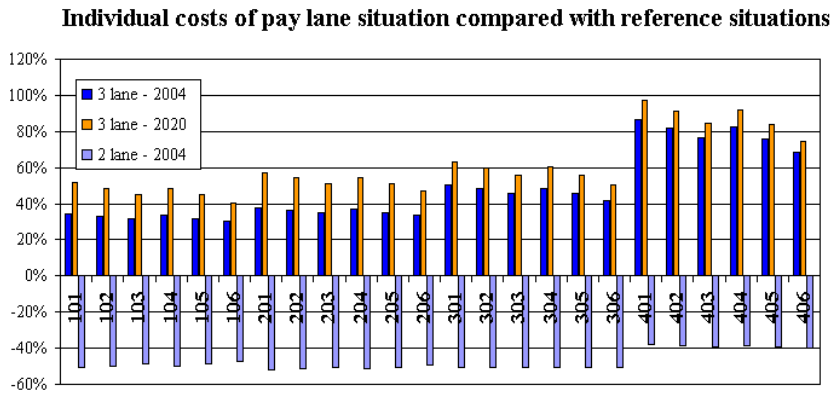
| | **Travel time costs** | **Schedule delay costs** | **Toll costs** | **Individual travel costs** | **Social travel costs** |
|---|---|---|---|---|---|
| 2004 – Reference three lanes | 29760.49 | 11122.5 | 0 | 40882.99 | 40882.99 |
| 2004 - Pay lane (toll 2,00) | 36501.16 | 10647.9 | 13385.74 | 60534.81 | 47149.06 |
| % - effect | 23% | -4% | | 48% | 15% |
| | | | | | |
| 2020 – Reference three lanes | 54824.66 | 23357.25 | 0 | 78181.92 | 78181.92 |
| 2020 - Pay lane (toll 3,00) | 73772.16 | 20763.71 | 30507.66 | 125043.5 | 94535.86 |
| % - effect | 35% | -11% | | 60% | 21% |
| | | | | | |
| 2004 - Reference two lanes | 97221.53 | 18537.5 | 0 | 115759 | 115759 |
| 2004 - Pay lane | 36501.16 | 10647.9 | 13385.74 | 60534.81 | 47149.06 |
| % - effect | -62% | -43% | | -48% | -59% |

**Table 14: Comparison of travel costs**

In comparison to the reference situation with three lanes, the pay lane situation results in much higher cost due to travel time and a small decrease in costs due to schedule delays. The higher travel time costs are the direct consequence of the much larger travel times at the free lane in comparison to the reference situation. The decrease in schedule delay costs can be explained by the guaranteed travel time for the pay lane users (what makes the expected schedule delay theoretically equal to zero at the pay lane section) and also by the fact that travel time variation for the reference situation is assumed to be only a little lower than for the pay lane situation (see table 10, page 56). There can be doubt about this as the average travel time is almost all the time equal to the free flow travel time. A lower variation factor for the reference situation would result in lower schedule delay costs for the reference situation with three lanes. The general conclusion can be that despite the advantages of a guaranteed travel time for pay lane users, the inefficient use of road capacity in the pay lane situation leads to both higher individual and social costs in comparison to the three lane reference situation.

The comparison with the two lane reference situation made for 2004 shows that the pay lane is able to strongly reduce the travel costs. At the same time the costs for the construction and maintenance of the pay lane are not incorporated in this comparison, which makes the comparison not suitable for a cost-benefit analysis. Therefore no statement can be made about the potential profitability of a pay lane exploitation for a private company. It therefore also has to be taken into account that only the toll income result in real cash. For a private exploitant of the pay lane therefore only the toll income will be incorporated in a cost-benefit analysis.

Figure 42 shows a comparison between the individual travel costs of the variants for each user classes. Each user class has a number that corresponds to a certain income class and a certain schedule delay class, as shown in the table next to the figure. As can be seen, the individual cost effects in comparison to the three lane reference situation are negative for all user classes and the effects in comparison to the two lane reference situation are positive for all user classes. In other words, the pay lane alternative offers the opportunity to avoid the congestion effects that wouldn't have been so large when the pay lane was constructed as a regular lane.




| nr | Corresponding userclass |
|---|---|
| 100 | < € 28.500 |
| 200 | € 28500 - € 45.000 |
| 300 | € 45000 - € 68.000 |
| 400 | > € 68.000 |
| | |
| 1 | SDE € 9,00 SDL € 10,00 |
| 2 | SDE € 9,00 SDL € 15,00 |
| 3 | SDE € 9,00 SDL € 25,00 |
| 4 | SDE € 15,00 SDL € 10,00 |
| 5 | SDE € 15,00 SDL € 10,00 |
| 6 | SDE € 15,00 SDL € 10,00 |

**Figure 42: Individual costs of pay lane situation compared with reference situations**

## 7.6 Evaluation of simulation results

In the previous paragraphs different simulation results are shown. The figures show that the traffic flow at the pay lane for certain toll levels is at such a low level that low travel times are guaranteed. At the same time this leads to a large traffic flow at the free lanes. In the reference situation the same road capacity is used more efficiently, what seems to result in a smaller average travel time. These results correspond to the expected results, because the pay lane results in a third best optimum in which average travel time costs are larger than in a first best or second best situation.

The resulting pay lane use for the different income classes and also the results of the cost analysis for the different income classes are very disappointing. They do not describe the effects that are expected based on the evaluation of the United States pay lanes and the high valuation of schedule delay for a share of the road users in low-income classes.

These disappointing results are fully related to the relation between the monetary valuation of reducing expected travel time and the monetary valuation of reducing expected schedule delay. The simulation results show that in this case the monetary valuation of reducing travel time is much larger (3,40 and 4,20 euro for the two highest income classes, see figure 35) than the monetary valuation for reducing travel time variability (less than 1,00 euro for the highest schedule delay class, see figure 36). As a consequence value of time has a much stronger influence on the choice to use the pay lane than the value of schedule delay.

The following assumptions that are made within this thesis have a strong influence on the results:

- Valuation of expected schedule delay:
  The valuation of expected schedule delay is based on the valuation of occurring schedule delay according to the study described by Tseng et al. (2005). There is a difference between the valuation of real occurring schedule delay and expected schedule delay, as described in chapter 5. It seems likely that a probability of 10% on a schedule delay of 10 minutes is not the same as a probability of 100% on a schedule delay of 1 minute. For this reason the valuation parameters were already corrected by a factor 2.0 (Schedule Delay Late) and 1.4 (Schedule Delay Early). It is possible that a higher correction or an alternative classification of expected schedule delay as suggested in chapter 5 is necessary to get a good representation of expected schedule delay costs within the choice model.
- Applied travel time variation:
  The schedule delay costs are estimated using the current travel time variation and a certain proportional correction factor. Because travel time at the free lane increases strongly in 2020 it is possible that travel time variation is much larger. At the same time it is likely that travel time variation is much smaller for the reference situation with three lanes. For the travel time variation at section 1 and 3 a relatively small variation is assumed. Higher values for this variation can result in a higher valuation of reducing expected schedule delay.
- Perception and real departure time choice:
  The developed choice model estimates an optimal departure time and for this departure time schedule delay costs are estimated. When in practice road users do not choose this optimal departure time, expected schedule delay costs will increase. Corresponding to the evalution results of the United States pay lanes it is also possible that road users perceive expected schedule delay higher than the actual expected schedule delay.
- Number of compensated road users:
  When the number of compensated road users would be lower, a lower toll level can be applied that still guarantees a low travel time. This can result in a larger share of schedule delay costs in total travel costs.

The simulation of the same traffic model with assumptions that increase the share of schedule delay costs within the model will likely result in the participation of low-income classes with high schedule delay parameters at the pay lane. The same result can be achieved if another traffic model is simulated at which peaks in travel time delay are smaller and travel time variation is stronger. As a consequence no absolute conclusions can be drawn about the equity effects of a pay lane between different income classes. Also the travel cost effects of a pay lane related to a reference situation with three lanes could change significantly when a share of the road users experiences a reduced expected schedule delay when this forms a significant part of total travel costs.

The sensitivity of pay lane use under different road conditions at the section before reaching the bottleneck is likely to increase when the schedule delay costs are relatively higher. Also actual information about the travel time at the free lane or the travel time after the bottleneck can reduce travel time variability. As a consequence this can result in a larger number of road users that switch between the free lane and the pay lane.

The strong reduction of travel costs by the pay lane in comparison with the reference situation with two lanes shows the value a pay lane can have in reducing congestion when regular capacity enlargements are not possible. When private exploitation of a pay lane seems to be profitable, this can result in an improved situation for the users of both the free lanes and the pay lane.

# 8. Situation Off-Ramp Sloten / Amsterdam

In this chapter the followed procedure and simulation results are described for the second pay lane case, the off-ramp at the Amsterdam city ring to Sloten. In the first section a general description of the created traffic network is made. The second section describes the implementation of the pay lane in the network. The third section evaluates the simulation results.

## 8.1 Traffic network without pay lane

The traffic network is selected from the national accessibility model as described in chapter 6. The resulting subnet is shown in figure 43. In the small figure the potential pay lane location is shown. The link bandwidths in the figure describe the traffic flow between 8:00 and 8:15. The colours give an indication of the corresponding speed according to a dynamic traffic assignment. As can be seen no congestion effects occur at the highway as a consequence of the off-ramp.

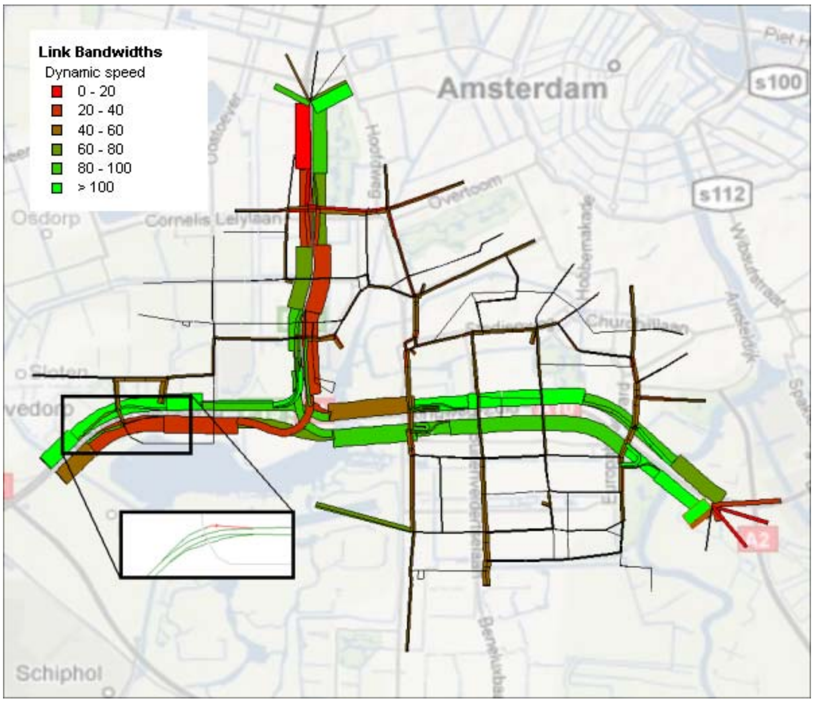



**Figure 43: Dynamic Traffic Assignment results traffic network without pay lane (8:00 – 8:15)**

Before the creation of the subnet a selected link analysis is applied to the national accessibility model for the red marked link in the small picture corresponding to the off-ramp, in order to determine the total number of passing trips. The results are shown in table 15. As can be seen the total number of trips between 6:00 and 7:00 is quite high. Furthermore it is remarkable that the number of trips in 2020 is lower than 2004. Because overall traffic increases, it seems that a share of the road users switches to alternative routes.

| Time | Traffic flow 2004 | Traffic flow 2020 |
|---|---|---|
| 5:00 – 6:00 | 840 | 360 |
| 6:00 – 7:00 | 2130 | 1370 |
| 7:00 – 8:00 | 1100 | 530 |
| 8:00 – 9:00 | 350 | 480 |
| 9:00 – 10:00 | 260 | 470 |

**Table 15: Overview of traffic flow at the off-ramp to Sloten according to the national accessibility model (2004 and 2020)**

Despite the high traffic flows at the off-ramp shown in table 15, no congestion effects occurred in figure 43. This is explained by the fact that no junction modelling is applied within the national accessibility model. This means that the implicit assumption is made that all traffic that passes the off-ramp, as long as it does not exceed the road capacity at the off-ramp, can pass the junction without problems. In practice the capacity of the junction will be much smaller, because at the junction also traffic from other directions has to pass and traffic signs are used to regulate this traffic.

Because no junction delays are incorporated in the traffic model, this delay is incorporated by lowering the capacity at the link closest to the junction. The capacity is lowered from 2160 to 1080 vehicles per hour. In order to keep the network conditions in the traffic model reliable, this procedure is also applied to the other off-ramps within the traffic network. When the same dynamic traffic assignment is applied, the congestion effects become much larger, as shown in figure 44.

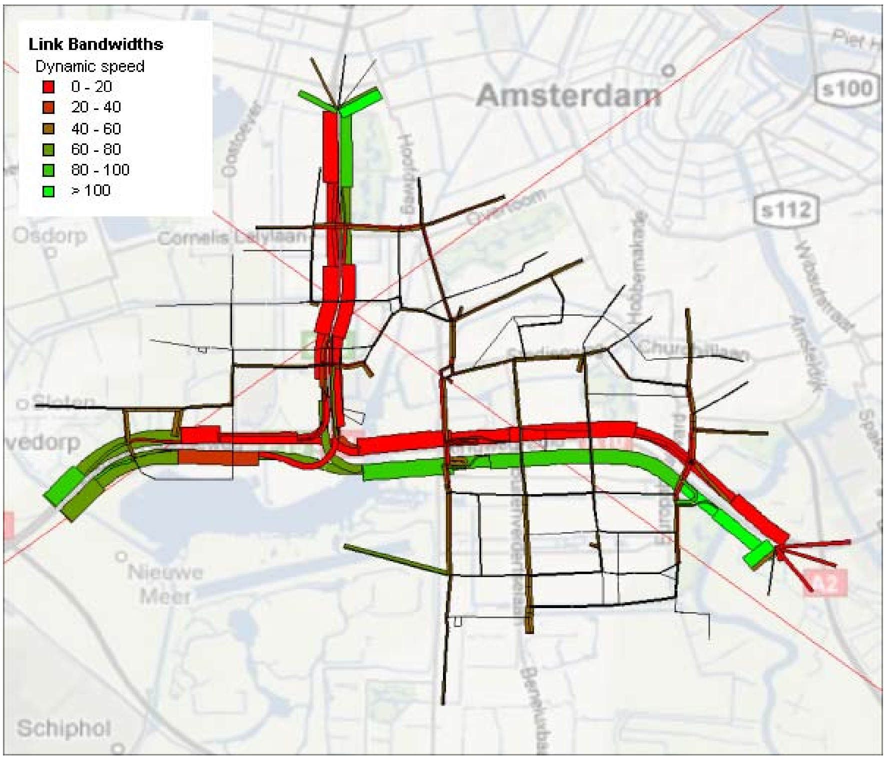



**Figure 44: Dynamic Traffic Assignment results of the traffic network with lowered capacity at off-ramps (8:00 – 8:15)**

## 8.2 Traffic network with pay lane

As can be seen in figure 44 the congestion effects as a consequence of queues at an off-ramp could have a large impact on the congestion situation at the whole network. As highway traffic further increases, it is very important to avoid turning traffic standing still on the main road. A potential measure to reach this could be the creation of an off-ramp with a large length, which can offer a buffer for waiting traffic to pass the off-ramp. The old off-ramp can be used as a pay lane alternative without an additional waiting time.

In figure 45 this construction is applied to the traffic network. The free lane is constructed as a new off-ramp with a total length of 1.0 km and a road capacity of 1080 vehicles per hour. The pay lane is constructed by adjusting the road capacity at the old off-ramp to 2160 vehicles per hour. Corresponding to the method described in chapter 6 the free lane is only accessible for the free lane mode and the pay lane is only accessible for the pay lane mode.

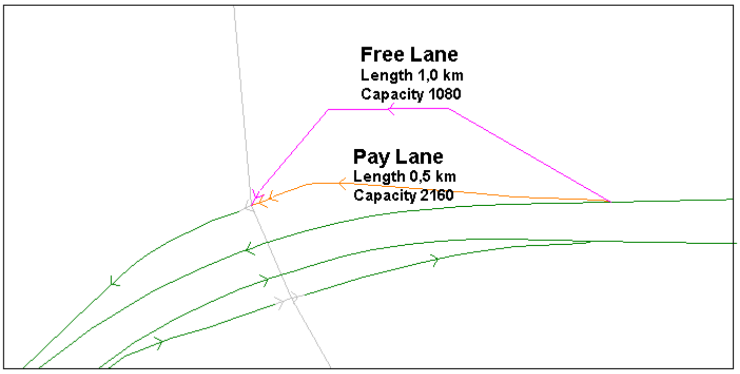



**Figure 45: Pay lane construction at the off-ramp**

The simulation of this traffic network with pay lane is firstly applied without using the choice model. Instead the assumption is made that 20% of the road users uses the pay lane and the other road users use the free lane. The simulation results for this situation show a total gridlock on the traffic network. As the traffic is even standing still at a circuit within the network, this situation remains unchanged during the rest of the simulation. As a consequence at the end of the simulation the critical density at all links is exceeded and no travel times can be estimated.

How can these results be explained? The route choice within the traffic network is determined using a static traffic assignment. Within this static traffic assignment the travel costs for using the free lane are larger than the travel costs in the old situation, because the length of the free lane is much longer. The static traffic assignment does not incorporate the congestion effects that are caused by one link but that occur at another link (for example the queue at an off-ramp that leads to congestion at the highway). As a result using the other off-ramps within the traffic network is much more attractive to road users than passing the long free lane according to the static traffic assignment. Therefore almost all traffic that in the old situation used the off-ramp to Sloten now changes route choice and uses another off-ramp to reach its destination. The traffic network is already loaded with such a large number of trips that congestion effects occur. This makes the traffic network very sensitive for large changes in route choice or changes in road characteristics. The congestion effects at other off-ramps grow and result in a total gridlock.

## 8.3 Evaluation of simulation results

The simulation results of the traffic network with pay lane shows large complexities . Because these complexities are a direct consequence of the modelling structure the decision is made not to execute further simulations with this model. In this paragraph the occurring complexities and the simulation results are analyzed.

Regarding the modelling structure the following problems can be stated:

- <u>Absence of junction modelling:</u>
  The absence of junction modelling within the national accessibility model makes it necessary to make some manipulations to the road capacity of the off-ramp. These manipulations could not fully represent the junction modelling effects.
- <u>Static traffic assignment is used to determine route choice:</u>
  MaDAM makes a dynamic traffic assignment (DTA) based on a route choice that is determined within a static traffic assignment (STA). Within a STA blocking back due to congestion is not incorporated. For this off-ramp situation the congestion effects at the highway as a consequence of a too long queue at the off-ramp are not taken into account. This means that within route choice much lower travel times are considered than the DTA shows. As a consequence the STA advices road users to choose routes that result in a gridlock within the DTA.
- <u>Separate application of the pay lane choice model:</u>
  Within the four stage model the pay lane choice model is integrated as a separate stage. As a consequence within the traffic assignment the route choice is determined, while in the pay lane choice model the share of the vehicles passing the off-ramp is determined. In this case this leads to a situation in which almost all travellers choose to use another route and subsequently this small number of travellers has to be divided for the two modes. In this situation where three different off-ramps are available to reach the same area and one of these off-ramps offers a pay lane alternative, it would be better to build a choice model that determines the choice between these four alternatives.

These difficulties make it in this case impossible to perform a good pay lane modelling. Even so it is possible to formulate some clear findings from this modelling experiment:

- <u>Problem owners within the traffic model:</u>
  While in the case of the A27 bottleneck the problem owners were the road users that use the free lane and the pay lane, in this case the problem owners are both the road users that are passing the off-ramp and the road users that want to drive straight ahead and are hindered by the queue at the off-ramp. Although a choice alternative is offered to the first group, it is the second group that experiences real benefits from this alternative, because it aims to dissolve the queues at the highway.
- <u>The impact of route choice:</u>
  Because road users that use the off-ramp do not experience the benefits of the creation of the pay lane and free lane, it seemed in this case for most of them attractive to change their route choice. For the road users that in the old situation were hindered by the queue from the off-ramp, now the same congestion effects occur at the other off-ramps and the resulting situation is much worser than the old, because road users no longer choose for the shortest trip. To avoid these negative side-effects, it seems desired to introduce these kind of off-ramp pay lane constructions at all off-ramps within an urban region.

# 9. Conclusions and recommendations

Based on the simulation results and the information described in the literature review in chapter 2, in this chapter the research questions as formulated in chapter 3 are answered. These research questions are:

1. *How can a travel time variability based choice model for a pay lane be composed and integrated in a traffic network simulation procedure?*
2. *What indicative conclusions can be derived from the simulation of two concrete pay lane situations with respect to the opportunities for introducing pay lanes in the Netherlands?*

In the first section the conclusions following from the simulations are formulated. In the second section the desirability of the introduction of pay lanes in the Netherlands is discussed. The third section contains the recommendations for the potential improvement used software and for further research.

## 9.1 Pay lane effects following from the simulations

The simulation of the pay lane at the A27 results in a clear view about the travel time effects. The pay lane is able to guarantee a free flow travel time and the travel time at the free lanes is much lower than the travel time at the reference situation with two lanes.

At the other side, the construction of a third free lane instead of a pay lane results in a further improvement of the travel time at the free lanes, the congestion effects are almost fully taken away. A nuanciation needs to be made as both alternatives have an attractiveness for new road users to use the A27. This can lead to increased congestion and this effect is not taken into account. A comparison of travel costs between both alternatives also shows that, despite the fact that the guaranteed travel time at the pay lane strongly improves the travel time reliability for pay lane users, the travel cost reduction of the pay lane is much lower than the travel cost reduction of the addition of a third free lane.

For different road users the choice between the free lanes and the pay lane at the A27 is determined. The basic assumption is made that road users have a monetary valuation for both the reduction of travel time and the reduction of travel time variability, where the first valuation mainly depends on income and the second has a strong variation within all income classes. Despite this variation, the simulation results of the pay lane at the A27 show that the pay lane is only used by high income road users.

This situation does not correspond to the representation of all income classes that is seen at the pay lanes in the United States. Next to this, another study of the pay lane locations in the United States shows that the absolute valuation for travel time is approximate equal to the absolute valuation for travel time variability. The simulation results of the pay lane at the A27 show a valuation for the reduction of travel time that is more than 4 euro for some road users, while the valuation for the reduction of travel time variability is less than 1 euro for all road users. This disproportionality seems to indicate that the valuation for a reduction of travel time variability is underestimated. As described in chapter 5, this underestimation can partly be explained by the fact that the used valuation parameters correspond to an occurring schedule delay, while the simulation is based on the expected value of a stochastically distributed schedule delay.

The simulation of the off-ramp near Sloten at the Amsterdam Ring shows that changed route choice can have a large influence on the effectiveness of a pay lane. When a pay lane offers a choice between two negative alternatives (a high travel time or a high toll) an alternative route can easily become more attractive for the road users at the road section where the pay lane is situated. At the same time this can have strong negative effects for the other road users. The gridlock that resulted from the simulation of the pay lane at the off-ramp is an example of this negative influence of changed route choice.

An important explanation for this negative effect of the pay lane construction is the fact that the problem owners in this situation are not the road users at the off-ramp, but the on-going road users that are hindered by the queues. Because the road users at the off-ramp do not benefit from the new situation, the probability that they decide to avoid the pay lane and change their route choice is much larger.

## 9.2 The desirability of pay lanes in the Netherlands

Based on the simulation results no absolute statement can be made about the desirability of the introduction of pay lanes in the Netherlands. The evaluation reports about the pay lanes in the United States formulate a positive conclusion: both for the road users at the free lane and the road users at the pay lane the situation is improved. The pay lane has users from different income classes and the pay lane guarantees a free flow travel time.

Despite the comparison of the simulation results of the pay lane with the two reference situations for the A27 lead to an ambiguous conclusion. Compared to the reference situation with two lanes, the situation is strongly improved. A share of the road users is able to avoid the queues and as a consequence the congestion decreases. Compared to the reference situation with three lanes, this research shows a small effectiveness of the pay lane. The third free lane is far more capable to reduce congestion effects and based on the made assumptions all user classes benefit more from this alternative than from the pay lane. But which of both comparisons is the most legitimate? There are roughly two perspectives from which this question can be answered.

### *Perspective 1: Opportunities for private exploitation*

The evaluation results from the United States show that for private companies it can be invest in the construction and maintenance of a pay lane. These investments can be earned back with the toll income. As a consequence of such a construction no taxes have to be paid by road users for the construction of the pay lane. Road users have a significant advantage from the construction of the pay lane, either as a pay lane user due to a guaranteed travel time or as a free lane user due to a reduction of congestion. As the public funding of road capacity enlargements is sometimes hindered by budget restrictions, the comparison with the reference situation with two lanes seems legitimate. From this perspective a pay lane is an effective measure.

### *Perspective 2: Effective usage of space*

In the second perspective it is aimed to effectively use the available space. At many places near the Dutch road network the space for road enlargements is limited. Road enlargement therefore has to be done effectively. In comparison to a regular capacity enlargement the construction of a pay lane seems to lead to more travel costs for both the free lane users (because of stronger congestion effects) and the pay lane users (although they have a willingness to pay for avoiding congestion, their travel costs would be much lower when the congestion at the free lane would have been strongly reduced). From this perspective and based on the simulation results there is a strong preference for a regular capacity enlargement.

Although from both perspectives a clear viewpoint can be deduced about the desirability of pay lanes, the following remarks need to be made:

- In this research the external valuation for the availability of pay lanes with a guaranteed travel time is not taken into account. This valuation can for example result in higher values of real estate or a higher economic attractiveness in regions where pay lanes are constructed. These effects can be significant and result in a better valuation of pay lanes, also from the second perspective.
- In the United States the private exploitation of pay lanes seemed to be profitable. The question is if pay lanes are profitable in the Netherlands and to what extent private organizations are willing to invest in pay lanes. When these conditions are not met, the argumentation for the first perspective is no longer valid.
- The application of another valuation structure for schedule delay costs and another procedure for the simulation of travel time variability, the effectiveness of pay lanes in terms of travel costs could improve in such a way that also from the second perspective a pay lane has to be preferred above a regular road capacity enlargement. Also the application of a flexible toll can result in such an improvement. In both cases the negative effects of an inefficient usage of road capacity becomes relatively smaller and the positive effects of the guaranteed travel time for pay lane users becomes relatively larger.

## 9.3 Recommendations

### Appropriateness of OmniTrans

The software package of OmniTrans offers a large flexibility to program alternative steps in a traffic assignment procedure. This flexibility makes it possible to incorporate a separate choice model for the free lanes and pay lane. Despite the execution of simulations as described in this thesis showed some problems and disfunctionalities. Mainly these are a consequence of the fact that it is not possible to incorporate schedule delay costs in the cost functionality in a proper way. This problem is evaded by applying the choice model within a separate stage during the procedure and based on the results of this stage the trips are assigned to one of both modes.

An important restriction following from this procedure is that the choice for the pay lane or free lanes is set at a different level from the choice between other route or alternatives. The real decision a road user makes is not limited to the free lane or the pay lane, but also these alternatives are incorporated. The simulation of the off-ramp near Sloten showed the possible consequences of this division of choice alternatives. The simulation of the pay lane at the A27 did not have this effect because no route alternative was available within the subnet.

For the improvement of the modelling quality the following recommendations are made:

- Integrate schedule delay costs within the cost functionality. These schedule delay costs should be based on the travel time variability at each link in the network. It is desired to relate this travel time variability to the traffic flow at a road, so that travel time variability functions in a way similar to travel time within an iterative procedure.
- Make it possible to apply route choice within MaDAM, in order to avoid that road users base their route choice on static traffic assignment conditions that can strongly differ from dynamic traffic assignment conditions.
- Make it possible to implement actual travel information and flexible toll levels in such a way that road users can switch route choice at the moment they arrive at the location where this information is given.

### General recommendations for further research

Next to these recommendations towards OmniTrans, the following general recommendations can be made for further research:

- This thesis shows a strong uncertainty about the valuation that road users have for a stochastically distributed schedule delay. It is recommended to study the way this valuation can be described, for example by using different schedule delay time intervals, as suggested in chapter 5.
- It is recommended to investigate the influence of traffic flow on travel time variability. This can be done by executing an analysis of detector loop data that is extended in such a way that the congestion effects that influenced the data analysis of chapter 4 can be excluded.
- The profitability of pay lanes in the Netherlands can be different from the United States. Therefore the opportunities for private exploitation of pay lanes in the Netherlands should be investigated.
- There is insufficient knowledge about the external valuation of pay lanes. An economical model could be more suitable for the estimation of this valuation than a traffic model. Applying such an economical model is therefore recommended.
- Applying a flexible toll or providing actual information about the travel time at the free lane and the travel time at the pay lane could result in a more effective distribution of road users between the free lanes and the pay lane. Applying these simulations can result in an improved effectiveness of pay lanes.

# References

Aarnink, J. (1998), Relatie rekeningrijden en maatschappelijke acceptatie, Rijkswaterstaat, Adviesdienst Verkeer en Vervoer, Rotterdam.

Akerboom, M.P. (1997), Rekening rijden en betaalstroken 1997, Onderzoek naar meningsvorming, NIPO, Amsterdam.

Baker, R. et al. (2008), Moving beyond Lexus Lanes: Equity considerations for managed lanes, Transportation Research Board, Paper 08-2422, 87th Annual Meeting.

Brownstone, D., Small, K.A. (2005), Valuing time and reliability: assessing the evidence from road pricing demonstrations, Transportation Research Part A, Volume 39, pp 279,293.

Brownstone, D. et al. (2003), Drivers' willingness-to-pay to reduce travel time: evidence from the San Diego I-15 congestion pricing project, Transportation Research Part A, Volume 37, pp 373-387.

Centraal Bureau voor de Statistiek (2007), Statline Databank, http://statline.cbs.nl/statweb/, verkregen op 21 mei 2008.

Cohen, H., Southworth, F. (1999), On the measurement and valuation of travel time variability due to incidents on freeways, Journal of Transportation and statistics, Volume 2, pp 123-131.

De Dios Ortúzar, J., Willumsen, L.G. (2001), Modelling Transport, Third Edition, Wiley & Sons Ltd, Chicister, United Kingdom.

DHV Milieu en Infrastructuur BV (1997), Betaalstroken verkend, Indicatief onderzoek naar de mogelijkheden en beperkingen van betaalstroken op het hoofdwegennet in de Randstad, DHV, Amersfoort.

Feenstra, W., Veling, I. (2001), Expressbanen A4, Evaluatieplan, Traffic test bv, Veenendaal.

Goudappel Coffeng (2008), De Nationale Bereikbaarheidskaart, www.nationalebereikbaarheidskaart.nl, verkregen op 4 maart 2008.

Lam, T.C., Small, K.A. (2001), The value of time and reliability: measurement from a value pricing experiment, Transportation Research Part E, Volume 37, pp 231-251.

Litman, T. (1999), Using road pricing revenue: Economic efficiency and equity considerations, Victoria Transport Policy Institute, USA.

Liu, H.X., He, X., Recker, W. (2007), Estimation of the time-dependency of values of travel time and its reliability from loop detector data, Transportation Research Part B, Volume 41, pp 448-461.

Mankiw, N.G. (2001), Principles of microeconomics, Second edition, Harcourt College Publishers, Texas, USA, pp. 205-220.

Ministerie van Verkeer en Waterstaat (1999), Betaalstroken als aanvulling op het verkeers- en vervoersbeleid, een onderzoek naar de (on)mogelijkheden van betaalstroken, Den Haag.

Ministerie van Verkeer en Waterstaat (1996), Dynamische en statische verkeersgegevens onder handbereik, Den Haag.

Ministerie van Verkeer en Waterstaat (2006,I), Mobiliteitsonderzoek Nederland 2006, Tabellenboek, Den Haag.

Ministerie van Verkeer en Waterstaat (2006,II), Nota Mobiliteit, www.notamobiliteit.nl, verkregen op 5 maart 2008.

Ministerie van Verkeer en Waterstaat (2006,III), Validatie reistijden geschat door MoniGraph met gemeten reistijden op de A13, verkregen via http://www.flexsyt.nl/monigraph.htm op 14 augustus 2008.

Noland, R.B., Polak, J.W. (2001), Travel time variability: A review of theoretical and empirical issues, Proceedings 80th TRB, Washington, USA.

Noland, R.B. et al. (1997), Simulating travel reliability, Working paper, University of California Transportation Center no. 372.

Nouwen, P.A et al. (2005), Advies Platform Anders Betalen voor Mobiliteit, www.andersbetalenvoormobiliteit.nl, verkregen op 2 maart 2008.

Pahaut, S., Sikow, C. (2006), History of thought and prospect for road pricing, Transport Policy, Volume 13, pp 173-176.

Parry, I.W.H., Bento, A. (2001), Revenue recycling and the welfare effects of road pricing, Scandinavian journal of Economics, Volume 103 (4), pp. 645-671.

Poole, R., Orski, K.C. (1999), Building a case for Hot Lanes: A new approach to reducing urban highway congestion, Reason Public Policy Institute (RPPI), Los Angeles.

Scholten, S., Jankovic, S., van Uden, J.H.A. (2000), De weg van de minste weerstand, literatuuronderzoek gedragsdeterminanten Betaalstroken, Rijkswaterstaat, Adviesdienst Verkeer en Vervoer, Rotterdam.

Shao, H., Lam, W.H.K. (2006), A demand driven travel time reliability based traffic assignment problem, Proceedings 85th TRB, Washington D.C., USA.

Small, K.A. (1992), Using the revenues from congestion pricing, Transportation 19, pp. 359-381.

Small, K.A., Yan, J. (2000), The value of “value pricing” of roads: Second-best pricing and product differentiation, Resources for the Future, Paper 00-08.

Snellen, J. Ettema, D, Dijst, M. (2007), Activiteitenpatronen en reistijdwaardering, rapportage onderzoeksproject Dessus, Universiteit Utrecht.

Sullivan, E. (1998), Evaluating the impacts of the SR 91 Variable-toll Express Lane facility, Department of Transportation, Sacramento, California, 1998.

Tseng, Y.Y., Ubbels, B., Verhoef, E.T. (2005), Value of time, schedule delay and reliability, Estimation results of a Stated Choice experiment among Dutch commuters facing congestion, Paper presented at the 45th ERSA congress, VU University Amsterdam.

Tseng, Y.Y., Verhoef, E.T. (2007), Value of time by time of day: A stated-preference study, Tinbergen Institute Discussion Paper, TI2007-061/3.

Tu, H., Van Lint, J.W.C., Van Zuylen, H.J. (2008), Travel time reliability model on freeways, Proceedings 87th TRB.

Ubbels, B., Verhoef, E.T. (2005), Acceptability of road pricing and revenue use in the Netherlands, ERSA conference paper 05 -120.

Van Amelsfort, D.H., Bliemer, M.C.J. (2005), Valuation of uncertainty in travel time and arrival time: some findings from a choice experiment, , Paper submitted for the 45th ERSA congress, VU University Amsterdam.

Van Amelsfort, D.H. (1999), Value pricing on the I-15, Willingness to pay for improved service, Technische Universiteit Delft.

Van Lint, J.W.C., Van der Zijpp, N.J. (2003), Improving a travel time estimation algorithm by using dual loop detectors, Transportation Research Record nr 1855, pp 41-48.

Verhoef, E.T. (1996), Economic efficiency and social feasibility in the regulation of road transport externalities, Thesis Publishers, Amsterdam.

Williams, H.C.W.L. et al. (2001), Highway investment benefits under alternative pricing regimes, Journal of Transport Economics and Policy, Volume 35 Part 2, pp 257-284.

Yang, H., Huang, H.J. (1998), Principle of marginal-cost pricing: How does it work in a general road network?, Transportation Research A, Volume 32, pp 45-54.

# Appendix A: Description of speed data sources

In this appendix an explanation is given of the PLSB (Piecewise Linear Speed Based) method that is applied to the data of the MonicaNet in order to calculate the travel times at the selected track on the A27. The PLSB method is based on the PCSB (Piecewise Constant Speed Based) method using linear speeds instead of constant speeds during certain space-time intervals. Therefore this appendix starts with a global description of this PCSB method and then gives the formulas based on linear speeds.

## Travel time using constant speed (PCSB-mothod)

The PCSB method estimates the travel time for a selected track and a certain departure time. The track is therefore subdivided in different sections that correspond with the available loop detectors at the selected track. The total time period is subdivided in small time intervals. For each combination of time interval and road section the average speed can be measured using the loop detector data.

The PCSB method considers this average speed to be the constant speed for the given time interval and road section. With the constant speeds of all combinations a space time diagram can be composed. Figure 46 shows an example of such a diagram. In the diagram the different combinations result in blocks for which the speed is constant.

For every chosen departure time a trajectory can be drawn to describe the movement of a fictive car from the beginning to the end of the track. The slope of this trajectory is equal to the constant speed of the block that is entered. At the moment the trajectory reaches the end of the road section or the end of the time interval the slope changes from that point to the speed of the adjacent block. With this estimated trajectory the travel time can be estimated as the time difference between the moment the fictive car enters the track and the moment the car reaches the end of the track.

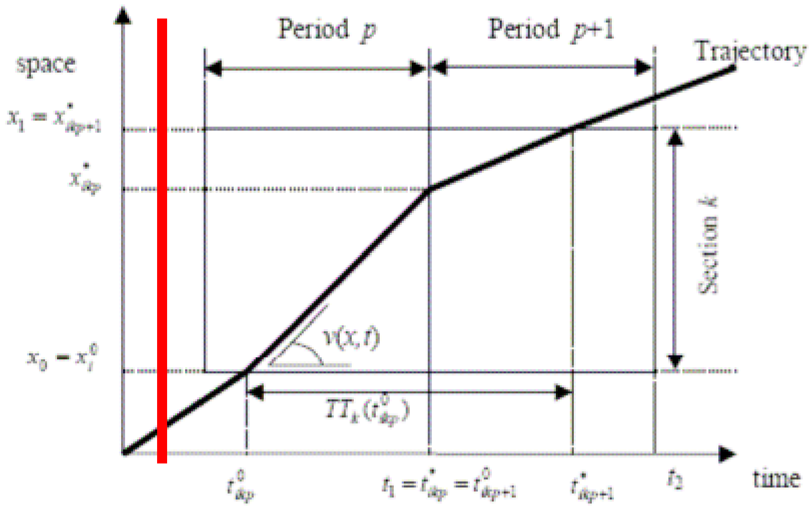



**Figure 46: Space-time diagram using a constant speed for each period (source: Van Lint et al. 2003)**

So the travel time is the result of a piecewise calculation of movements in the time space diagram. The place $x$ of trajectory $i$ on a certain moment $t$ is here calculated with the following formula (Van Lint et al., 2003):

$$x_i(t) = V(k, p) \cdot \left(t - t_{ikp}^0\right) + x_{ikp}^0 \qquad (58)$$

Where:

| | |
|---|---|
| $V(k, p)$ | Average speed for road section $k$ and time interval $p$ |
| $t_{ikp}^0$ | Moment when trajectory $i$ entered the block for road section $k$ and time interval $p$ |
| $x_{ikp}^0$ | Place where trajectory $i$ entered the block for road section $k$ and time interval $p$ |

When further $x_0$ and $t_0$ are considered to be the start of the current road section and the current time interval and $x_1$ and $t_1$ to be the end of both, the movement of trajectory $i$ can for each block passed be calculated:

$$\left\{x_{ikp}^{*}, t_{ikp}^{*}\right\} = \begin{cases} \left\{x_1, \dfrac{\left(x_1 - x_{ikp}^{0}\right)}{V(k,p)} + t_{ikp}^{0}\right\} & for \quad \left[V(k,p)\cdot\left(t_1 - t_{ikp}^{0}\right) + x_{ikp}^{0}\right] > x_1 \\ \left\{V(k,p)\cdot\left(t_1 - t_{ikp}^{0}\right) + x_{ikp}^{0}, t_1\right\} & otherwise \end{cases} \tag{59}$$

The first formula results in the moment when the end of the current road section is reached and a new road section with a different average speed is entered. The second formula results in the place where the current time interval expires and a new time interval begins with a different average speed. With these formulas trajectories such as shown in Figure 46 can be piecewise estimated.

## Travel time using linear speed (PLSB-method)

The described PCSB method is a relative simple method to calculate trajectories and travel times, but is has a significant disadvantage. The measured speeds are considered as constant speeds and result in a trajectory that is discontinuous where it enters a new time interval or road section. In reality the average speed increases or decreases gradually over time and space. To draw trajectories that fit better with occurring movements the PLSB method replaces the constant speed with a speed that changes linear between detector locations $d$ and $d+1$ according to:

$$v_i(t) = V(d,p) + \frac{x_i(t) - x_d}{x_{d+1} - x_d}\left[V(d+1,p) - V(d,p)\right] \tag{60}$$

This formula is in fact a differential equation which together with a chosen departure time results in a trajectory. The solution of this equation results in the following formulas for a piecewise estimation of the trajectory similarly to the formulas used in the PCSB method (Van Lint et al.,2003):

$$\left\{x_{ikp}^{*}, t_{ikp}^{*}\right\} = \begin{cases} \left\{x_1, t_{idp}^{0} + \dfrac{1}{A}\ln\left[\dfrac{\dfrac{V(d,p)}{A} + x_1 - x_0}{\dfrac{V(d,p)}{A} + x_{idp}^{0} - x_0}\right]\right\} & for \quad x_{idp}^{0} + \left[\dfrac{V(d,p)}{A} + x_{idp}^{0} - x_0\right]\cdot\left(e^{A\cdot\left(t_1 - t_{idp}^{0}\right)} - 1\right) > x_1 \\ \left\{x_{idp}^{0} + \left[\dfrac{V(d,p)}{A} + x_{idp}^{0} - x_0\right]\cdot\left(e^{A\cdot\left(t_1 - t_{idp}^{0}\right)} - 1\right), t_1\right\} & otherwise \end{cases} \tag{61}$$

$$A = \frac{V(d+1,p) - V(d,p)}{x_{d+1} - x_d} \tag{62}$$

When the resulting trajectory is compared to the trajectory estimated with the PCSB method, the overall error that occurs decreases nearly by 50 percent and the travel time increases using linear speeds and better fits measured travel times. It seems that when using the PCSB method there is an underestimation of the effect incidentally low speeds have on the travel time. This confirms that the PLSB method is more accurate to estimate travel times for a situation with more than one detector loop and different time intervals than the PCSB method.

# Appendix B: Method for the estimation of the distribution of different user classes in the national model

This appendix describes the method that is applied to divide the general origin destination matrices for the morning peak hours into specific matrices for the defined user classes. As explained in chapter 6 the matrices firstly are divided into four different income classes in the national accessibility model and afterwards the matrices are divided further for the other characteristics. This appendix also begins with the procedure that is applied to generate the trip production for the income classes. Then the method for estimating the trip distribution is explained. At the end the procedure to generate matrices for all user classes is made clear.

## Trip production of the income classes

The national accessibility model contains the trip productions $O_i$ for each zone $i$ for each morning peak hour. These trip productions are the boundary conditions for the trip productions $O_{ik}$ for each zone $i$ and income class $k$ that have to be estimated:

$$\sum_k O_{ik} = O_i \qquad (63)$$

The trip production for each income class is estimated based on the distribution of different income classes in the specific zone and the average trip frequency of the income class. As described in chapter 6 the distribution of the income classes has been based on the New Regional Models, which contain the number of households for each income class in each zone. The trip frequency distribution is determined based on the Dutch Mobility Research (Ministerie van Verkeer en Waterstaat, 2006,I).

Table 16 shows the trip frequency and the average travelled distance per person per day for different individual income classes. Because instead of the individual income the household income is selected as the user class characteristic, these trip frequencies cannot be used directly.

| Individual income | Trip frequency | Distance travelled (km) | Average trip length (km) |
|---|---|---|---|
| < € 7.500 | 0,67 | 8,34 | 12,45 |
| € 7.500 - € 15.000 | 0,96 | 11,73 | 12,22 |
| € 15.000 - € 22.500 | 1,48 | 22,84 | 15,43 |
| € 22.500 - € 30.000 | 1,69 | 30,48 | 18,04 |
| > € 30.000 | 1,99 | 44,83 | 22,53 |
| **Totaal** | 0,97 | 16,26 | 16,76 |

**Table 16: Average trip frequency and distance travelled per person per day as a car driver (source: Ministerie van Verkeer en Waterstaat, 2006,I)**

To estimate the trip frequency for the different household incomes the individual incomes have to be related to household incomes. The Statline database of the Dutch statistical authority CBS contains the distribution of household incomes for different characteristics including the number of persons in a household with an income. This distribution has been shown in table 17.

| Household income | Number of persons in household with income | | | |
|---|---|---|---|---|
| | **1** | **2** | **3** | **4** |
| < € 13.500 | 504 | 36 | 4 | 1 |
| € 13.500 - € 20.500 | 818 | 154 | 4 | 0 |
| € 20.500 - € 34.000 | 844 | 544 | 32 | 4 |
| € 34.000 - € 56.000 | 653 | 884 | 123 | 35 |
| > € 56.000 | 371 | 1389 | 368 | 221 |

**Table 17: Households x 1000 distributed for persons in household with income (source: Centraal Bureau voor de Statistiek, 2007)**

For each number of persons in a household with income and each household income an estimation is made for the distribution over the individual incomes. For example, a household of two persons with a total income between € 13.500 and € 20.500 is defined to correspond to 0.7 persons with an individual income smaller than € 7.500, 1.0 persons with an income between € 7.500 and € 15.000 and 0.3 persons with an income between € 15.000 and € 22.500. Because table 17 shows that there are 154.000 of this kind of households and the average trip frequencies of these three individual income classes are 0.67, 0.96 and 1.48 respectively (see table 16), the estimated number of trips for this group is:

$$154.000\ \textit{households} \cdot \left(0{,}7 \cdot 0{,}67\,\textit{trips} + 1{,}0 \cdot 0{,}96\,\textit{trips} + 0{,}3 \cdot 1{,}48\,\textit{trips}\right) = 300.000\ \textit{trips}$$

Table 18 contains the similarly estimated number of trips for all household incomes and number of persons with income. The trips are totalled for each household income class and subsequently divided by the total number of households in this class. This results in the average trips per household that are shown in the last column of the table. These estimated trip frequencies can be used for the household income classes.

| **Household income** | **Number of persons in household with income (Trips x 1000)** | | | | **Total trips x 1000** | **Number of house-holds x 1000** | **Trips per household** |
|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | | | |
| < € 13.500 | 440 | 54 | 6 | 1 | 501 | 546 | 0,92 |
| € 13.500 - € 20.500 | 1040 | 300 | 7 | 0 | 1347 | 975 | 1,38 |
| € 20.500 - € 34.000 | 1406 | 1247 | 73 | 10 | 2736 | 1424 | 1,92 |
| € 34.000 - € 56.000 | 1300 | 2577 | 358 | 102 | 4337 | 1695 | 2,56 |
| > € 56.000 | 739 | 5078 | 1346 | 810 | 7972 | 2350 | 3,39 |

**Table 18: Estimation of trips per household**

The average trip frequency can be multiplied with the number of households in each zone $i$ for each income class $k$ to estimate the total number of trips $O_{ik}$ that are produced in each zone for each income class. But this trip number corresponds to a whole day instead of one morning peak hour and the calibrated total trip production $O_i$ is defined as a boundary condition for the total of the trips $O_{ik}$. For these reasons the estimated trips are not considered as the absolute trip production for each zone $i$ and income class $k$, but they are only used as a scaling factor that can be applied to the total trip production, using the formula:

$$O_{ik} = \frac{\textit{Households}(i,k) \cdot \textit{average trip frequency}(k)}{\sum_k \left(\textit{Households}(i,k) \cdot \textit{average trip frequency}(k)\right)} \cdot O_i \qquad (64)$$

## Trip distribution of the income classes

After the estimation of the trip production the next step is to estimate the trip distribution. As shown in table 16 not only the trip frequency but also the average trip length increases as the individual income increases. Therefore high income households are responsible for a relative larger share of the long distance trips and a relative smaller share of the short distance trips. It could be important to include these distribution differences in the estimated trip distribution to better represent the trip characteristics of the different user classes in the model.

This distribution effect could be incorporated by applying Gravity Models with various trip distribution functions for each income class. This will result in four different matrices with an average trip length that correspond to the average trip length of table 16. However a large disadvantage of this uncalibrated method is that the total number of trips for each origin-destination (OD-) combination can differ strongly to the calibrated number of trips the national accessibility model contains. For this reason an alternative method is developed that has to result in the same total trip distribution as the National Model and at the same time an average trip length that approaches the income class characteristics.

Firstly the average trip length of each household income class is estimated using the average trip length of each individual income class as shown in table 16 and the distribution of the number of persons with income for each household income class as shown in table 17. This method is completely similarly to the method that is used to estimate the average trip frequency and results in table 19. The last column contains the estimated average trip length.

| Household income | Number of persons in household with income (Distance travelled x 1000 km) | | | | Total distance x 1000 km | Number of trips x 1000 | Average triplength |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | | | |
| < € 13.500 | 5725 | 415 | 46 | 11 | 6197 | 501 | 12,36 |
| € 13.500 - € 20.500 | 16001 | 2753 | 63 | 0 | 18816 | 1347 | 13,97 |
| € 20.500 - € 34.000 | 28990 | 14467 | 842 | 117 | 44417 | 2736 | 16,23 |
| € 34.000 - € 56.000 | 37569 | 36391 | 5050 | 1446 | 80455 | 4337 | 18,55 |
| > € 56.000 | 28300 | 95098 | 25207 | 15164 | 163769 | 7972 | 20,54 |

**Table 19: Calculation of average triplength**

When the total distance and the total number of trips are summed for all income classes the average trip length is 16.76 kilometres. For the matrices of the national accessibility model the total distance and total number of trips can also be summed. As shown in Table 20 the average trip length varies over time during the morning peak hour. By dividing these average trip lengths by the value of 16.76 kilometres a general correction factor is determined for the specific hours.

| Time | Average trip length | Factor related to MON average |
|---|---|---|
| MON average | 16,76 | 1,00 |
| 5:00 - 6:00 | 27,55 | 1,64 |
| 6:00 - 7:00 | 21,68 | 1,29 |
| 7:00 - 8:00 | 17,12 | 1,02 |
| 8:00 - 9:00 | 15,83 | 0,94 |
| 9:00 - 10:00 | 14,79 | 0,88 |

**Table 20: Factor average trip length for each time period**

The first step to estimate the trip distribution $T_{ijk}$ from each zone $i$ to each zone $j$ and each income class $k$ is to estimate the distribution proportionally to the trip production $O_{ijk}$ and the calibrated total trip distribution $T_{ij}$. This can be done using the formula:

$$T_{ijk} = \frac{O_{ijk}}{O_{ij}} \cdot T_{ij} \tag{65}$$

For these trip distributions the average trip length $\overline{d_{ik}}$ for each zone $i$ and each income class $k$ can be calculated by:

$$\overline{d_{ik}} = \frac{\sum_j \left(T_{ijk} \cdot d_{ij}\right)}{\sum_j T_{ijk}} \tag{66}$$

Where $d_{ij}$ represents the distance between zone $i$ and zone $j$. With the proportionally estimated trip distribution this average trip length will be the same for all income classes. The second step is to calculate the desired average trip length $d_{t,k}$ based on the average trip length from Table 19 multiplied by the time dependent correction factor from table 20.

Now for each income class the relative difference can be calculated by:

$$\partial_k = \frac{\overline{d_{ik}} - d_{t,k}}{d_{t,k}} \tag{67}$$

The next step is to find the income class $k$ with the largest relative difference (positive or negative) and the opposite income class $c$ with the largest difference in comparison to class $k$. The used method aims to move a part of the relative difference from class $k$ to class $c$ so that the relative difference of class $k$ and class $c$ approximately become the same. This corresponds to a shift $\Delta\overline{d_{ik}}$ of the average trip length by:

$$\Delta\overline{d_{ik}} = d_{t,k} \cdot \frac{1}{2} \cdot \left|\partial_k - \partial_c\right| \quad (68)$$

Figure 47 shows an example for a fictive situation. The solid lines show the trip frequency $T_{ijk}$ in the old situation as a function of the distance $d_{ij}$ for income classes $k$ and $c$.

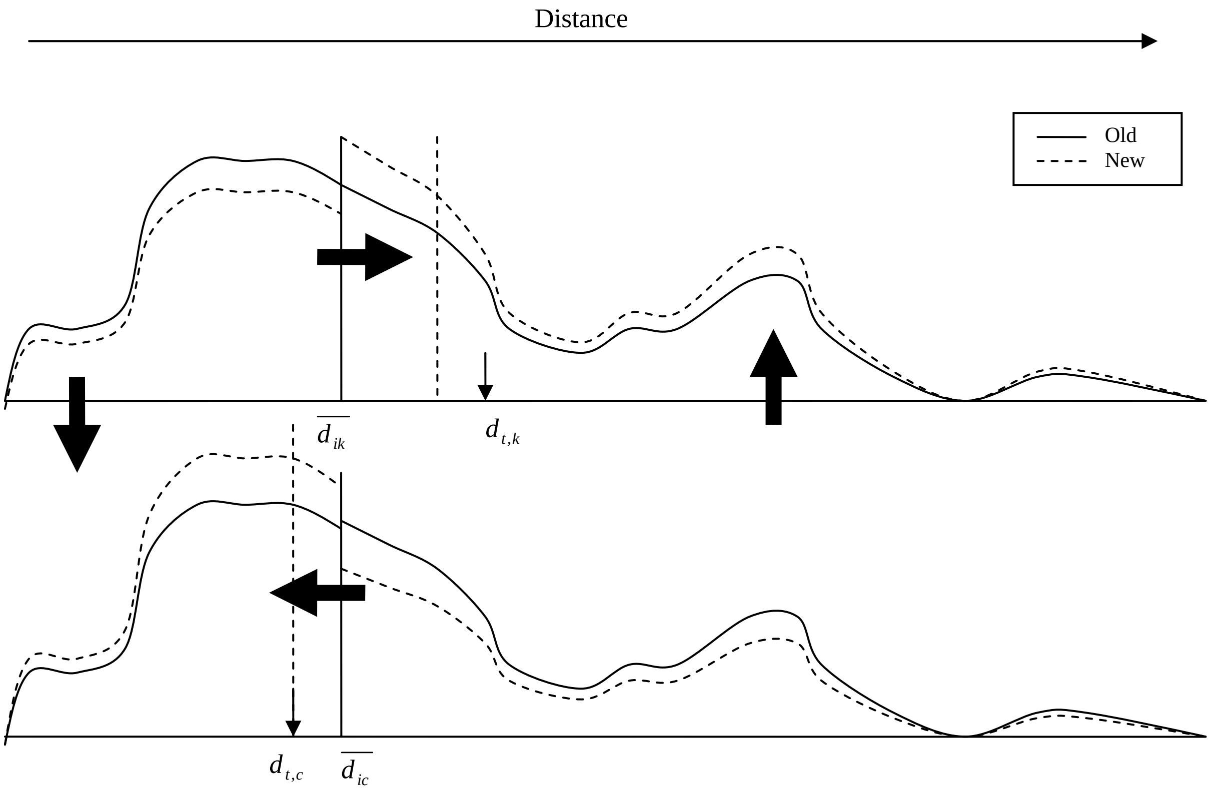



**Figure 47: Example of moving trips to improve average trip length**

As the desired average trip length $d_{t,k}$ is larger than the current average trip length $\overline{d_{ik}}$ (which in fact is the same as the weighted average of the trip frequency distribution) the weighted average has to be moved to the right. This can be done by moving a share of the total surface under the trip frequency distribution (which is the distance difference multiplied by the trip frequency) at the left part of the average to the right part. The total surface at the right and the left are the same and can both be calculated using the formula:

$$\Delta Dist_{ik} = \frac{1}{2} \cdot \sum_j \left|d_{ij} - \overline{d_{ik}}\right| \cdot T_{ijk} \quad (69)$$

The total trip distribution of the calibrated national accessibility model for each OD-pair is a basic assumption for this method. As a consequence this movement of trips $\Delta T_{ijk}$ has to be compensated by a movement of trips $\Delta T_{ijc}$ in the opposite direction for income class $c$ so that the following conditions are met:

$$\sum_j \Delta T_{ijk} = \sum_j \Delta T_{ijc} = 0 \quad (70)$$

$$\sum_j \left|\Delta T_{ijk}\right| = \sum_j \left|\Delta T_{ijc}\right| \quad (71)$$

The movement of trips $\Delta T_{ijk}$ between income classes $k$ and $c$ for each arrival zone $j$ can be estimated as the result of the total trip production multiplied by the factor corresponding to the desired moved surface for zone $j$ in relation to the total surface. This results in the following formula:

$$\Delta T_{ijk} = -\Delta T_{ijc} = \alpha_{ijk} \cdot \frac{\Delta d_{ik} \cdot T_{ijk}}{\Delta Dist_{ik}} \cdot O_{ik} \qquad (72)$$

$\alpha_{ijk}$ is a factor ($-1 \le \alpha_{ijk} \le 1$) that indicates the direction of the movement. The factor is smaller than 1 if:

- Using a factor of 1 leads to a movement $T_{ijc} - \Delta T_{ijc} < \frac{1}{2} T_{ijc}$ or $T_{ijc} + \Delta T_{ijc} > 2 T_{ijc}$
- Using a factor of 1 the basic assumption $\sum_j \Delta T_{ijk} = \sum_j \Delta T_{ijc} = 0$ has not been met

The calculated movements $\Delta T_{ijc}$ result in the dotted lines in figure 47. Also the new average trip lengths are shown by the vertical dotted lines. As can be seen the relative differences have become smaller. At the same time the basic assumptions are met, what means that the number of moved trips represented by the four broad arrows should exactly be the same.

This procedure is repeated 10 times for every departure zone $i$. Each iteration uses different income classes $k$ and $c$, so all income classes are adapted to the desired trip length. Table 21 shows the results of these 10 iterations. As can be seen there are significant differences between the average trip lengths for the different income classes. At the same the differences are not as large as the desired differences. Within this study these results are considered as acceptable, but it is expected that further specification of the method will deliver results that are more accurately.

| | 5:00 – 6:00 | | 6:00 – 7:00 | | 7:00 – 8:00 | | 8:00 – 9:00 | | 9:00 – 10:00 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $d_{t,k}$ | $\overline{d_{ik}}$ | $d_{t,k}$ | $\overline{d_{ik}}$ | $d_{t,k}$ | $\overline{d_{ik}}$ | $d_{t,k}$ | $\overline{d_{ik}}$ | $d_{t,k}$ | $\overline{d_{ik}}$ |
| < € 20.500 | 21,96 | 24,71 | 17,28 | 19,24 | 13,66 | 15,11 | 12,59 | 14,14 | 11,79 | 13,24 |
| € 20.500 - € 34.000 | 26,63 | 27,69 | 20,94 | 21,94 | 16,56 | 17,27 | 15,26 | 15,93 | 14,29 | 14,85 |
| € 34.000 - € 56.000 | 30,42 | 28,13 | 23,93 | 22,43 | 18,92 | 17,74 | 17,44 | 16,32 | 16,32 | 15,24 |
| > € 56.000 | 33,69 | 30,43 | 26,50 | 24,46 | 20,95 | 19,42 | 19,31 | 17,91 | 18,08 | 16,75 |

**Table 21: Iteration results for trip distribution multiple income classes**

# Appendix C: Description of making the subnet

This appendix describes the procedure that is executed to make the subnet of the A27 bottleneck (and similarly the subnet of the Amsterdam case). As described in chapter 6 the subnet is based on the national accessibility model and the procedure that is applied to divide the trip distribution matrices into distribution matrices for all user classes as described in Appendix B. First the deducing of the subnet from the national accessibility model is described. Then the addition of the travel time classes is explained. Finally the dynamic calibration is made explicit.

## Selecting the subnet from the national accessibility model

The boundaries of the desired subnet can be indicated within the national accessibility model by defining a cordon. This cordon in fact is a list with all links that cross the boundaries of this area. The cordon can be used to determine the cordon matrices for the different morning peak hours and the different user classes. These cordon matrices are calculated by applying a Volume Averaging assignment with 10 iterations. The assignment results give together with the trip distribution matrices information about the trips within and crossing the area, their origin, their destination and the link where they entrance or leave the area. When the cordon links are assumed to be centroids, with this information the cordon matrices can be built containing the centroids within the area and the centroids at the boundaries.

These cordon matrices form the starting point for the subnet. In the subnet the cordon links are also replaced by centroids. The links and centroids within the area are copied to the subnet and with the boundary centroids the subnet is a closed network. The boundary centroids are connected with the nearest link by so called connectors. The characteristics of these connectors are set equal to the characteristics of this nearest link, so no congestion effects occur as a consequence of a speed difference. The capacity of the link has been set very high, what results in a guaranteed regular inflow.

## Adding the travel time classes

After making this subnet the different distance classes are added. This is done by creating new centroids at the four locations where a highway enters the subnet. Each centroid represents one of the four travel time classes. Subsequently a selected link analysis is executed in the national accessibility model. The selected link analysis has also applied a Volume Averaging assignment with 10 iterations. During this assignment it analysed for each OD-pair which share of the trips crosses the network link that represents the Merwedebrug in the model. After the assignment also a skim matrix is generated containing the travel times due to the traffic assignment.

This skim contains the total travel time from departing zone $i$ to arrival zone $j$. The travel time classes, however, are based on the travel time to reach the bottleneck and the travel time from the bottleneck. These travel times are estimated by using the skim data of centroid 3038, which is positioned very near to the north entrance of the Merwede Bridge.

The followed procedure is illustrated in figure 48. For all OD-pairs $i, j$ of which a share of the trips uses the Merwede Bridge, the travel times are collected. Also the travel times from all zones $i$ to the centroid of zone 3038 are collected. For each trip the travel time from the bottleneck is equal to the difference between the travel time from zone $i$ to $j$ and the travel time from zone $i$ to the centroid of zone 3038. The travel time at the Merwede Bridge can be deduced from the traffic assignment. The travel time to reach the bottleneck is the remaining travel time.

After applying this procedure for each OD-pair the travel time before and after the bottleneck and the number of trips passing the bottleneck are calculated. Because now the travel times are known, the trips can be classified and the total number of trips for each travel time class can be calculated. Table 22 shows the results of this procedure for the total morning peak. On this way all the trips that enter or leave the network by a highway and pass the bottleneck are redistributed for the separate travel time classes.

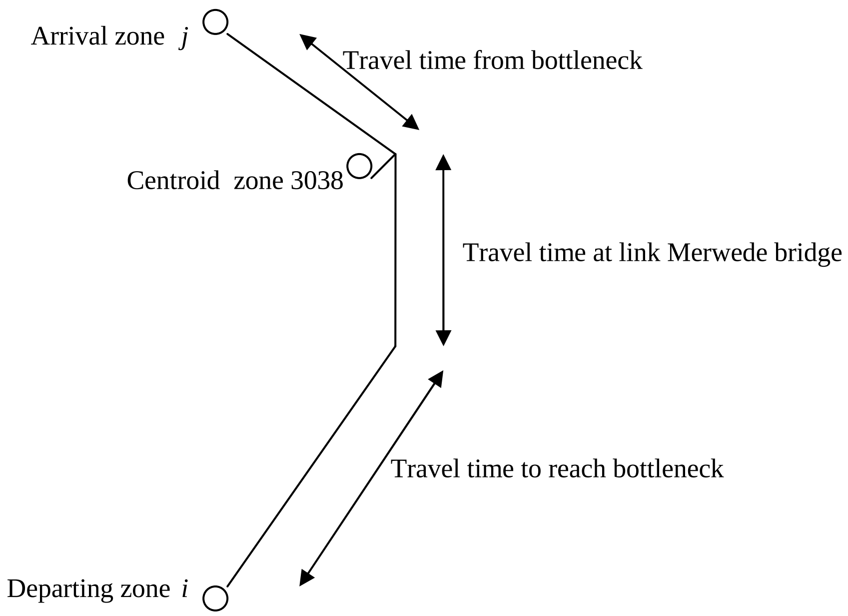



**Figure 48: Schematic view of travel time elements**

The new centroids have to represent the different travel time classes. That means they need to be placed in the network in such a way, that the travel times before and after the bottleneck are fully integrated in the subnet. This is done by giving the connector links of each centroid a fictive length that corresponds to the travel time of each travel time class. The travel times are 12, 24, 40 and 90 minutes which are the estimated median travel time of each travel time class. The travel time to reach the boundary of the subnet has to be extracted from this median travel time. The fictive length of the connectors are calculated based on these travel times and a velocity of 120 kilometres per hour (connectors have no congestion effects).

| | | | **Traveltime from bottleneck (minutes)** | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Time interval | Median | < 15 | 15 - 30 | 30 - 60 | > 60 | Total | % |
| **Traveltime to reach bottleneck** | < 15 | 12 | 596 | 686 | 458 | 56 | 1796 | 16% |
| | 15 - 30 | 24 | 1480 | 2043 | 1773 | 368 | 5663 | 52% |
| | 30 - 60 | 40 | 463 | 983 | 992 | 213 | 2651 | 24% |
| | > 60 | 90 | 98 | 243 | 350 | 130 | 821 | 8% |
| | Total | | 2638 | 3955 | 3573 | 766 | 10931 | |
| | % | | 24% | 36% | 33% | 7% | | 100% |

**Table 22: Traffic flows 5:00 – 10:00 sorted for travel time before and after passing the bottleneck, resulting from the Selected Link analysis**

## Calibration of the subnet

The national accessibility model is calibrated using traffic counts at different places in the road network. The trip distribution matrices are adapted several times in order to decrease the differences between the traffic counts and the modelled traffic volume at the same link. Because the national accessibility model contains a much larger area than the subnet, the accuracy of this calibration at the scale level of the A27 subnet is likely to be low. Therefore another calibration is applied based on traffic counts within the subnet.

For this calibration MTR data are used. These data contain the average traffic flow for each hour of the day for a large number of highway tracks in the Netherlands. These data can be differentiated for the day of the week and the month of the year. There are four tracks available that are situated within the subnet, at the A27 north and south of Gorinchem and at the A15 west and east of Gorinchem. For all four tracks traffic counts are available in both directions, what results in a total of eight links that can be calibrated. For all eight locations the MTR data are averaged for all workdays (no Saturdays, Sundays or Holidays) and for the months March, April, October and November. These months are considered to be representative, because during these the smallest influence of bad weather conditions and vacations occur.

Table 23 shows the MTR counts for each morning peak hour and for all four tracks. The traffic counts are shown in only one direction, namely at the south the direction where vehicles enter the subnet and pass the express lane and at the other places the direction where these vehicles leave the subnet.

| | | 5:00 - 6:00 | 6:00 - 7:00 | 7:00 - 8:00 | 8:00 - 9:00 | 9:00 - 10:00 |
|---|---|---|---|---|---|---|
| A27 South | MTR counts (vehicles) | 1896 | 3514 | 3662 | 3614 | 3117 |
| | static before calibration | +99% | +74% | +16% | -41% | -36% |
| | dynamic before calibration | +30% | +16% | +16% | +17% | -15% |
| | dynamic after calibration | 0% | +3% | -3% | -5% | +5% |
| A27 North | MTR counts (vehicles) | 1762 | 3502 | 3072 | 2673 | 2724 |
| | static before calibration | +79% | +28% | +11% | -32% | -36% |
| | dynamic before calibration | +13% | -5% | +12% | +17% | -19% |
| | dynamic after calibration | 0% | -1% | +3% | 0% | 0% |
| A15 West | MTR counts (vehicles) | 1535 | 3151 | 2959 | 2752 | 2562 |
| | static before calibration | +145% | +58% | +31% | -23% | -23% |
| | dynamic before calibration | +74% | +29% | +43% | +11% | -17% |
| | dynamic after calibration | -1% | 0% | +2% | +3% | +2% |
| A15 East | MTR counts (vehicles) | 487 | 1498 | 2244 | 2163 | 1800 |
| | static before calibration | +189% | +39% | -29% | -50% | -40% |
| | dynamic before calibration | +108% | +17% | -26% | -38% | -35% |
| | dynamic after calibration | 0% | 0% | 0% | +1% | -1% |

**Table 23: Deviations static and dynamic assignment and results dynamic calibration method**

Below the MTR counts the relative difference is shown between the static assignment results and the MTR counts. This static assignment is executed using the generated trip distribution matrices of the subnet and the volume averaging method with 10 iterations. As can be seen the differences are very large. The differences also show that the static assignment results are generally too large for the early hours and too small for the late hours. This can be explained by the fact that the static assignment does not keep into account the time (including congestion time) road users spend to make their trip and the fact that as a consequence of this the road users pass some links at a later hour. As this inaccuracy is mainly the consequence of the travel time classes, this inaccuracy was already present in the national accessibility model.

This supposition is confirmed by the results of the dynamic assignment that is applied based on the same trip distribution matrices. Because the dynamic assignment calculates the movement of all trips on the subnet during time, the time effects are included in the assignment results. As can be seen, the overestimation at early hours and the underestimation at late hours are reduced significant.

Because of these significant improvements the calibration is not based on the usual static assignment results, but on the dynamic assignment results. For all eight counted links four calibrations are applied. During each calibration all traffic passing the calibration link is increased or decreased with a factor $\eta$. This factor is calculated using the formula:

$$\eta = \frac{\sum_k V_{ak}}{N_a} \qquad (73)$$

Where $V_{ak}$ is the modelled traffic volume using a dynamic assignment of user class $k$ at link $a$. With this factor for all OD-pairs the calibrated number of trips can be calculated using the formula:

$$T_{ijk}' = \eta \cdot \delta \cdot T_{ijk} + (1-\delta) \cdot T_{ijk} \qquad (74)$$

Where $\delta$ is a factor between 0 and 1 describing the share of the trips that passes the calibration link (when $\delta = 0$ the trips remain the same). The calibrated trips for all OD-pairs are used to make a new static and dynamic assignment. After these assignments the factor $\eta$ is calculated again for the next calibration link. After applying this procedure four times for all eight calibration links, the relative differences are such small that the modelling results could be assumed to describe the measured situation (see also table 23).

Table 24 shows the trip distribution during the whole morning peak for the different income classes in terms of percentage. First all trips in the national accessibility model are analysed. Then all trips in the subnet before and after the calibration are analysed. At the end also a selected link analysis of the link corresponding to the Merwede Bridge is applied to analyse all trips that pass the bridge before and after the calibration. As can be seen, there are no large differences between these five methods. As can be expected, there are relatively more high income trips than low income trips, because it is a highway track. Table 25 shows this distribution for all morning peak hours. These differences seem to be very small.

| Method | < € 20.500 | € 20.500 - € 34.000 | € 34.000 - € 56.000 | > € 56.000 |
|---|---|---|---|---|
| National accessibility model | 25% | 35% | 27% | 13% |
| Subnet before calibration | 22% | 38% | 26% | 14% |
| Subnet after calibration | 22% | 38% | 26% | 14% |
| Selected link before calibration | 22% | 35% | 26% | 17% |
| Selected link after calibration | 22% | 34% | 26% | 17% |

**Table 24: Trip distribution between four income classes using different objectives**

| Time interval | < € 20.500 | € 20.500 - € 34.000 | € 34.000 - € 56.000 | > € 56.000 |
|---|---|---|---|---|
| 5:00 - 6:00 | 22% | 35% | 26% | 17% |
| 6:00 - 7:00 | 22% | 35% | 27% | 17% |
| 7:00 - 8:00 | 23% | 34% | 26% | 17% |
| 8:00 - 9:00 | 23% | 34% | 26% | 17% |
| 9:00 - 10:00 | 23% | 34% | 26% | 17% |

**Table 25: Trip distribution between four income classes for 5 time intervals**