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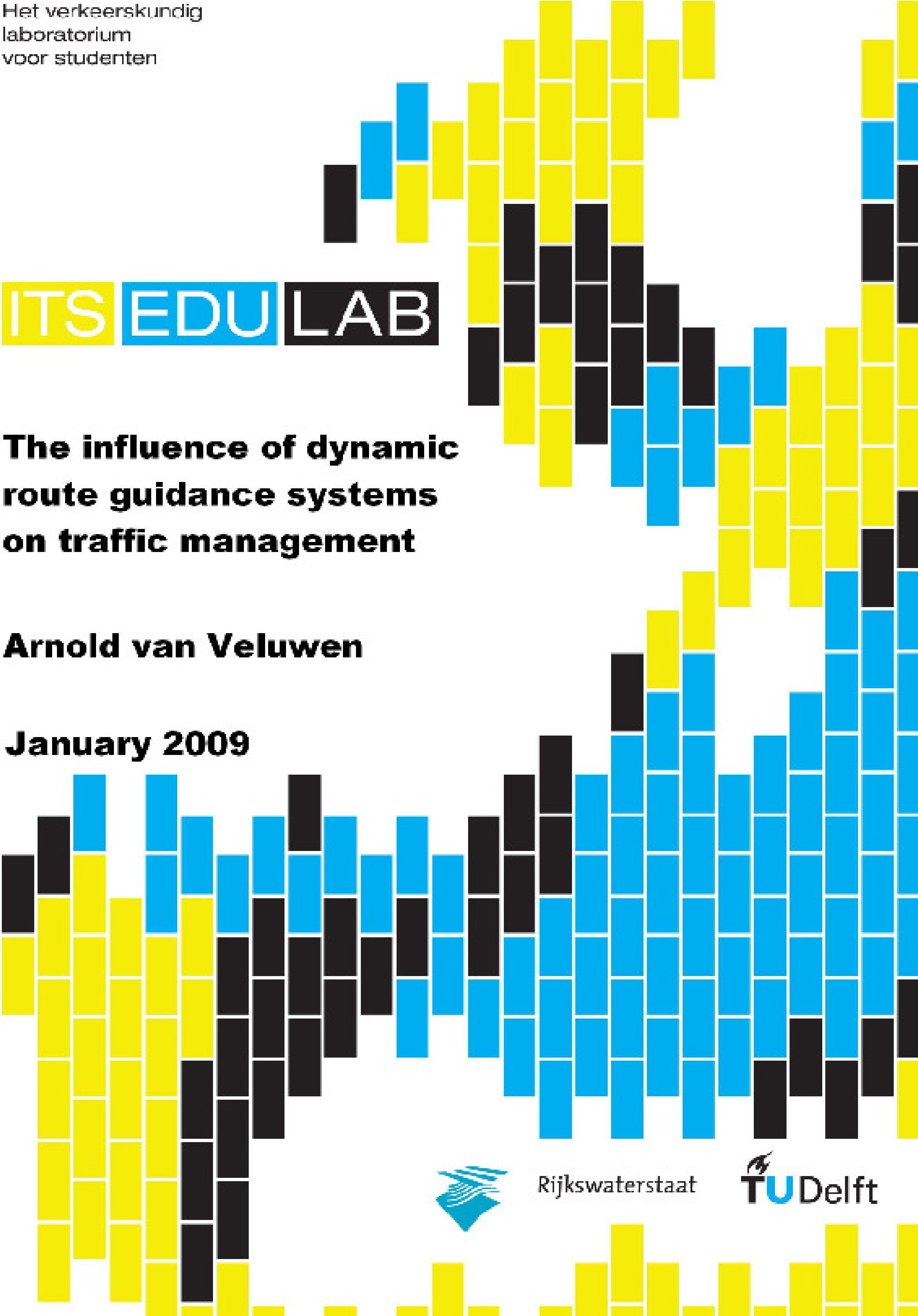

The influence of dynamic route guidance systems on traffic management

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Rijkswaterstaat

TU Delft

The influence of dynamic route guidance systems on traffic management

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Samenvatting

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Aan het einde van 2007 is er een nieuwe vorm van route geleiding voor individuele weggebruikers op de markt gekomen, het zogenaamde dynamisch navigatiesysteem. (DNS) Dit systeem adviseert welke route te kiezen mede op basis van de huidige verkeersinformatie. In beperkte mate was een dergelijk systeem reeds beschikbaar via radio kanalen. (RDS-TMC) Het ligt in de lijn der verwachting dat de invloed van deze dynamische navigatiesystemen op verkeersmanagement aanzienlijk zal worden en de vraag is dan ook hoe groot deze invloed zou kunnen worden en welke maatregelen moeten worden getroffen om de voordelen optimaal te benutten en eventuele nadelen tegen te gaan.

Het is reeds bewezen dat de statische variant van deze navigatiesystemen leidt tot aanzienlijke voordelen voor de gebruiker in termen van kortere routes en reistijdwinst dientengevolge. De dynamische navigatiesystemen die rekening proberen te houden met de actuele verkeerssituatie zouden daar in theorie nog extra winst aan toe kunnen voegen. Er zijn echter een aantal aspecten die het lastig maken om de invloed van dergelijke dynamische systemen expliciet zichtbaar te maken.

Te verwachten valt dat aanzienlijke hoeveelheden reizigers dergelijke systemen gaan gebruiken. De consequentie daarvan zou kunnen zijn dat, als iedereen geïnformeerd is, het voordeel van het hebben van die informatie steeds minder wordt. Daarnaast is de vraag gerechtvaardigd te stellen in hoeverre dergelijke systemen in staat zijn in de gebruiker volledig juist te informeren en wat de gevolgen van eventueel imperfecte informatie kunnen zijn. Als derde kan gesteld worden dat het onwaarschijnlijk is dat iedereen, die een dergelijk navigatiesysteem aanschaft, deze adviezen in zijn geheel opvolgt. Ook dit heeft consequenties voor de interpretatie van de invloeden van deze systemen.

Het doel van dit onderzoek is daarom het bepalen van de effecten voor de reizigers, die andere routes gaan maken, op basis van een groeiend aantal dynamische navigatiesystemen en het aangeven hoe Rijkswaterstaat, als the nationale wegbeheerder, daar het beste mee om kan gaan.

Om grip te krijgen op welke processen er spelen is er in eerste instantie gekeken naar de theoretische achtergronden die hier een rol spelen. Hiervoor zijn de invloed van de penetratiegraad (het percentage dynamische navigatie systemen die in het totale verkeerssysteem aanwezig zijn), de kwaliteit van de informatie en de invloed van het opvolggedrag van de gebruikers apart onderzocht.

In het algemeen kan worden gesteld dat, volgens algemene economische principes, naar mate de penetratiegraad oploopt, de individuele winst voor elke gebruiker zal afnemen.

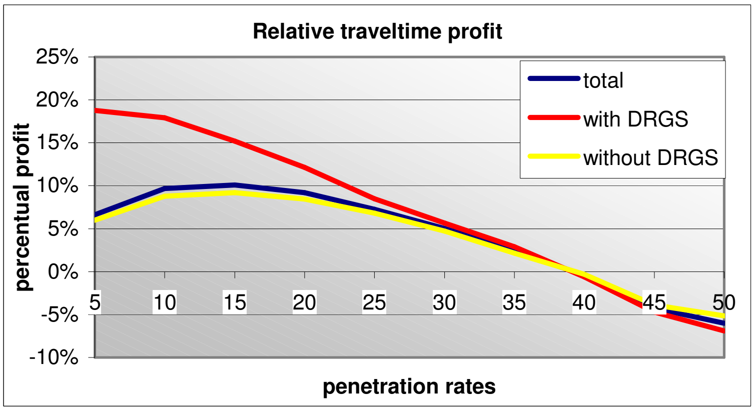
Met betrekking tot de kwaliteit van de informatie speelt met name de accuraatheid van de informatie een belangrijke rol. Er zijn verscheidene

oorzaken die maken dat de route informatie van de gebruiker niet actueel kan zijn. Dat leidt er toe dat het advies van het dynamisch navigatiesysteem ook niet optimaal en accuraat is, wat de routekeuze negatief kan beïnvloeden.
Als laatste is er ook de invloed van de gebruiker die om verschillende reden het advies van het dynamisch navigatiesysteem naast zich neer kan leggen en verkiest een andere route te nemen. Dit heeft te maken met de kwaliteit van de informatie, de karaktereigenschappen van de gebruiker en de ervaring die de gebruiker met het dynamisch navigatiesysteem opdoet.

Om de invloed van deze drie aspecten nader, en in combinatie met elkaar, te onderzoeken is er gekozen om een model te gebruiken dat specifiek met deze drie aspecten kan omgaan. Uiteindelijk is de afweging gemaakt om een nieuw model te ontwikkelen dat goed is staat is om de invloed van deze drie aspecten, en de daarmee samenhangende verkeerskundige gevolgen, in kaart te brengen. De consequentie daarvan is dat het model verkeerskundig iets minder gedetailleerd is. Dit model is vervolgens toegepast op een theoretische situatie waarbij 2 goed uitwisselbare alternatieve routes worden vergeleken. Daarna is het model ook toegepast op een meer realistisch netwerk, dat zich tot op zekere hoogte laat vergelijken met het netwerk rondom de stad Rotterdam.

De belangrijkste uitkomst die met dat model is berekend, is dat er een optimale situatie is, waarbij alle gebruikers beter af zijn. De voordelen voor de gebruikers van het dynamisch navigatiesysteem nemen af naarmate de penetratiegraad oploopt, maar door de efficiëntere keuze van deze gebruikers ontstaan er voordelen voor de niet gebruikers. In het geval van het theoretische netwerk en indien er vanuit wordt gegaan dat alle gebruikers het advies van het dynamisch navigatiesysteem opvolgen, ligt dat optimum rond een penetratiegraad van 15% en levert het een totale reistijdwinst van rond de 10%. Voor de gebruikers van het dynamisch navigatiesysteem is de maximale reistijdwinst bij lage penetratiegraden rond de 20% en die winst neemt min of meer lineair af naar nul bij een penetratiegraad van rond de 40%. Ook voor de niet gebruikers ligt het punt waarop geen winst meer wordt behaald rond een penetratiegraad van 40%, ten opzicht van een verkeerssysteem zonder dynamische navigatiesystemen. Verandering in netwerk, opvolggedrag en kwaliteit van de verkeersinformatie hebben een verschuiving van dit optimum tot gevolg.

Algemene uitkomst van deze studie waarbij de reistijd winst slechts afhankelijk is van de penetratiegraad



Dit optimale punt is via meerdere criteria te vinden; zowel de uitkomsten voor voertuig verlies uren, als reistijdwinst en filelengtes binnen het systeem laten min of meer dezelfde curven qua opbrengst voor de gebruikers zien.

Het verbeteren van de accuraatheid van de verkeersinformatie als input voor het dynamisch navigatiesysteem heeft tot gevolg dat het optimum zoals hierboven beschreven opschuift naar een iets hogere penetratiegraad (20%-25% penetratiegraad) en dat het, bij het gebruik van dynamische navigatie systemen, langer duurt voordat de invloed van deze systemen negatieve consequenties heeft. (Rond de 50% penetratiegraad) Overigens leiden verbetering in de accuraat niet tot significant hogere winsten voor de individuele gebruikers.

De reactie van de gebruiker heeft een behoorlijke invloed op de hierboven beschreven optimale situaties. Het feit dat verschillende soorten gebruikers, zoals forensen, business reizigers en dagjes reizigers, verschillende reacties kunnen hebben ten opzichte van prestatie criteria, zoals de voorspelde aankomsttijd, het aantal route wisselingen, of het minimaliseren van de reistijd, leidt er toe dat een significant percentage gebruikers, het advies van het dynamisch navigatiesysteem niet opvolgt. Hierdoor verschuift de optimale situatie naar een hogere penetratiegraad van rond de 30% en ook het moment dat de situatie slechter wordt vergeleken met een verkeerssysteem zonder dynamische navigatiesystemen verschuift naar een penetratiegraad van rond de 85%, dit omdat met name bij hogere penetratie graden de prestatie criteria van de gebruikers vaker worden overschreden.

In het geval deze analyses worden toegepast op de uitgebreidere netwerksituatie dan blijkt dat de voordelen van het dynamisch navigatiesysteem lager zijn voor zowel de gebruikers, als de niet gebruikers. Doordat er veel reizigers zijn die geen of slechte alternatieve routes hebben (rond de 60% in deze studie) zijn er veel reizigers, die ondanks dat ze de beschikking hebben over een dynamisch navigatie systeem, geen verandering van route kunnen maken en daardoor dus geen positieve of negatieve invloed hebben op het verkeerssysteem. Hierdoor verschuiven de optimale percentages wederom naar hogere penetratiegraden. Daarom komt het optimale maatschappelijke punt bij een penetratiegraad van rond de 25%-30% te liggen en is er zelfs een marginale reistijd winst bij penetratiegraden van 95%-100%.

Voor Rijkswaterstaat betekent dit dat deze dynamische navigatiesystemen in eerste instantie bijdragen aan een efficiëntere verdeling van het verkeer over het netwerk, hoewel er op individueel niveau uiteraard reizigers zijn die slechter af zijn. Naarmate de penetratiegraad oploopt neemt de maatschappelijk winst eerst toe, er is echter een optimum waarna deze winst gaat afnemen. Tot aan dat optimum zou RWS stimulerende maatregelen moeten nemen aangezien een dergelijk systeem een bijdrage levert aan het maatschappelijk nut. Vanaf dat moment, dat de winst gaat afnemen moet men maatregelen nemen om dergelijke verslechteringen tegen te gaan.

Het is echter de vraag of het geschetste optimum vanzelf kan worden bereikt, aangezien de kosten van de aanschaf van een dynamisch navigatiesysteem de baten van een betere routekeuze overschrijden, daarvoor zou RWS stimulerende maatregelen kunnen nemen.

Abstract

At the end of 2007 a new route guidance application for individual road travellers became available, a dynamic route guidance system (DRGS). These systems advice a best route also based on the current traffic information. Although not used very often a comparable system is already available via radio channels (RDS-TMC). It is to be expected that the influence of these dynamic route guidance systems on traffic management will become quite significant. Therefore it is questioned how big this influence will be and which measurements should be taken to benefit as much as possible from its advantages and how to challenge the drawbacks of these systems.

It is already proven that the static version of these route guidance systems provide significant advantages in terms of shorter routes and travel time savings because of that. Dynamic route guidance systems, which do incorporate traffic information, could theoretically improve on that benefit even more. However there are a few aspects that make it difficult to determine the influence of these systems explicitly.

It is to be expected that a significant amount of travellers will use these systems. The consequence of that could be that, when everybody becomes informed, the advantage of getting information is decreasing. Besides that it is questionable to what extent these system are capable of informing the travellers accurate and moreover what are the consequences of non-accurate and imperfect information. A third aspect is, that it is unlikely that all equipped travellers will fully follow the advice provided by the dynamic route guidance system. This also can have major consequences for interpreting the impacts of these systems.

The goal of this study is therefore to determine the effects for travellers who make different route choices influenced by an increasing number of dynamic route guidance systems and present the consequences of that for Rijkswaterstaat as the national road authority.

In order to get a better understanding of the processes that play a role first of all some theoretical aspects are researched. Therefore the influence of the penetration rate, (the percentage of vehicles that is equipped with a dynamic route guidance system), the quality of the traffic information and the influence of the compliance behaviour are investigated separately.

It can be stated that, according to general economical principles, as the penetration rate will increase it is to be expected that the individual benefits if the users will be decreasing.

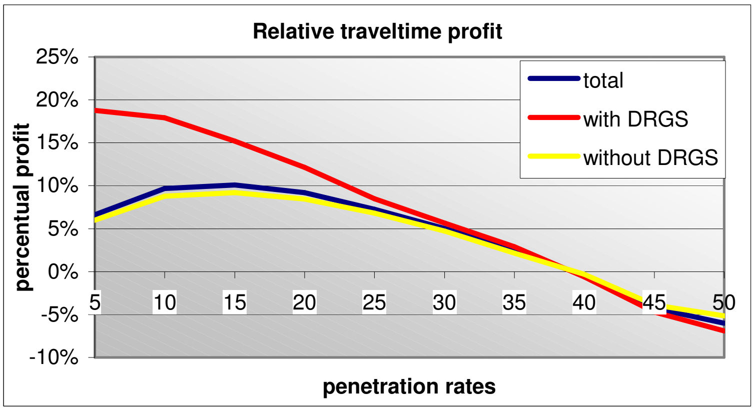
Concerning the quality of the information, there is a significant influence to be expected when it comes to the accuracy of the traffic information. There are several reasons that cause the traffic information for route guidance to be non-accurate. This consequently makes the advices of the dynamic route guidance system inaccurate, which can thus negatively influence on the route guidance.

Finally also the influence of the users themselves is of significant importance. A traveller can have several reasons to neglect the advices of the dynamic route guidance system and take a different route. This behaviour is in general influenced by the quality of the information, the personal characteristics of the travellers and the experience gained with the system.

In order to investigate these three aspects more in detail and in combination with another it is chosen to use a model that is able to cope with these aspect specifically. Eventually it was decided to develop a new model, which would be capable of dealing with these aspects and its traffic related influences, instead of using an existing traffic model. A consequence of that is that the model used performs a little less detailed in they vehicles are moved compared to existing models.
This model is then used in a scenario where two rather good exchangeable routes are compared to each other. Afterwards the model is also used on a more realistic network situation, which is to a certain extent comparable to the Rotterdam motorway network.

The general result that is computed with this model is that there is an optimal situation, where all travellers together in the system benefit most. The advantages for the users of the dynamic route guidance system decrease as the penetration rates increases, however due to a more efficient route choice of these equipped travellers also the non-users benefit from that. In case of the theoretical 2-link network and in case every equipped traveller is considered to follow the route advice of the dynamic route guidance system, that optimal situation is around a penetration rate of 15% and on average the profit in term of travel time saving is then around 10%. For the users of the dynamic route guidance system the travel time profit at low penetration rates is around 20%, afterward this profit more or less linearly decreases to a point where there is no profit anymore at a penetration rate of 40%. Changes in the network configuration, the compliance behaviour and the quality of the traffic information in general cause a shift of this optimum.

General result of this study where travel time profit is only depending on the penetration rate



This mentioned optimal point could be determined via different performance criteria; total travel time loss, as well as travel time profit and the length of the queues in the systems, all show more or less the same figures in terms of profit and they all show more or less the same optimal points.
An improvement on the accuracy of the traffic information as an input for the dynamic route guidance system results in a shift of these optimal points to a higher penetration rate. (Around 20% to 25%.) Besides that the total system remains beneficial at higher penetration rates. (More or less 50%.) So the moment that the situation becomes worse compared to a system without dynamic route guidance systems is delayed. On the contrary to those improvements, it should be mentioned the general individual profit is not significantly improved by making the traffic information more accurate.
The reaction of the users themselves has an important influence on the optimal situation as presented above. The fact that different types of users, like commuters, business travellers and holiday travellers, can have very different reactions, to for instance, the predicted arrival time, the number of route changes and whether or not their travel time is minimized, can cause that a lot of equipped travellers do not follow the route advice. As a consequence of that the optimal social point shift to a penetration rate of around 30%. Besides that, the moment that the situation becomes worse compared to a situation without dynamic route guidance systems, is delayed to a penetration rate of 85%, this is because at higher penetration rates the performance criteria of the users are violated more often.
In case this analysis is applied to the more realistic Rotterdam network, it turns out that the advantages of the dynamic route guidance system are significantly lower for both users and non-users. Because a lot of users don't have any alternative, or only a bad alternative, there are a lot of travellers that, although having a dynamic route guidance system, cannot change anything about their situation. They become more or less captive of a certain route and have no influence on changing the traffic situation in the network. (In this study that percentage is around 60%.) Because of this, the optimal penetration rate again shifts to a higher rate. The optimal social point is at around 25%-30%. Even at penetration rates of 95%-100% there is still a marginal profit visible, compared to a situation without any dynamic route guidance systems.

For Rijkswaterstaat this implies that the dynamic route guidance systems do cooperate to a more efficient distribution of traffic of the network. As the penetration rate increases the social profit increases as well, there is however an optimal situation, where after the profit will decrease. Before that point is reached Rijkswaterstaat should somehow support the DRGS, as they are beneficial for society. When the optimal point is reached Rijkswaterstaat should intervene in the process and try to guide the process such the negative consequences can be countered.
It is also questionable whether the described optimum will be achieved without support. Because the costs of purchasing the dynamic route guidance system does exceed the benefits of making better route

choices, at a certain penetration rates, Rijkswaterstaat might need to stimulate the purchase of these dynamic route guidance systems.

Preface

This report is the final product of my education towards becoming an engineer. This study is executed within the Edulab environment, the institute where Rijkswaterstaat and the Technical University of Delft cooperate in educating students. Edulab offers students the opportunity to get involved in practical issues that Rijkswaterstaat deals with every day and provides the opportunities to research that in an academic environment under supervision of the university. I'm grateful that I got the opportunity to be part of that.

I would like to specially thank my daily supervisors, Hans van Lint and Michèle Coëmet. Although in some periods of this project the qualification "daily supervisor", could easily be replaced by "monthly supervisor", I appreciate your support very much. Both of you have helped me a lot by your clear and direct advices, but also in placing the subject in the right perspectives. Thank you for that!

Furthermore I like to thank my fellow Edulabbers, including the Edulab-supervisors, Henk, Ido and Serge in that as well. There is always time to discuss in general the whole world with you, but also my tiny little Matlab problems, that I appreciate a lot. Thanks for your support and good luck with finishing your own theses.

Finally I would like to thank my family as well for being so patient with me. Right now it is over 9 years ago since I started studying in Delft. Thanks a lot for giving me the opportunities to do so and supporting me for nearly a decade.

January 2009,

Arnold van Veluwen

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Notations

Used abbreviations:

RWS:	Rijkswaterstaat
ATIS:	Advanced travel information system
RDS	Radio Data Service
TMC	Traffic Message Channel
DRIP	Dynamic Route Information Panel
GPS	Global Positioning System
DRGS	Dynamic Route Guidance System
MTS	Mobile Traffic Service
DTM	Dynamic Traffic Management
VMS	Variable Message Sign
VCNL	Verkeerscentrale Nederland
BPR	Bureau of Public Roads
MoniCa	Monitoring Casco
MoniBas	Monitoring basis application
DynASMART	Dynamic Assignment simulation model for advanced road telemetics

Used variables:

t (s)	(travel) time in general
x (m)	location in general
q (veh./u)	flow in general
k (veh./km)	density in general
u (m/s)	speed in general
n	number of vehicles
C (veh/u)	Capacity in general
r (s/veh)	arrival interval
P(R1)	Probability for taking a certain route (R)
R_{advice}	Advised route by DRGS
$tt_{measuered}$ (s)	Measured travel time on a link
t_a	Travel time on link a
t_a^0	Free flow travel time on link a
α ,β	Parameters in BPR function

1. Introduction

1.1 General overview on transportation

People in general, have the natural tendency to try to improve their situation. In very different matters of life people like to achieve a better situation as they have right now: they prefer better jobs, a higher income, a bigger house and a lot of other improvements. Of course these improvements can be measured in very different forms, like economical benefits, social welfare, or just the feeling of being happy. One out of the very broad range of consequences of this willingness to improve is the need for people to transport themselves, or to transport goods, in order to increase their benefit. On the other hand there is the peoples natural tendency to keep the situation as it is, as changing their situation will cost some effort.

So when there are for instance better jobs in another city, it is likely that people like to go there, or when a product is not available at a certain location people will try to transport it from another location to their own location. However when the benefit is not large enough compared to the effort of transportation, there might be no change at all.

In transportation terminology this behaviour is usually called maximizing utility. Because travelling costs time and money, there is a certain disadvantage (disutility) of making a trip to another location. In general it can be stated that a trip is made when the benefit (N) of being at another location (j) is larger than the disadvantage of travelling (Z) and of course also larger than staying at the original location (i). This is shown in *Figure 1-1* [1]

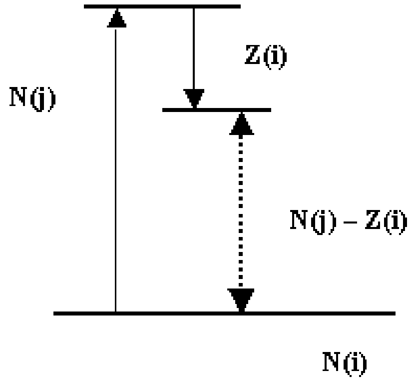
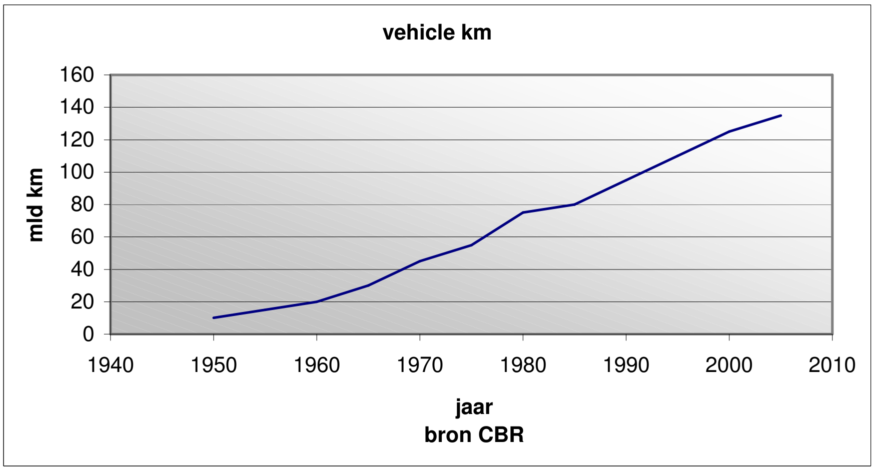


Figure 1-1 Utility function for making a trip. (Where N is the utility of the preferred location (j) and the current location (i) and Z(i) the disutility of travelling for i to j . N(j)-Z(i) equals the gained utility profit)[1]

In the early days, when it was physically difficult to access to all preferred locations, the main drawback for making a trip was that it would simply take too much time to reach a beneficial destination. As transportation methods have improved rapidly over the last 2 centuries, more locations became accessible for more people and thus people started to make more and further trips. Besides also more location became attractive due to technological innovations, which strengthens the need for transportation. *Figure 1-2* shows the increase of the mobility over the last decades in the Netherlands (in travelled kilometres). Of course also the number of people in general increased rapidly (from around 10 million in 1950 to 16 million in 2007) and so there is more people that can make a trip, but the mobility increased much faster according to *Figure 1-2*.

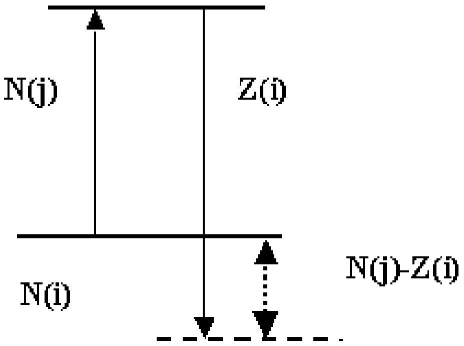
Figure 1-2 growth of mobility over the last decades



At the current moment transportation methods have become so sophisticated that it is possible to physically access nearly every preferred location. The question is however what the consequences for the accessibility are, when it turns out that lot of people are trying to access those locations. When too many people are trying to access certain locations they might start hindering each other when the capacity of the chosen transportation method is not sufficient. That hindering of each other when making a trip is nowadays a substantial part of the disutility in transportation. In general it can be stated that improving the accessibility attracts more traffic, which is on the other hand harmful to the accessibility.

So hindering each other, in accessing beneficial locations, causes an increase in the disadvantage of travelling, as it takes longer to travel certain distances at certain time periods. (Especially in peak periods.) In general this leads to a loss of welfare. However it turns out that people still make the trip, even though these increased disadvantages, so it can be defended that that there is still profit. People will be making trips unless the disadvantage of travelling (the physical distance that needs to be covered together with the hindering aspect) is becoming so high that staying at home becomes more profitable. *(Figure 1-3)*

Figure 1-3 If the disadvantage for making a trip (Z(i)) is higher than the utility of being at N(j), trip, its is preferable to stay at home.



Traveller's choices

From the approach before it becomes already clear that a traveller has several choices to make. A beneficial location has to be determined, but also a route with a low disutility is preferable to keep the overall benefits as high as possible. In general transportation theory a set of five different choices for a traveller is applicable which all have their influence on the total travel performance. [1]

- Trip choice
- Destination choice
- Mode choice
- Departure time choice
- Route choice

The first choice, whether or not, to make a trip depends on the question whether one can have more benefits somewhere else. The second question is what is the best location to do so. Third is by what transportation mode does one get there. Fourth is the moment one needs to leave to arrive to that location in the preferred time. The final question is via which route does one get there best.

These 5 choices are ordered by the sequence they are usually made. For this study the last question is most important. As mentioned above when lots of people start hindering each other, the disutility rises. That happens when travellers are already on their way (en-route) and the 4 preceding choices have usually been made already.

Rijkswaterstaat

Besides the travellers themselves, who are all individually optimising their profit, using their choices as mentioned above, there is also the government, who wants to increase the total national benefit (GNP). The Dutch government states that they do not want to wait for that moment, when people stop travelling themselves because the disutility of making trips becomes too high and meanwhile lose so much welfare due to people standing in traffic jams. Such a situation will eventually occur and then people will stop making extra trips, but the negative consequences of that equilibrium are rather high. Therefore the government has declared in the "Nota Mobiliteit" [2] that they want to decrease the negative effects of people hindering each other while travelling. Also some other disadvantages of travelling, like the unreliability of the system, the unsafety and the negative consequences for the environment are stated to be of importance. Some general targets are mentioned to decrease these disadvantages, of travelling:

- The increasing need for mobility should be facilitated. Although people like to travel more, the disadvantage of doing so should not increase.
- The reliability of travelling should be improved, the more reliable the system is the less the disutility becomes.
- Travelling should become safer.
- The negative consequences of travelling for the environment should somehow be reduced.

Providing in these requests is one of the main tasks of Rijkswaterstaat. In general they use constructing, pricing and utilization as their main pillars to for their policy. Some possible measurements that they can use to achieve improvements are:

- Adding extra capacity to the existing transport network.
- Try to manage all the travellers in such a way that they don't hinder each other so much.
- Try to improve the travellers behaviour
- Create limitations, for instance to limit the amount of air pollution.

More specifically for road transportation this implies that RWS is responsible for building extra roads to give the travellers more space to travel and create systems tot manage traffic, such that travellers make their trips in a more efficient way. There are lots of measures that can be thought of in managing traffic. There are for instance traffic rules and roadside signals, which inform travellers how to act in a certain situation. These measures have a rather static way of managing traffic, more sophisticated are for instance traffic lights, ramp metering and advanced traveller information systems (ATIS) that can cope better with the dynamic character of traffic and tell travellers how to handle according to the traffic situation.

In general it can be stated that informing travellers more and better about their situation is an opportunity to reduce the disadvantage caused by people hindering each other while travelling.

Traffic information

So in informing travellers on the traffic situation is in general beneficial for the travellers. Travellers can avoid traffic jams and try to take smarter routes, when they know what might be ahead of them. One of the most common ways to provide that information is via the radio channels. Every hour or half an hour, most radio channels give traffic information on which travellers can adjust their choices.

However as the volume and compactness of traffic was (and is still) rising and the traffic situations are changing more rapidly, so a more frequent system was preferable and therefore RDS-TMC system was created. This coded traffic information is transmitted via FM frequencies to the radio systems in the cars and from that on the traffic information is displayed on a screen. The main advantages are that information is always available, that the information includes all traffic information and that the code is international, so it can be used abroad. [4] There are even possibilities to select only that information that is useful for the travellers route. Besides these systems that provide traffic information in the vehicle, there are of course much more systems along the road (DRIPs) and at home (teletext, internet) that inform travellers about the traffic situation.

Figure 1-4 In-car traffic information system (based on RDS TMC)

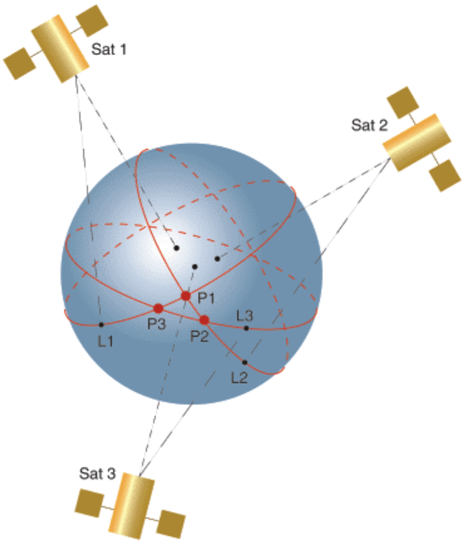
GPS and route guidance

Often the terms GPS and route guidance systems are considered to be the same, as both can operate together to inform travellers, however in principal GPS is something totally different than route guidance, GPS is used to navigate.

Since 2000 the global positioning system (GPS) became available to use by commercial parties. Before that it was only applicable by the American army. To make it inaccessible for other purposes a noise was added that made the signal inapplicable for commercial determination of locations. Only with an extra signal from a fixed beacon positioning was possible. After 2000 the noise was removed and any party can now use the signal for determining locations [5]. Based on the location of 3 or more satellites that are somewhere in an orbit around the earth, positions on earth can be determined. So when one is able to "see" 3 of these satellites one can determine the location on earth.

A remark that also has to made is that this is a one sided signal, so the satellites "don't know" the position of the receiver on earth. In 2013 also a European system (Galileo) will be launched to make an even more detailed system.

Figure 1-5 GPS system



Company's like TomTom, Garmin, VDO Dayton, grabbed the opportunity to make this a feature beneficial for travellers. By informing travellers which route they can take best, based on their current location, (measured by GPS) their preferred destination and a digital map, they made a system that can guide a traveller to a desired location and thereby help people to improve their route choice behaviour. Especially in urban area's where there are a lot of route alternatives this proved to be a very helpful tool, for instance in finding the best routes to unknown destinations. It is stated that travellers make up to 18% shorter trips and save about 16% more time when using a route guidance system. [6]

Later on GPS based systems became available to which traffic information could be added, so the route guidance system itself could determine the preferred route including the information on traffic. As this system copes with the dynamics of the traffic it is called a dynamic route guidance system. (DRGS) These systems know where they are (via GPS), they know where to go (programmed by the users) and they know the traffic information. The first available systems that could do so were the already mentioned RDS TMC systems, as that signal did already exist it had only to be coupled to the route guidance systems. By doing so travellers could not only choose a route based on a shortest path algorithm, but also algorithms that took into account the traffic information.

At the end of 2007 a new system became available when TomTom, one of the route guidance systems companies, started a system to collect traffic information via mobile telecom provider Vodafone. By measuring the locations of mobile phones at certain time intervals an average speed for a certain section of the network can be generated. When this is done for 4 million users (the total number of people using the network of Vodafone is somewhere in that range) an overview of the current traffic situation can be generated. This system is called Mobile traffic service (MTS). Like RDS TMC this information can be send to the route guidance systems to provide route guidance based on traffic information.

As it is likely that the influence of these dynamic route guidance systems will increase in the coming years, it is worthwhile to investigate on the benefits of these systems and its drawbacks. It seems evident that systems like these tend to influence on traffic efficiency matters, besides that it is also shown that (dynamic) route guidance systems can achieve improvements on for instance the environmental topics as well. [3]

1.2 Problem description

As mentioned (dynamic) route guidance systems are made to be beneficial for travellers as they are programmed to inform travellers on their shortest (best) routes, and perform even better when traffic information is involved. When travellers know what they can expect, they can make better choices. So far there are no problems at all for the travellers, only advantages. They know where the problems are and they can avoid traffic jams as stated by their designers. [7]

However there are a few possible scenarios in which the effects might not be so positive as expected, especially when traffic information is included and the traffic situation is near its capacity.
When a traveller uses a dynamic route guidance system the traveller determines his route based on the given (somehow measured) traffic situation. As the traffic situation changes (rapidly) over time the traveller will never encounter the traffic situation given at the moment of his choice, especially when longer distances are travelled. That does

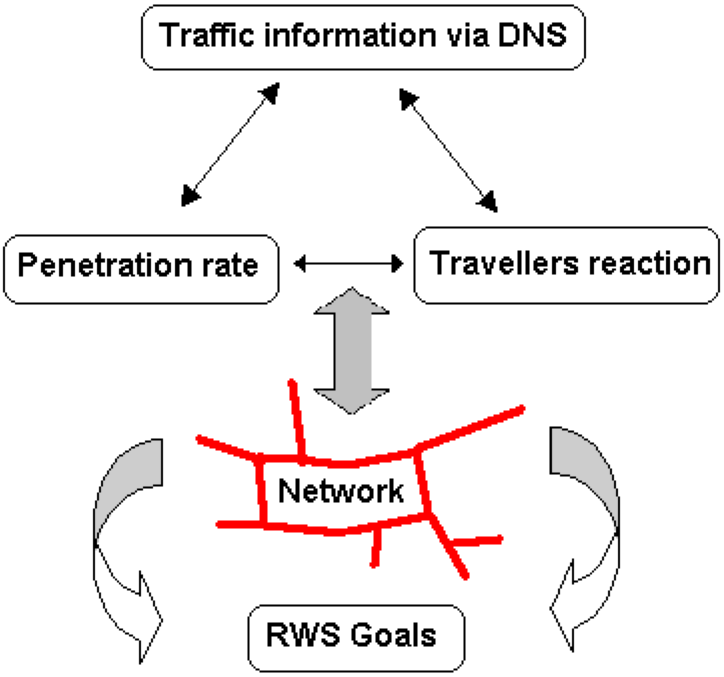
not automatically imply that the choice that is made at that moment is wrong, but at least it is based on imperfect information. However it might turn out that in the end it would have been better for the traveller to choose a different route, because the situation has changed a lot meanwhile. The general problem is that the DRGS cannot predict the traffic situation for the moment the traveller will arrive at the critical location. Of course this is not typically a drawback of a DRGS but it is embedded in all forms of traffic information.

A second problem that might occur is when lots of travellers are going to use the dynamic route guidance system. When only a few users have the advantage of knowing more then the rest, it is clear that they can benefit a lot, but when more and more people are using the system the advantage of being informed more is likely to decrease. Eventually when everybody knows the best route, it might turn out that having a route guidance system is not so beneficial anymore, especially when the previous point concerning the unpredictability of the future traffic situation is taken into account.

In the third place there is the most complex factor and that is the traveller himself. The question is how does he cope with this information. When travellers do not fully rely on the advices given by the route guidance system, (or any other information) they will not comply automatically, so there is a difference between penetration rate (the percentage of travellers that has a route guidance system, or is informed) and the compliance rate (the number of people that actually uses the system and follows the advice)

These three interacting aspects may lead to a situation where the profitability of a route guidance system cannot be proven so straight forward as expected by many. Furthermore there is the question whether and how these effects contribute to the mentioned goals of RWS and whether or not RWS has measures to interfere in case of non-preferable situations. *Figure 1-6* shows this graphically.

Figure 1-6 graphical problem description



In general this problem can be stated as follows:

Problem definition:
It is unclear what the influence of imperfect traffic information is, provided by an increasing number of dynamic route guidance systems, on the general traffic performance. Thereby is it also unclear how travellers do react to such a situation and how that influences on that traffic performance. Eventually it is also unclear how this contributes to the goals RWS.

Goals
The goal of this study is to investigate some aspects of the problem defined in the previous section. There is a rather new situation where a new form of advanced travel information system (ATIS) is providing travel information and it is likely that the influence of it will be significant, as lot of travellers will use it. The question how this affects the behaviour of users and non-users and what are the consequences of that.

Goal:
Determining the effects for travellers, who make different route choices, influenced by an increasing number of dynamic route guidance systems and present the consequences of that for RWS as the national road authority.

Research questions
The picture (*Figure 1-6*) shows that there are mainly 5 directions of interest that together have an influence on the goal of the study. For further investigation these five subjects have been converted to 5 general questions the represent the problem description in more detail:

- What is the influence of penetration rates for traffic performances and what is it influenced by?
- What is the influence of ATIS in general and route information provided by in-car route guidance in particular on the traffic performance?
- Which parameters determine the user compliance and what is the effect for the all the users?
- What is the total influence of these three interacting parameters on the traffic performance?
- How does that contribute to RWS goals?

1.3 Approach

The general approach to achieve the goal stated above will be described in the next section. Therefore the goal as stated above and the general research questions are described more in detail.

In order to get a good overview on the goal in general all major parts of the goal stated should become clear, therefore all parts are elaborated more in detail. Or stated the other way around, al important parts of which the general goal consists are elaborated in detail in the next sub-sections.

Determining the effects…
In this formulation there is a very wide range of possible consequences for the processes that will be investigated. Therefore it needs to be investigated what are the effects that are of interest and more important how are they to be measured.
First of all from literature it should become clear what is likely to occur when combining penetration rates, users reaction and traffic information, thereafter a method to measure this should be provided. Of course as the combination of these three is not commonly researched on, some new approaches need to be found.

- Which effects are to be expected?
- How can these effects be measured?
- Which new tools are required in order to enclose the effects of the whole process?

…for travellers…
Eventually the travellers are those that experience the effects mentioned above. In order to not "forget" some of them, all travellers are mentioned together in the goal. This group however needs to be split up as different groups of travellers can have different demands.
In general two groups of traveller are logical to distinguish: on the one hand there is the group of users of the dynamic route guidance system, which get the extra information and via the DRGS. On the other hand there is the group of non-users, face the consequences of the actions of the of the DRGS-users.

- Which different user classes need to be distinguished?
- Is it sufficient to use DRGS-users and non-users?

…who make…
This "who" refers again to the travellers mentioned above. It implies they are not only experiencing the effects of the mentioned process but they are active participants as well. This part of the goal refers to the 3rd research question, where the influence of the users compliance is questioned.
From literature it should therefore become clear how a travellers react on traffic information in general and personal route guidance in particular, in order to determine the effects of this on the total process.

- How do users react to different forms of ATIS?
- How do users react to (dynamic) route guidance systems in particular?

…different route choices…
As shown in section 1.1 travellers have a lot of choices to make in their process of travelling. First of all this part of the goal limits the research to that last choice in the travellers' choice set: "the route choice". A reason for that is that a DRGS in particular tends to influence on route choice and besides in that part of the process all other choices have all ready been made.

- How does a DRGS influence the traveler's route choices?

…influenced by an increasing number of dynamic route guidance systems…
This part of the goal contains two of the general research questions. On the one hand it focuses of the impact of an increasing number of dynamic route guidance system. On the other hand it mentions the system for applying traffic information itself, namely the DRGS. The second research question already states that it is of importance how such a system works and what are the possibilities and drawbacks of these systems.

- What is the influence of in increasing number of DRGS's?
- What is the influence of the DRGS itself?
- How does it provide its information?
- What can be stated about the quality?

…and present the consequences of that for RWS as the national road authority…
By only measuring effects (as mentioned in the first part of the goal) there are in general no consequences drawn form what is might be occurring.
The consequences can be drawn for all different groups that are mentioned. However RWS as national road authority and thus stakeholder that serves the interests of all users together should be added to these groups of actors.

- What are the goals of RWS?
- Do the consequences contribute to these RWS goals?
- What measures should be taken to cope with negative influences?

From this elaboration of the goal, in general two main steps have to be taken; on the one side from literature it should become clear how these three interacting processes operate. From that more or less theoretical approach a better scientific insight in the processes should be obtained.
On the other hand, from those theoretical considerations a representation of reality should be made, in order the see the coherent

influences of these processes. Finally it should then be possible to make some more practical recommendations towards RWS.

Literature review

A literature review of most aspect mentioned above is required to get a better insight in the whole process of the three first general research questions. In most studies these aspects are not researched together, so the literature review will deal with these three aspects separately. Based on journals, papers and other investigations a view on the interaction of real-time route guidance, penetration rates and travellers compliance should be obtained. From that on the most important aspects should be elaborated and based on that eventually the *"effects"* should be computed.

Furthermore investigations have to be made on possibilities of several traffic models and the way they can contribute to solving the goals of this study. Finally the goals of RWS have to be described in more detail to see what are their matters of interest and where do they come from. So at the end of the literature review a more detailed methodology will be presented based on which the real solutions can be provided.

Traffic model

As stated, the effects for the travellers somehow will be determined. In order to observe effects, measurements have to be obtained. Therefore measurements on traffic need to be made, of course based on the criteria that the literature review eventually comes up with. Such measurements could be done via an experiment in real life, but as that would take a lot of time and cost a lot of money it is chosen to simulate the impact of penetration rates, traffic information via a DRGS and users reaction in a simulation environment.

The considerations, which network is needed, which criteria are needed to evaluate the performance and some other choices that have to be made will explained also at the end of the literature review.

Limitations

Within the approach described before a lot of directions for investigation are open. Therefore a few limiting assumptions will made within the next sub-section

The influence of penetration rates

Penetration rate seem a straightforward parameter. This parameter determines the level of equipped travellers. However not every equipped user necessarily uses the device. It might be turned off or operating without the user paying attention to it. A basic assumption that is made is that whoever has a device, does use it. So the number of devices in the system is equal to the number of active devices. Of course people can choose to neglect the advices but that deals with the compliance of the users. In chapter 3 that reaction of the user will be elaborated more specifically.

- The penetration rate (percentage of DRGS) and the percentage of devices used are equal.

The influence of traffic information

The influence of information is very much depending on the type and level of information that is given. For this study the focus is on traffic information via dynamic route guidance systems and therefore the investigations should be as close as possible to that sort of information systems. Of course improvements can be made in providing traffic information (for instance by predicting it) or having several sources of traffic information combined, but that would make the study too complicated. So only one type of traffic information is used and that is de DRGS. Although within the possibilities of the model the influence of the information quality will be investigated.

- The current level of providing traffic information via dynamic route guidance systems will be a fixed and only input parameter for providing traffic information in this study.

The effect on the users reaction

Users can act very differently on information provided as they have a large number of choices as mentioned in the introduction. This leads from the choice whether or not to make a trip to the choice of the route. The focus will be on the last choice option as that is typically the choice that is influenced via a dynamic route guidance system.

- Focus on only route choice
- No influence on departure time choice or other choices taken into account

Traffic performance

A very wide range of variables influences the traffic performance. Of course there are the above-mentioned three specific variables. But also the layout of the network, the influence of other DTM applications and differences in transportation patterns do influence on the way traffic "performs". For this study all these other aspects are considered to be fixed network properties, but their influence might still be significant. For the study an appropriate fixed network with fixed parameters and a fixed transportation demand will be chosen.

- One fixed network with fixed travel demand
- Network configuration itself like will not be taken into account, that implies that the next 3 aspect are no subject of investigation
    - Route choice locations
    - Locations of bottlenecks
    - Size of the network
- Other DTM applications will not be taken into account
- Differences in transportation patterns will not be taken into account

Contribution to RWS goals
As mentioned in the "nota mobiliteit" [2] there are a lot of goals RWS tries to achieve when improving on traffic performance and a lot of these can be influenced by dynamic route guidance. However the focus will be on the traffic efficiency.

- Focus on traffic performance and efficient choices
- The impact for the environment will not be taken into account.
- The impact on safety will not be taken into account.

1.4 Outline

After this introduction, in chapter 2 the main theoretical aspects on which the rest of the study will be based are being described and from that point of view the direction for the rest of the study will be presented. Chapter 2 will end with the description of the methods to be used in the rest of the study. The 3rd chapter shows the basic structure of the model that has been developed to investigate this topic. Chapter 4 will show validity of that model. In the 5th chapter the results of the model are presented. Finally in chapter 6 the conclusions and recommendations for RWS will be presented.

2. Theoretical background

In this part the theoretical interaction between penetration rates, traffic information and user compliance will be described. The interacting triangle, as presented in the problem description, can be described in more detail as shown in *Figure 2-1*.

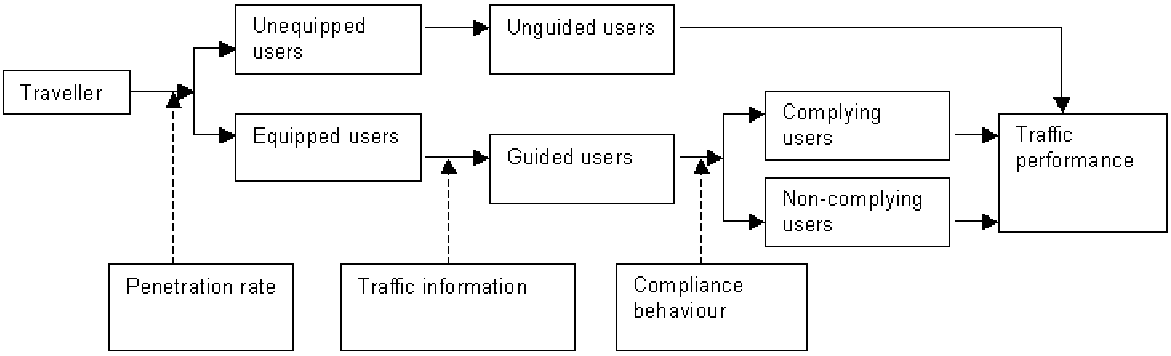
From that figure it can be seen that it is the penetration rate that divides the travellers into two groups, either equipped or unequipped users.

By providing traffic information to the travellers via a DRGS, a distinction is created between guided and unguided travellers. Of course unguided travellers can receive traffic information, but not as detailed and *prescriptive* as via a DRGS. The general information an unguided traveller gets is usually *descriptive*, which means that travellers have to find out themselves what to do with it. For instance when a traveller listens to the radio and receives information about queue lengths he has to elaborate himself how to cope with that information. When traffic information is added to a DRGS, travellers are given a route advice, which means the travellers are told how they can act best according to the information. This *prescriptive* information guides the traveller through the route choices he has to make. So in this case, where a DRGS is involved, the provision of traffic information creates a distinction between guided and unguided travellers.

Finally the willingness to act according to the *prescriptive* information determines whether the travellers comply or not with a route advice given. All these three steps lead to a traffic situation where unguided (perhaps even uniformed) travellers, guided and complying travellers and guided but non-complying travellers interact and experience the effects of their behaviour in a traffic situation. In general this process can be seen as in *Figure 2-1*

Within the next sections the theory behind these 3 main aspects (penetration rate, traffic information and compliance behaviour) will be presented.

Figure 2-1 general process of penetration rate, traffic information and compliance behaviour



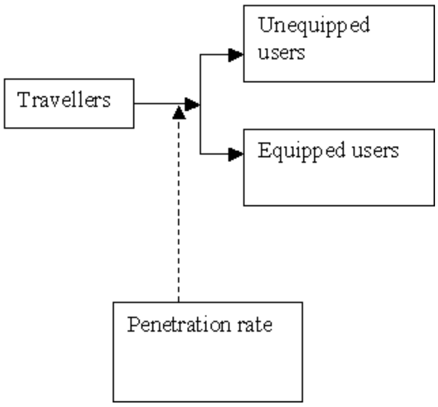
The beginning and end of the process
The scheme (*Figure 2-1*) starts with the traveller, who has of course a lot more options (choices as mentioned in the introduction) than only choosing between different routes, but for this study we don't take the other choices into account as mentioned in the approach. So a traveller has a fixed origin and destination, a fixed modality and a fixed departure time. Of course different travellers can have different origins and destinations or departure times, but it will not be a choice option for the individual traveller.

The same holds for the end of the process, traffic performance is influenced by much more than travellers' reaction to information. Other aspects like different network configuration, different DTM measures etc. do influence travel performance and therefore one should be careful when attributing all results to the penetration rates, traffic information or compliance behaviour.

2.1 Penetration rates

In this section the questions will be answered of what is the influence of the penetration rate and which subjects have an influence on the penetration rate itself.

Figure 2-2 influence of penetration rate



The influence of penetration rates
Figure 2-2 (which is the first part of *Figure 2-1*) states rather straightforward that the penetration rate does determine whether a vehicle is equipped or not. So the higher the rate becomes the more travellers that become equipped. On the contrary to that easiness, the effect of penetration rate is quite difficult to measure, because the process can only be measured by the effects on the traffic situation (which is the end of the process, see *Figure 2-1*). Sometimes the effect of increasing or decreasing penetration rates is combined with the effects of informing the travellers with different information and their reaction to it. By doing so the effects of all three aspects are incorporated together. So it is important to be aware of this, especially because it is difficult to measure the effects of all separately.

The influence on penetration rate

If possible it would be interesting to see what is a more or less realistic penetration rate, and which factors do influence that rate. It seems logical that the number of route guidance devices that are sold influences the penetration rate. The more people buy a route guidance system the higher the rate of penetration becomes. Then the question turns up: why do travellers buy a route guidance system? From utility perspectives it can be stated that travellers buy a route guidance system when their benefit in terms of travel time savings is higher then the costs of a system. This is shown in *Figure 2-4*.

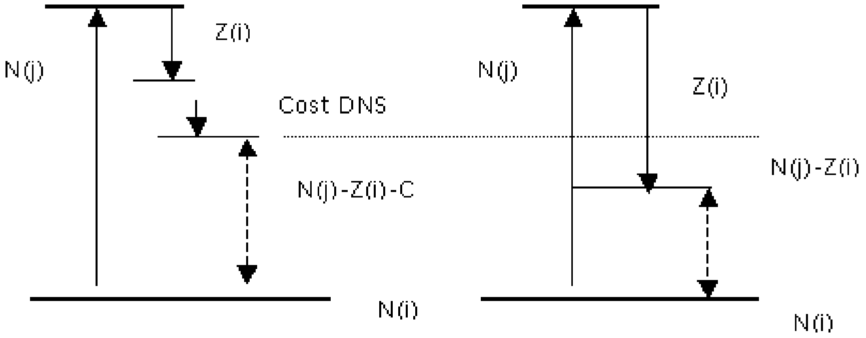


Figure 2-3 Utility of travelling with a navigation system (left) versus travelling without one (right)

A study is performed in which the average of time saving for travellers equipped with a traffic information device is compared to those of non-equipped travellers [8]. For certain levels of costs that leads to different optimal penetration rates. Besides that it is stated that penetration rate is not a fully exogenous parameter. Or stated the other way around: the rate of penetration is influenced by itself via some economical process and the system characteristics.

So the time saving for equipped travellers is depending on the amount of equipped travellers and it is likely that the benefit for each new equipped traveller is less then the previous one. From general economic theory the *law of diminishing returns* [9] is then applicable, which states that every new single product (or traveller in this case) has less profit than it predecessor. This means in this case that the more people who have knowledge about the traffic situation, the less their individual profit becomes. The two figures below *(Figure 2-4 and Figure 2-5)* show the effect of this theory, which results in a decreasing profit for every extra traveller. First the profit for every new user is less than its predecessor but the overall profit is increasing. In the second case even the total utility decreases and adding an extra unit wouldn't make any sense.

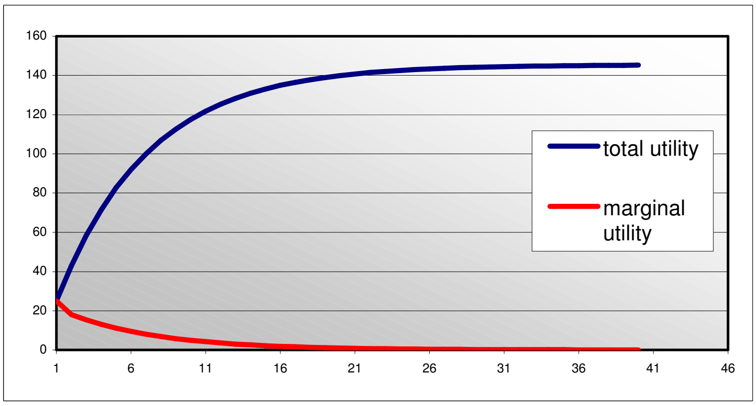
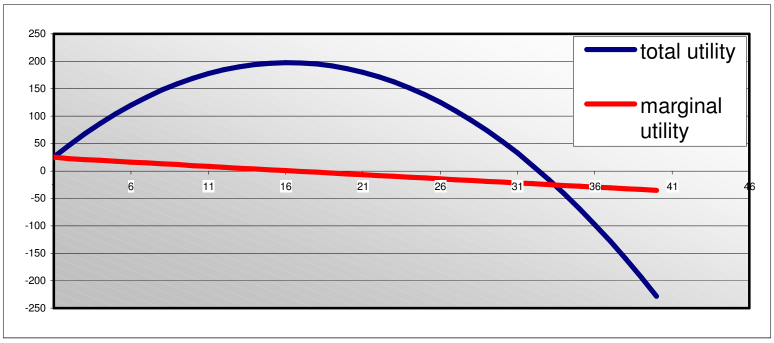


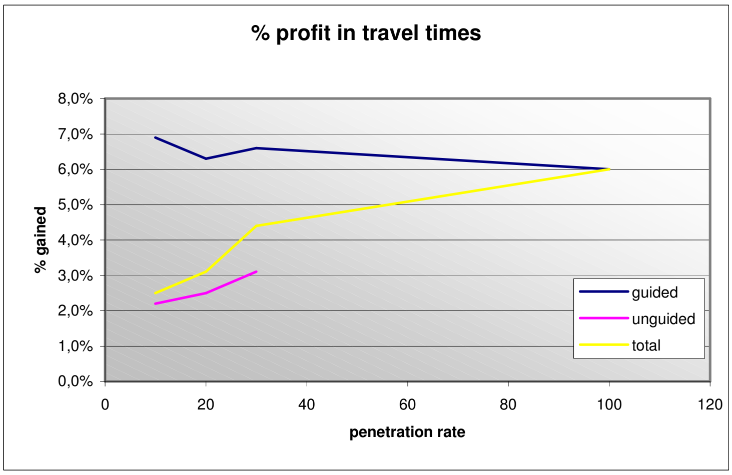
Figure 2-4 law of diminishing returns with an overall increasing profit

Figure 2-5 law of diminishing profits with first an increasing later on a decreasing profit



Another study is performed to determine the influence of penetration rates for some sort of route guidance system [10]. The difference is that in that study some sort of managing system elaborates the traffic information in order to let travellers make better decisions. Of course for a system without such a "traffic supervisor" the benefits are likely to be less. One of the most interesting results would be the percentage of penetration unto which an autonomous system can perform well and from whereon a supervising system should take over.

Figure 2-6 percentage of travel time profit according to "autoguide" study



Furthermore in literature quite some investigations are performed to get a quantitative view on these penetration rates. It is stated that only in case of perfectly predicted travel information the users optimum can be reached with a penetration rate up to 100% [11]. When information is less perfect the optimal rate will decrease. Up to a market penetration of 30% there is on average a travel time reduction from 10% to 20% for al travellers [12]. Furthermore from these investigations it is concluded that when the penetration rate exceeds 50%, average travel time seem to increase, so the situation becomes worse for all travellers. It should be mentioned that these resulted are based on a general ATIS and in a period that traffic information was less accurate then it is right now, but it is a good indication of where the above-mentioned turning points can be expected.

Impact on this study

For the study this implies that different penetration levels should be used, preferable in the range of the studies mentioned to see what is their effect. This will lead to preferable (more or less optimal) penetration rates.

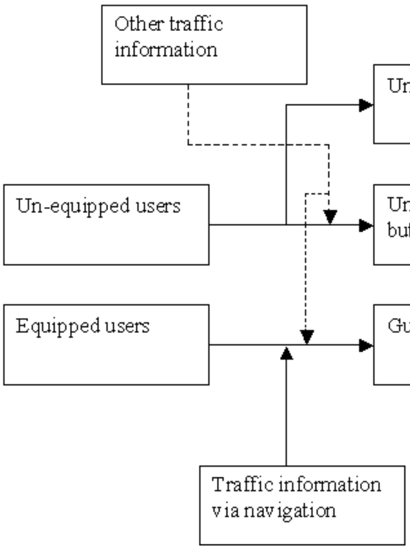
- Different penetration rates should be used to see the influence of equipping more and more travelers with a DRGS

2.2 Route guidance via dynamic route guidance systems

As mentioned in the introduction dynamic route guidance systems are a rather new form of ATIS that try to improve the route choices that travellers make. Right now 3% of the traffic uses route guidance systems to get informed on the traffic situation [13]. This implies that also some new methods have to be found to cope with these systems when modelling and simulating traffic.
Figure 2-7 shows that in general three groups of users can be distinguished after the general step of information input:

- Guided and informed travellers
- Guided and uninformed travellers
- Un-guided but somehow informed travellers (e.g. via roadside information systems)
- Totally uninformed travellers

Figure 2-7 influence of a route guidance system



In most traffic models, (groups off) travellers choose their routes mostly on the base of shortest travel time combined with some sort of (logit) route choice model. In these models it is likely that a traveller chooses the shortest route but also have a chance to choose another. On the contrary to such a system the equipped travellers now have access to the dynamic route guidance system and will react to that.

The route choice based on such a logit model is rather fixed and mostly doesn't change over time, a traveller determines a route when entering a network and once a route has been chosen a traveller stays on that route and doesn't change it anymore. So by using such a model only pre-trip route choice is taken into account. In case of dynamic route guidance at every moment (or at least choice-moment) the route can be reconsidered. This implies that besides pre-trip route choice, also en-route route choice is incorporated.

Influence of traffic information

Like the influence of penetration rates the influence of traffic information is rather clear. It basically provides the equipped user with traffic information on which DRGS bases a prescriptive route advice and finally the traveller has to decide how to react. (Which is elaborated in the next section about compliance.) On the contrary it seems obvious that the non-equipped users stay unguided, but mostly will somehow be informed. (With descriptive information)

Influence on traffic information

In general there are a lot of aspects that influence the quality level of the traffic information and thereby the route choice of travellers. Basically five different aspects can be mentioned which determine this level.

- The moment of providing information.(Section 2.2.1)
- The difference between general or personal information. (Section2.2.2)
- The difference between static or dynamic information. (Section2.2.3)
- The accuracy of the information. (Section 2.2.4)
- Aiming for a system or a users optimum. (Section 2.2.5)

2.2.1. Pre-route versus en-route information

A difference that has to be made is the moment of providing traffic information. As mentioned before, most of the traffic models determine the route for a traveller in advance of the trip. Most of the travellers themselves do the same; they determine a route, which they would like to follow. Most of the time this initial route is the habitual route, a route that the more frequent traveller usually takes.

For some travellers the interaction with information supply then stops. They stay on their initial route and don't get (or listen to) any further information. However most of the travellers do receive additional en-route information and are reconsidering their routes all the time. It is nevertheless shown that even in a severe congestion only 7 percent of all travellers does change its route to take an alternative route [29]. Thereby it is not know how many travellers are informed (pre-trip or en-route) but only the effect 7% changing its route is measured.

The en-route information can be provided via roadside systems that are fixed to certain location along the network, radio, but also via in-car devices that provide information everywhere the traveller is situated. A dynamic route guidance system is typically such system that gives the traveller at every location a route advice.

2.2.2. General versus personal information

The second aspect that influences the traffic information is the difference between personal and general information. The mentioned roadside systems such as DRIPs and VMSses, but also radio etc. are *general* information systems, which provide all users with the same information. Mainly that is descriptive information, like traffic queue lengths or sometimes travel times, only in a few cases a general system produces descriptive information about which route to take. Mainly information is collected at a central traffic centre and then transmitted to the general systems not concerning the individual needs of the travellers, so the travellers themselves have to consider how to act according to the information.

On the other hand there are the systems, which give individual information to every single equipped user, although it is based on general input. Most of the time this information is prescriptive as the system knows its location and the destination and thereby can determine an individual (prescriptive) advice. RDS-TMC and the new dynamic route guidance systems based on MTS do so.

When obtaining general traffic information (descriptive) one can easily neglect the information and act different, but for a route guidance system a traveller has paid and the information is personal so the level of influence is likely to be higher, compared to general ATIS. It can be concluded that when personal information is added the response is larger than in case of general information. In case of individual information 34% changes their route compared tot 22% in case of general information [14] [15].

2.2.3. Static versus dynamic information

The most common versions of route guidance systems are static systems. They show routes based on some sort of shortest path algorithm without taking into account what is actually happening on the road [6]. It can be shown that the improvements that are made by these static systems are significant. People take shorter routes (16% shorter on average) and save travel time (up to 18%). The advantage of dynamic systems is that it takes into account the traffic information in advising on routes and thereby can have even a larger profit.

In general dynamic systems do of course already exist but most of them are mainly non-personal systems that provide general information on main routes. So its advice is not receivable at all locations (DRIPs can only be read at the location where they are located) and is not a personal advice (it doesn't know your route). Besides not all of the dynamic systems are applicable for en-route route choice.

Some systems that do provide dynamic information are for instance:

- Traffic information on radio
- Internet sites
- Teletext
- DRIPs

Dynamic personal en-route traffic information

Besides the dynamic route guidance systems based on MTS there is one other system available that also combines the three above mentioned aspects to one device and thereby becomes a dynamic personal en-route route guidance system, this is the route guidance based on RDS TMC.

The difference between both systems is the information it bases the advice on. RDS TMC advices are based on the traffic information of the Dutch traffic information centre (VCNL), which gives traffic information in lengths of traffic jams. MTS data is measured in travel times and results in average speeds as input data for the DRGS.

A drawback of the RDS TMC data is that only information is given on those locations where actual traffic jams are measured (mainly highway network) and other roads are not included. Besides that the lengths of traffic jams don't say so much about travel times. The MTS service on the contrary does measure on all location where there are vehicles, which is of course beneficial however only if the accuracy of the information is good enough.

2.2.4. Accuracy of information

Providing a dynamic personal en-route route choice advice, based on somehow measured travel times is very time dependent. Especially the use of real time traffic information in providing input for the DRGS is complicated, as the situation can change rapidly especially in congested periods. In general there are three time-based matters that influence accuracy of the information.

- Time dependency of measuring data
- Computation time of travel information
- Time dependency of predicting travel times

Measuring data

In general there are 2 types of acquiring traffic information. Data can either be collected via local roadside measurements, or non-local by following the cars themselves. Systems that collect data via local measurements are for instance:

- Camera's
- Detection loops
- Radar systems

Such systems mainly present an overview of the state of the network at the measuring locations. In general every vehicle is detected once via these systems. For locations in between these measurement locations estimations can be made.

There are also systems that measure local but as different local measurements are combined more detailed information about the vehicle and the network can be obtained.

- Two (or more) camera systems that follow a car through a network

On the other hand there are systems that collect data via non-local measurements by "following" the vehicles (floating car data). These systems are for example:

- MTS data
- "Real" floating car data where data from inside a vehicle is returned to the measuring system. (Like returning positions based on the GPS)

These systems collect individual data, which has to be averaged over all measured vehicles to get an overview of the network. Of course it is possible to combine and elaborate several sorts of measurements (data fusion).

The advantage of local measurements is that every car is detected, and so a big sample size is created, which make computations more reliable. Furthermore the date is instantaneous, at the moment of measuring the situation is as it is measured. The disadvantage is that it is information that is collected at the locations of the equipment and not in between. So for the situation in between assumptions have to be made. That holds also for the computation of for instance the travel times. Besides that the equipment has to be built in or aside the road and also needs to be maintained, which makes it an expensive method.
Those disadvantages are on the other hand the main advantages of the car following systems. Typically in case of MTS data, data can be collected everywhere in the network and so on all locations in the network a traffic state can be acquired. And, as it is executed by measurements of cell phones, which are already available, the system is not so expensive. However as not all vehicles are followed, not all travellers are included, so the data is smaller as in case of local measurements, but when the number of counted travellers is large enough, that should not be a problem. A larger drawback of these car following systems is that travel times, which is the variable that is in general measured by these systems, are only measured when a car has completed a certain path. This means that the measured time is always outdated and an average of what happened in between the last measurements. (*See Figure 2-8*) What is measured is a realized travel time, which is significantly different from an actual travel time. [16]

For instance if a car travelling from A to B is considered and it is measured at A at t=0s. When it is measured at B at t=60s, it is easy to compute the travel time (60s.). This can only be measured when the car has arrived at B and is not travelling on the considered part of the network anymore. So the actual travel time of a vehicle leaving from A at t=60s. is likely to be different from the measured travel time at t=60s.

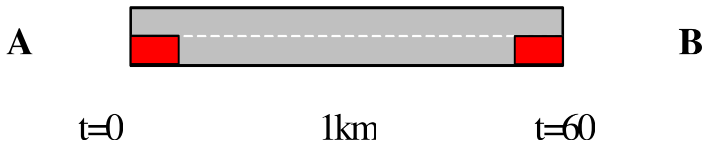
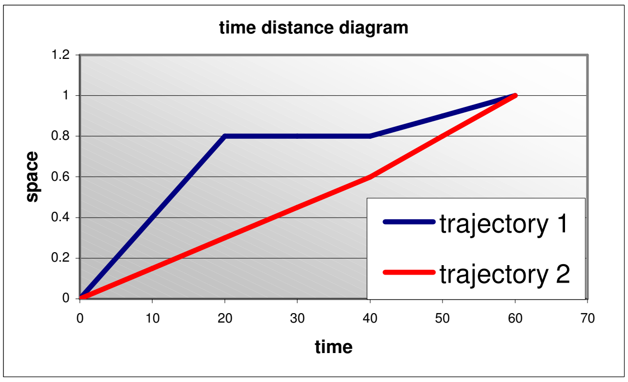


Figure 2-8 Example of travel time measurement

In general this way of measuring is always half the time interval late with the measurements. Of course the bigger the time interval becomes the larger this disadvantage becomes.

Furthermore a difficulty is that a measurement is an average. There are lots of things that can happen in between measurements. For example both the trajectories in *Figure 2-9* lead to the same average travel time but have a very different path. Of course for the eventual measured travel time this doesn't make a difference, but for a good view of what is actually happing on the road (vehicle 1 is not moving for a while) measuring in this way has some drawbacks.

Figure 2-9 different trajectory can lead to same travel time



Several studies already have been performed and they show that there are indeed doubts whether the data provided by MTS is the best base to found traffic information on. It seems that MTS data consequently overestimates the average speeds especially in congested areas, which is likely to give travellers a too optimistic view on their alternatives. [16] Furthermore it could be stated that instantaneous data travel times based on Monica data via Monibas (the loops in road) is more accurate then MTS data. [17] It should however be stated that it is likely that the accuracy of the MTS data will increase within the next years, as it is still under development.

Computing travel times

Besides this time loss at the measuring of travel times, there is also a loss while computing the travel-times for the travellers. All the different information of the single phones and/or single loops has to be collected and elaborated to obtain a total view of the state of the network. That again must be transmitted to the route guidance devices in the individual vehicles or the roadside signals. It is obvious that these steps take some computation time and that the travel times created, cannot be considered as instantaneous as one would like.

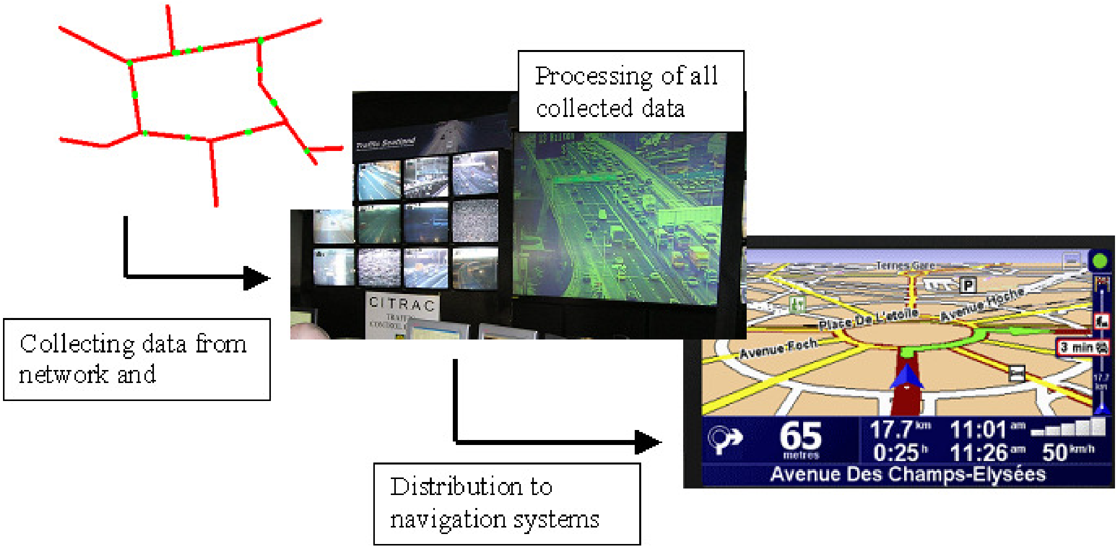


Figure 2-10 Processing of measured travel times

Predicting travel times

In addition to the above-mentioned time losses in time, which influence the instantaneousness of the input data for the route guidance device, there is another aspect that should be considered. When route choice advice (based on the computed travel times as shown above) is given at the current moment, the car has not entered that part of the network that the traffic information is about. So the information influences the trip a traveller is going to make. It is likely that the traffic situation will change in time and the traveller will encounter another situation, compared to the information that the route guidance system has based its advice on. What the route guidance systems basically does is an extrapolation of the measured situation to the future and assume that is stays the same. Of course this is not directly wrong, as people still can make the right decisions, but one can image that when trips get longer and the different routes are not so exchangeable the consequences might worsen and it might turn out that a traveller should have taken a different route at the end. Of course it would be best to predict, or at least estimate the future state of the traffic network somehow, but then one has to know where all vehicles are going.

It could for instance happen, when "predicting" the future to be the same as the current situation until it is measured different, that the traffic system starts oscillating, because it is reacting on consequences of its on advices. That can typically happen in case of two good exchangeable routes, where a significant number of travellers are willing to act according to the advice. This oscillating behaviour can cause significant time losses. [11]

2.2.5. System versus users optimum

The general goal of providing traffic information is to let travellers make better choices and reduce the disadvantage of travelling. There is however a big difference in the way that can be achieved. On the one hand every single traveller can be guided to the individual best route. As all travellers do so they might be hindering each other when all travellers apart try to optimise their route individually. On the other hand one (in this case RWS as the road authority) can try to force the traffic in such a way that the disadvantages are less for all travellers combined.

The result of the first option, the users optimum, can work counterproductive, when large numbers of travellers are trying to optimise individually. Therefore a general controlling system that strives to a system optimum is probably more preferable. Such a system would guide all travellers and controls the total traffic system. By doing so usually a better optimum can be achieved.

Impact on for study

For this study the influences mentioned in the previous section mean that a distinction has to be made between the different types of informed users there are in the system. As the equipped travellers have the route guidance system to base their choice on, also for the non-users a choice behaviour should be created. They also do receive some information or no information at all, but they have to make a route choice.

Also the DRGS should be modelled in such a way that it can at all moments (pre-trip and en-route) provide personal, (based on a travellers own O-D) dynamic traffic information, such that it works the way a dynamic route guidance system does. It should also be taken into account that the information, on which the dynamic route guidance system bases its advices, is imperfect (measured and not actual). For example a time slack can be added to the travel times to create the effect of the travel times not being actual. It might also be a good option to apply a measure that drives the system more to a system optimum, in case the effect of people individually trying to optimise their route is causing big disadvantages.

- Route choice for both users and non-users needs to be determined. Groups of informed travellers.
- Pre-route versus en-route information should be possible.
- A The DRGS should provide personal information based on general measurements.
- The fact that the measured travel times are that bases for the DRGS should be incorporated
- The impact of measured travel times instead of actual travel times are used should be incorporated and elaborated.
- Distinguish what is best for the users and what is best for the system.

2.3 User compliance

Probably the most difficult part of this project is to grasp the behaviour of the users. In general one might think that travellers tend to react rather random on the traffic situations they encounter and the provided traffic information they are provided with. However as most travellers are “bounded” rational people there must be some reasoning behind their choices. Therefore in these sections the reaction of the users to traffic information will be described.

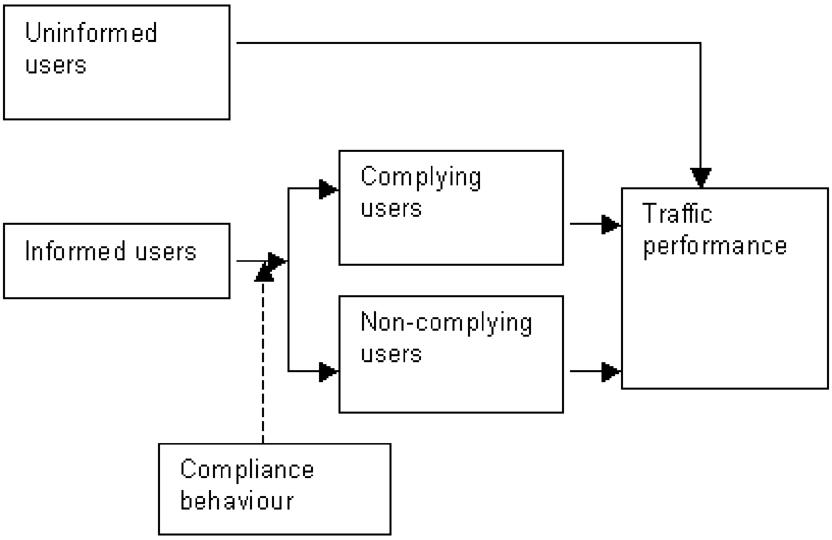


Figure 2-11 Influence of user compliance

Basically the result of adding compliance to the system can be described as people either changing or not changing their routes according to the information they get and thereby influencing the network state in a certain way. Most easy would be to model this compliance behaviour as a sort of black box, that lets a percentage of travellers change their routes, given certain information. This of course would not per definition be wrong when the percentages are checked and compared with reality. An experiment for instance can provide good information on how (groups of) travellers react in different situations according to different information. That could than provide the desired compliance percentages.
Another trivial option would be to let all travellers' changes their routes according to provided travel information (which implies 100% compliance). By doing so one gets only insight in the interaction between penetration rates and information level, which is worthwhile and should be one of the scenarios, but the influence of the travellers themselves is then neglected.

To provide this insight into the behaviour of the traveller, it should be modelled more in detail. Therefore it is worthwhile the take a view from inside the travellers perspective and see based on which aspects choices can be made. 5 different aspects can be mentioned to describe the compliance behaviour [18].

- Quality of advice
- Previous advice
- Familiarity
- Other information (corroborating or contradicting)
- Personal characteristics

In general these aspects can be divided in three directions of influence that determine the behaviour of the traveller. First there are the properties of the user, these parameters determine preferences of the traveller. For instance whether or not he has the natural tendency to comply in his character. Second there is the type of information that the traveller gets. On the one hand there is the information of the DRGS, but also via other purposes and the interaction with other cars travellers gain information. Third is the learning process of the travellers; from previous trips the travellers know how to react to the information and the possibility recognise repeating situations. (Familiarity) That would lead to the following division:

- Difference in types of characters (natural willingness to comply)
- Reliability of the information (determines how the traveller weights the information provided)
- Learning based on previous trips (experience on choices made)

Adding these 3 aspects to the scheme of *Figure 2-11* leads to the figure below. (*Figure 2-12*) From this perspective there are three directions of interaction that need to be investigated on.

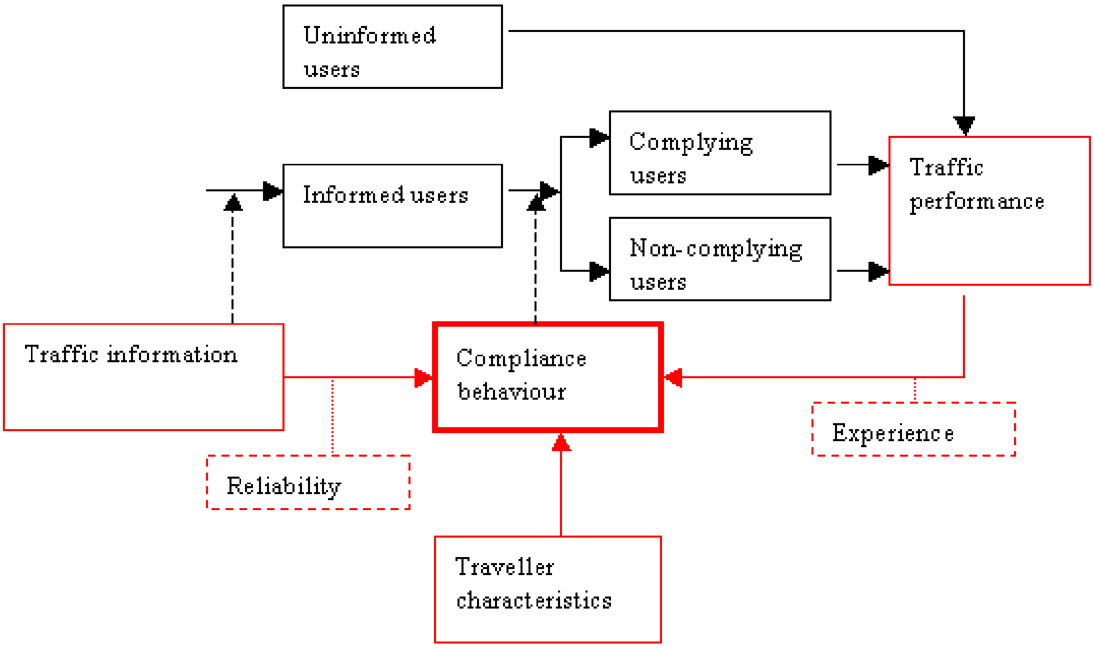


Figure 2-12 Influence on users compliance

2.3.1. Influence of characteristics on compliance behaviour

In *AVV (2002)* a survey has been performed to get in insight in the different characteristics of the travellers. Here 6 different types of travellers are presented based on characteristics of the traveller [19].

- 26% Purposeful travellers (tend to drive as efficient as possible)
- 17% Conscious travellers (tend react according to social welfare)
- 17% Enjoying traveller (basically doesn't care about anything)
- 14% Performance driven travellers (likes to be the smartest traveller of all, without paying for it)
- 15% Accepting travellers (they take it as it is and don't seem interested in improving)
- 11 % can't be divided in one of these groups

Although these groups give a good description of the composition of the traffic it is rather difficult to identify one individual traveller of these groups. So another more common subdivision is made which represents 4 different user classes that include all these different groups.

- Commuters
- Incidental (or event) travellers
- Freight traffic
- Business travellers

For three of these four groups the reaction on travel information in general is measured, so this includes the whole set of choices a traveller has. [13] For this study of course the reaction on route choice behaviour is important, but it is obvious that there also is a relation to departure time choice, mode choice and even the decision to make a trip or not. In the table below the percentages of travellers that sometimes do change their routes based on travel information are given. It should be mentioned that within the sources of information (DRIPS, radio, teletext etc) personal dynamic route guidance is a very small fraction (3%), so it is likely that percentages might increase, especially because also one of the conclusions of this report is that there is a need for more actual traffic information, like for instance dynamic route guidance systems.

Table 2-1 travellers changing there routes according to [16]

	moment	
travellers	pre trip	en route
commuters	22%	45%
incidental	<5%	6%
Long distance	-	-

Even in more detail, an effort can be made determine the influence of characteristics of the traveller. [20] In a large survey, characteristics like gender, occupation, income and age are related to different types of traffic information. The major results are that young drivers with flexible working schedules have increasing probability to take alternative routes and female travellers are more likely to remain on the same initial route compared to man. It is however questionable whether or not such results can be incorporated in a study as this.

2.3.2. Influence of traffic information on compliance behaviour

For this study it is the information of the dynamic route guidance system that is most important aspect on which a traveller bases the decisions. However it is likely that real travellers base their decisions on more types of information. (Of course non-equipped travellers also gain information somehow.) If for example travellers see actions of other travellers in their surrounding they might choose to do the same or act opposite. (Probably according to the properties of their character) Furthermore based on other ATIS they might be able to value the information of the dynamic route guidance system.

The behaviour of travellers according to information was investigated in a stated preference experiment in case of unexpected congestion. [20] In this study 5 different types of information, given to the travellers, were investigated (via different types of ATIS):

- Qualitative delay information (congestion or not)
- Quantitative real-time delay information (current delay on a route)
- Quantitative real-time delay on best alternative route (current delay on alternative route)
- Predictive real-time delay information (expected delay)
- Prescriptive best alternative route (route guidance without delay information)

The reaction of the users to these types of information is also given in 5 categories

- Definitely take the original route
- Probably use the original route
- Definitely take the best alternative route
- Probably take the best alternative route
- Cannot say.

The reaction: "prescriptive best alternative route" and "predictive real-time delay information" are from these 5 types of information the two that describe a dynamic route guidance system best. The " prescriptive best alternative route" states the best alternative route for a traveller, which a route guidance system in general does. The "predictive real-time delay information" determines the expected travel time compared to a free flow travel time, which most DRGS's do predict as well. For these two ATIS's the results are as follows (*Table 2-2*)

Table 2-2 travellers reaction on different ATIS according to [22]

Behaviour	ATIS	
	Predicive dealy	prescripive route
Definately take usual route	9.3%	6.3%
Probably take usual route	16,0%	13.9%
Definately take best alternative	41.3%	53.2%
probably take alternative	29.3%	22.8%
cannot say	5.3%	3,8%

As to be expected most of the travellers take the alternative in both cases of information, but it is remarkable that a significant percentage of travellers does take the initial route or at least consider taking the initial route when they are advised to act different. Of course these are results for a study in Brisbane (Australia) and local influences might be a major reason for these results, but in general it can be stated that there is a significant amount of travellers neglecting the advices.

2.3.3. Influence of experience on traveller's compliance

It seems obvious for this part of the compliance behaviour that a traveller has to make more trips within the considered environment to gain any experience. In general it can be stated that after every trip a traveller updates the experiences parameters on which, for the next trip(s), the route choice will be based. It is difficult to capture experience in one variable as a traveller can learn a lot within several trips. In the next figure this learning process is scheduled.

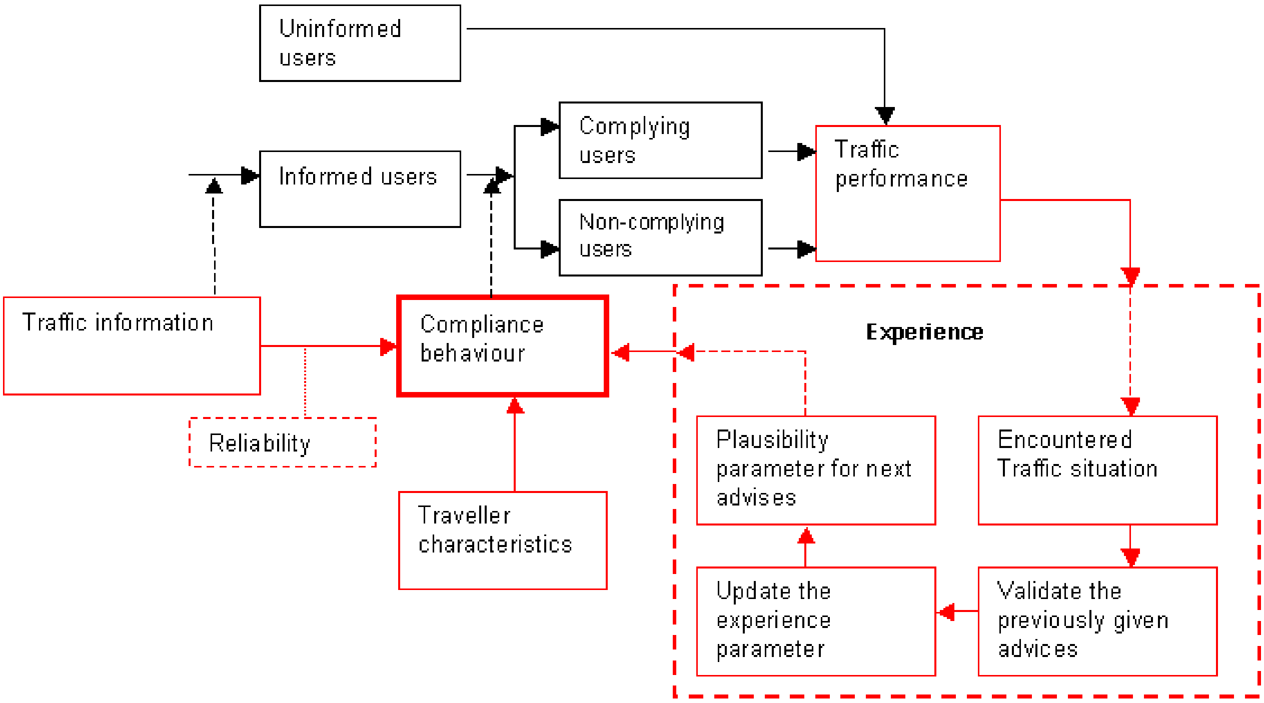


Figure 2-13 Influence on users compliance

Encountered traffic situation

A traveller will, when the desired destination is accessed, somehow evaluate the trip. To do so the traveller has to obtain information about the result (performance) on his own trip but also on possible alternatives. By measuring the travel time, the length of the traffic jams encountered and probably even other parameters a traveller can get that feedback.

Correctness of the advice

A traveller can learn about the correctness of the dynamic route guidance system, by comparing the encountered traffic situation to the in advance expected situation. A traveller can question himself if the DRGS at the end gave the best route advice and if the predicted travel time was right. Every single traveller has a certain error acceptance for the encountered traffic situation? So when a traveller reaches the destination a comparison can be made between experienced and expected travel time and if possible the time on other routes.

Another aspect is the number of route changes a traveller gets. Every time the route guidance system changes its advice a travellers knows that the previous advice would have been wrong. To verify the route guidance advice afterwards there are a couple of parameters applicable:

- Check whether the chosen route was the best route in the end.
- Check whether the "predicted" travel time is achieved.
- Check the total number of route changes during a trip

Learning process

It can be shown that travellers can learn about the traffic situation in general, get acquainted to situations and improve on route choices trip by trip. [21] It can be seen that for four different classes of equipped travellers an improvement is created for every new trip made, both for the groups using ATIS and the non-users. In general it is concluded that both equipped en unequipped groups profit from learning about the situation. This does imply that both equipped and non-equipped travellers do increase their experience after every run to perform better next time they make a trip.

The problem with this learning aspect is that more runs with a model have to be made to provide the travellers with information to base experience on. A traveller has to build a sort of database with information of previous trips. A way to tackle that is to let more or less identical users share the same data in building up experience. However a problem with doing so is that the encountered traffic situation is very much dependant of moment of the trip.

Plausibility of the next advice

By getting familiar to the network, the possible route advices and the results of previous trips, the traveller is more able to value the plausibility of the current advices. When for instance the route guidance systems guides the traveller trough the inner city, the traveller might consider that as an implausible advice because he is familiar with the problems of that route and at least tends to know better then the route guidance system that only uses average speeds. So based on experience a trade of is made to either comply or not.

Impact on this study

From the different studies parameters have to be chosen to simulate the travellers behaviour based on their character, the type of information and their gained experience.

It is very useful to use different types of users like commuters and long distance travellers, which as group tend to have the same sort of behaviour. Furthermore based on the performance criteria of the route guidance system (like correctness of the route) the experience of travellers has to be built up so they can verify the next situation. Of course more or less similar travellers can in a micro simulation use each other's experience to more rapidly increase their knowledge about the network. When the model will be presented the implementation of users behaviour will be described more in detail, as this is very depending on the possibilities of the model.

- How do non-complying travellers choice.
- Incorporate different users types with different characteristics
- Learning behaviour
- Reaction on traffic information

2.4 Model choice

In order to see what is the influence of the mentioned aspects in the previous three sections, it should somehow be checked how travellers or vehicles perform when these aspects are changing. To do so an experiment can be performed to see how travellers act in reality, however in this case it is chosen to use a model that simulates traffic and travellers and is capable of changing the variables mentioned in theory.

In general there are two options to simulate the mentioned aspects. An existing model can be used and should be adapted, such that it can incorporate the required aspects, or a new model should be developed such, that the required aspects are implemented.

Requirements

It is therefore important to investigate on the requirements for a model more in detail. From the previous sections the following characteristics for the model are demanded.

- Variable penetration rate
- Distinction between DRGS-users and non-users
- En-route route choice for DRGS-users
- Pre-trip route choice for all users
- Route choice based on individual routes
- Include influence measured travel times
- Include travellers reaction to traffic information (users and non-users)
- Incorporate different users with different characteristics
- Include learning behaviour

Besides those aspects there are some other preferable aspects that a model should contain.

- Possibility to determine and implement performance criteria
- Good representation of traffic characteristics like:
    - Queue spillback in this case
    - Microscopic interaction
    - Macroscopic interaction
- Trip generation
- Availability of existing (often) calibrated networks
- Dynamic traffic demand

In *Table 2-3* for al these criteria it is shown how those criteria are valued case of a new model is developed and in case of an existing model is used. It can be concluded from *Table 2-3* that developing a new model is a better option compared to using in existing model although the difference between both is small.

Table 2-3 criteria for model choice

Criterion	create new	use existing
Variable penetration rate	+	+
Distinction between DRGS users and non-users	+	+
En-route route choice	+	+/-
Pre-trip route choice	+	-
Individual route choice	+	+
Inclusion of measured travel times	+	-
Inclusion of travellers reaction to traffic information	+	+/-
Inclusion of different caracteristics	+	+
Inclusion of learning behaviour	+	-
Possibility to implement perfomance criteria	+	+/-
Spillback	+/-	+
Mircoscopic characteristics	-	+
Marcoscopic characteristics	+/-	+
Trip genration	+/-	+
Availible networks	-	+
Dynamic demand	+	+

+ = possible
+/- = difficult
- = not availble

The first option, using an existing traffic model would be most preferable, as the way traffic performs is already implemented and calibrated. So the way traffic is treated is more realistic and more detailed in its use. Besides lots of data output and input variables are already available. When satisfying the demand for a dynamic and microscopic way of modelling the traffic, there are in general two models available that satisfy that demand, Vissim and Paramics.
However on another aspects, like the (en-route) route choice and their learning and complying aspects, their options are limited. In both cases it would take some effort to implement a system that could simulate the working of a dynamic route guidance system. Therefore it is chosen to develop a new traffic model that is capable of all required aspects for this study.

In order to get a rough idea of the influence of all the aspects mentioned in theory a small model, within the mathematical programming tool “Matlab”, has been developed. In general that model turned out to be quite familiar with another traffic model called Dynasmart. [22] (DYnamic Assignment Simulation Model for Advanced Road Telematics) Dynasmart is a microscopic model (it considers individual vehicles) that makes computations based on macroscopic network parameters. In that way one of the main drawbacks, namely that the model should preferably be microscopic is avoided. As the "Matlab model" did perform quite well it was chosen improve that model bit by bit such that it could deal with all required aspects of *Table 2-3*.

2.5 Performance criteria

As the different input variables are described an the model is chosen one of the remaining topic is the output variables of the model, or the performance criteria on which the influence of the penetration rate, the traffic information and the users behaviour can be measured. To do so a set of criteria will be described below. The advantage of the choice to develop a new model is that all preferred criteria can be implemented.

Total vehicle delay time
The most common used parameter to measure the effect or performance of a traffic state is the total travel time loss of all vehicles together (in Dutch "voertuig verlies uren") This can be measured by comparing the difference between free flow travel time and experienced travel times of vehicles. When this is done so for all travellers, the different scenario's can be compared.

- Total vehicle delay compared to free flow travel time
- Total vehicle delay compared to initial free flow travel time

Distance travelled
A problem, which does occur when only comparing to free flow conditions, is the occurrence of detours, that is not measured in case of the above mentioned criteria, so another criteria is needed. A parameter to tackle the above-mentioned problem of detours is the total distance that is travelled by all the vehicles. When that parameter is increasing over the scenario's it can be doubtful whether the situation is really improving. Thereby from an environmental point of view it can stated that it is worthwhile to keep the total travelled distance as low as possible.

- Total distance travelled by all vehicles

Total travel time savings
Besides the total delay there is another aspect that is worthwhile investigating on and that is the benefit of the users. One could simple state that if the total delay time decreases the benefit will increase. That is not totally true, as the total vehicle delay time doesn't necessarily compare the impact of a measure compared to the referential state. When a reference run is done where every vehicle gets an initial travel time, which can be compared for all scenario's the benefit for each traveller can be computed and averaged.

- Total travel time savings compared to reference state without any influence of penetration rates, users reaction and traffic information.

Choices.
As route choice is one of the main topics for this study it can be worthwhile to investigate on the quantitative impact on this parameter. Further details about route choice will be elaborated further on, but to count the impact it is interesting to see how often people do change their route, as that can have large impact in the way people will react to the information next time. [14]

- Number of route-changes in total.
- Number of route changes per user

Length of traffic jams
A more visible parameter in real life (and therefore commonly used) is the total length of the queues, al radio stations use that in their traffic information supply, so it is useful to use that as parameter as well.

- Length of the traffic jams on the network

Effects on different road levels
It is worthwhile to investigate on the difference in impact on different parts of the network. (Different types of links) From road authority perspectives it is interesting to see effects on different types of links within a network. A shift from traffic from highways to inner city links is not preferable taking into account the environmental and safety perspectives.

- Impact on different types of links on the network

2.6 Scenarios

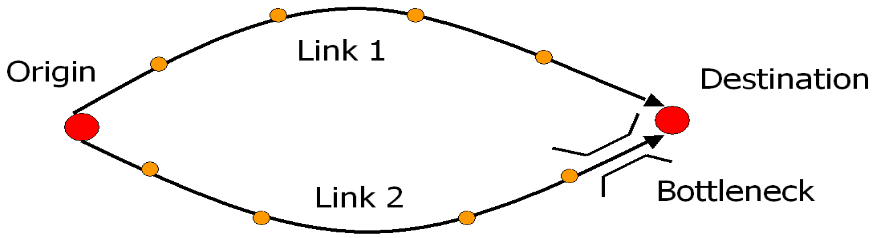
From the theory of the previous sections the situations that need to be investigated on are rather obvious. The 4th case has been added, mainly to provide a better insight in the difference between theoretical and practical results.

1. First the influence of penetration rates themselves will be checked so without changing the information, or the users reaction, it will be investigated what is the influence of equipping more travellers with a DRGS.
2. The quality of the information will be investigated. Providing the system with more accurate information should lead to changes in the traffic performance.
3. The influence of the users themselves is the third case. By adding the reaction of the users, which will be described in more detail the next chapter, also changes in the traffic performance in general are to be expected.

4. Differentiation between a simple 2-link system and a more realistic network case.

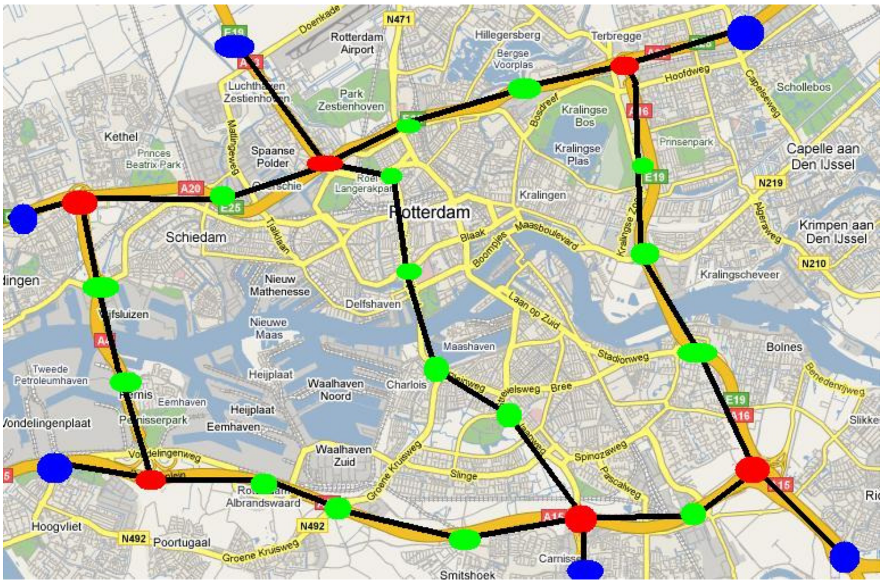
For that fourth scenario a simple 2-link network and a more realistic network will be used. The 2-link "network" is presented in *Figure 2-14* where two links have in general the same properties however on one of them is a bottleneck inserted.

Figure 2-14 network with two links



For the more realistic case, a network is chosen, where travellers form several routes can interact with each other and travellers can en-route reconsider their route choice.
It was chosen to create a network based on the Rotterdam motorway network as that has some good exchangeable routes. See *Figure 2-15*. Where in blue the origins and destinations are shown, in red the route choice locations and in green the transition between different sub-links. Appendix B shows more details on this Rotterdam network.

Figure 2-15 Rotterdam network



🔵 Origins and Destinations

🔴 Route choice locations

🟢 Link transitions

3. Description of the model

To verify the three interacting aspects as mentioned in the theoretical background from chapter 2, a model has been constructed that is able to deal with the major topics of this study. One of the other options was to use an existing model (either microscopic or macroscopic). However as most exiting models are not capable of performing all required aspects well, it is chosen to develop a model that could cope with the main topics of this study and as a consequence of that might perform a bit less detailed in its traffic assignment. This has been described in section 2.4. As mentioned the model to develop should in general be able to:

- Cope with different user classes (route guidance or not)
- Support route choice (basically en-route route choice)
- Have possibilities to simulate a dynamic route guidance system
- Support different types of compliance (also different user classes)
- Include the learning aspect of travellers.

In section 1 of this chapter the general structure of the model will be presented. Further on in section 2 the traffic generation and demand is described. In section 3 the route choice is described together with the modelling of the dynamic route guidance system. In section 4 the way the model deals with traffic itself is presented, followed by the performance criteria that the model should deliver in section 5. The way compliance of the travellers is implemented, is finally discussed in section 6

3.1 General structure

To be able to simulate all aspects mentioned above, a model has been developed and implemented within the mathematical programming tool "MATLAB". This model simulates the movement of individual vehicles (microscopic) on a network using generally macroscopic parameters. The main advantage of doing so is, that the simulation of vehicles moving in a network can be done quite rapidly and they still can be investigated at the moments of interest. (Mainly at the moments of route choice) A vehicle can be moved from the beginning to the end of the link in one act, based on for instance the macroscopic variable link-travel time (see *Figure 3-1*)

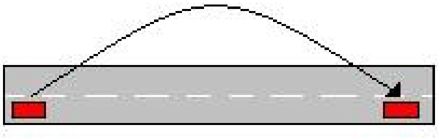


Figure 3-1 example of moving a vehicle over a link

One of the consequences of doing so is that the model is *event driven*. Where most models use time as the most important variable to base the simulation on, this model uses the vehicles themselves as the main variable. The variable "time" is therefore based on the moments where the vehicles are actually moved. The big advantage of doing so is that large periods, where no actions of interest for a vehicle are happening, can be passed by in the model, which saves a lot of time. Besides that it makes the programming of the traffic itself easier, because the microscopic interaction that does takes place on can be neglected. Doing so does of course influence results on a detailed scale level, but on the route choice, which is the main aspect here, such a detailed level is not required.

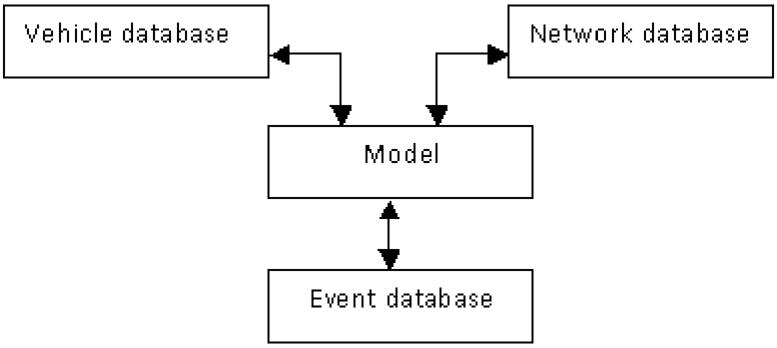
In general this way of modelling or simulating is called *discrete event simulation.* [23] This implies that the events that are scheduled to happen are executed stepwise in the right order. The variable "time" in the model thus follows the time of the discrete events, and is thereby discontinues.

Use of event driven model has advantages:

- Uninteresting periods can be skipped
- Detail traffic interaction on microscopic level can be avoided

The model that is developed basically works within three databases. First there is the *event database*, which guides the model to the first event that is scheduled to happen. Second there is the *vehicle database*, which stores all data for every individual vehicle. Finally the *network database* stores all information for all the links and sub-links on the network. The model itself is basically the part where the real traffic computations are performed based on the information of the 3 databases.

Figure 3-2 General model structure

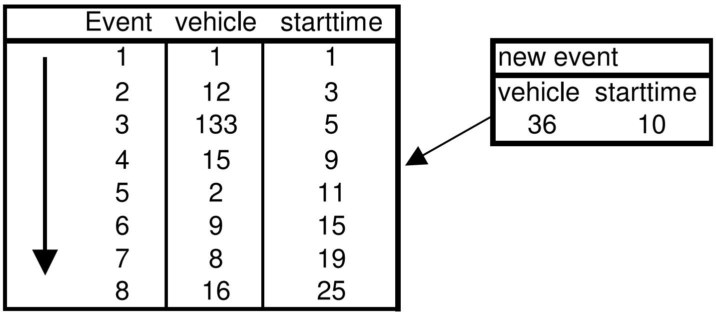


Event database

In the event database the activities, which are scheduled to happen within the model, are ordered by the moment they should happen. The model computes for every vehicle when it arrives at a link or an

intersection. (Or any other moment of interest.) Based on that list of events, the first event that is going to happen will be simulated in the model. Thereby the actual (current) time in the model follows the time of the events happening, so time is a discontinuous and irregular function. This database consists only of two parameters. Both the vehicle identification number of the vehicle involved (unique for every vehicle) and the moment that the vehicle has to become active are stored in that database. Of course when a new event is generated, (for instance: a car has left one intersection and will move to another) the old event needs to be removed from the list and a new event has to be inserted. (Not necessary at the last position) In Appendix A.1 the scripting of this event database is shown.
Using this event database in general means that the way traffic is moved, is not necessary according to FIFO (first in first out) constrains. A vehicle can be scheduled to arrive before its predecessors. Of course when FIFO constraints are valid that traffic model should cope with this.

Figure 3-3 process of handling events.



Event	vehicle	starttime
1	1	1
2	12	3
3	133	5
4	15	9
5	2	11
6	9	15
7	8	19
8	16	25

new event

vehicle	starttime
36	10

The event database consist of:

- Time of the events
- Vehicle number of the vehicles involved.
- Ordered by the moment the events are scheduled to happen

Vehicle database

In the vehicle database all information about the vehicles is stored based on the vehicles identification number. So once a vehicle is the active vehicle according to the event database, all other relevant information can be coupled to that model via the vehicle database. Most important is the location where the vehicle is and what is its destination. So when the model activates a certain vehicle based on the event database, it knows where that vehicle is and where it has to go.
Furthermore the personal characteristics of a traveller, the fact whether a traveller is using a route guidance system or not, how the traveller will react to the traffic information provided and the experienced travel times are stored as well in the vehicle database.
Besides these general parameters there is also some more information stored that is basically to verify whether the model performs well.

The vehicle database consist of:

- Current location of a vehicle (at the next moment it will be active)
- Origin
- Destination
- Start time
- Travel time
- Type of user
- Reaction on the encountered traffic situation
- Route guidance system or not

Network database.
In this database all properties of the network are stored. On the one hand there is the initial structure of the network, which consists of the lengths of the links, the number of lanes, the capacities and so on. On the other hand there are the properties that change over time like the number of vehicles on the links and the travel times over the links.

The network database consist of:

- Link properties (length, speed, lanes, capacity, etc.)
- Vehicles on the links
- Travel times on the links
- Measured travel times on the links
- Available routes

The “model part”, as shown in *Figure 3-2*, is the part where the actual traffic computations are made. Here the interaction between these 3 databases takes place, based on those computations a vehicle is moved. So based on the network properties a vehicle is moved through the network and based on those movements the network is updated every time a vehicle has been moved. In general for a vehicle the procedure of Figure 3-4 will be run until the vehicle has reached its destination. Every time a vehicle becomes active, according to the event database, it will be checked in which part of the procedure of Figure 3-4 the vehicle is situated, based on that information the vehicle is moved over right part(s) of the network.

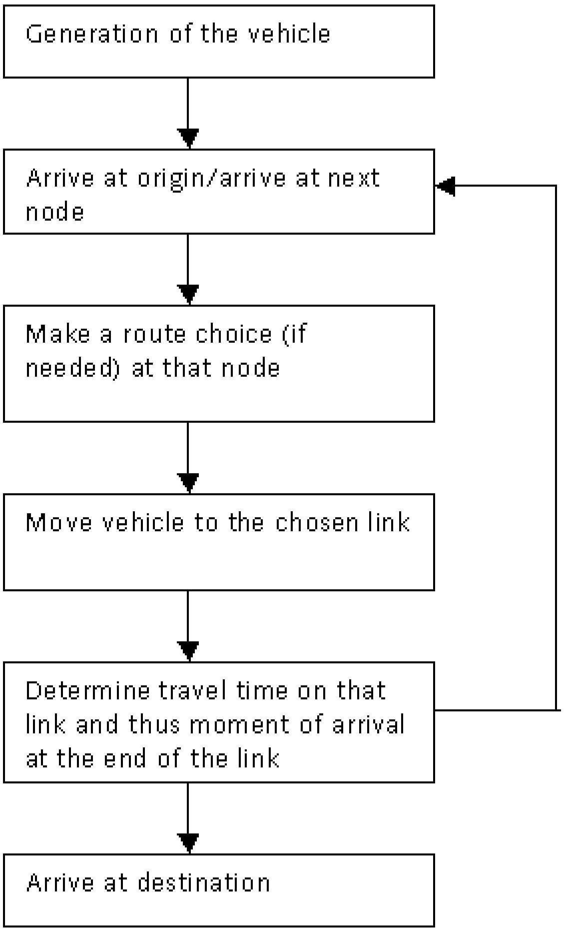


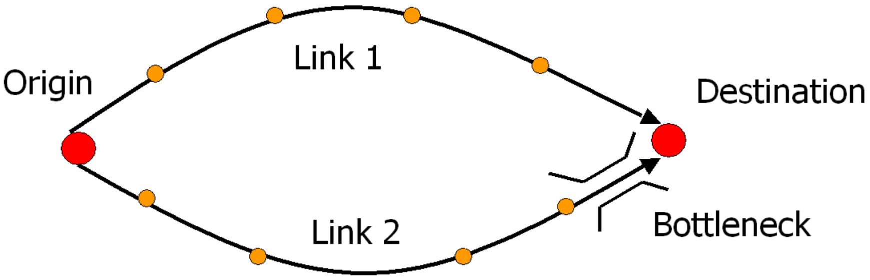
Figure 3-4 General model sequence

Within the loop presented above there are three main processes that need to be executed to actually move the vehicles through the model. First there is the movement along the node where the route choice is performed. (Besides that nodes are also used for a good computation of congestion spillback along other links) The other 2 processes deal with the movement of vehicles along the links. Because this is a discrete model that cannot deal with movement of vehicles on one link by one single process, two processes are used. One that involves the actual movement on a link an the other that determines the moment a vehicle can leave a link (see section 3.4)
The most important steps of this scheme will be elaborated within the next sections. For all steps within these process the actual processes schemes and program codes are presented in Appendix A.

To test all steps from the scheme above and to provide a better insight in the explanations in the next sections there are explained for the theoretical 2-link network. For better results, the 2 links have been divided into 5 sub links and sub-nodes.
Furthermore in this theoretical situation a bottleneck (reduced capacity) has been added to the last sub- link of route two. From that bottleneck

on congestion can then start to occur, in case the demand is near the capacity. To simulate traffic situation at least close to the capacity, the value of the total traffic demand should be close the capacity of both links.

Figure 3-5 Basic 2-link network



For this theoretical model the values of the link properties are shown in *Table 3-1*.

Table 3-1 link properties

property	value
density	35 veh/km
freeflow speed	100 km/h
length link	10 km
length sub-link	2 km
capacity link	4000 veh/h
capacity bottleneck	2600 veh/h

3.2 Traffic generation

Important in a simulation model is the input of the vehicles. As mentioned in the previous chapter, this is something that has to be elaborated for a new developed model in detail. Some the vehicles need to be generated and assigned to the model. The way this is done is shown in this section.
To simulate the traffic in a realistic way the entering of vehicles should not be a constant (every car arriving with the same time interval) but it should have peaks and drops in arrival rates of the vehicles. Most simple alternative would then be to model traffic inflow as two constants that change over time. *(Figure 3-6)*

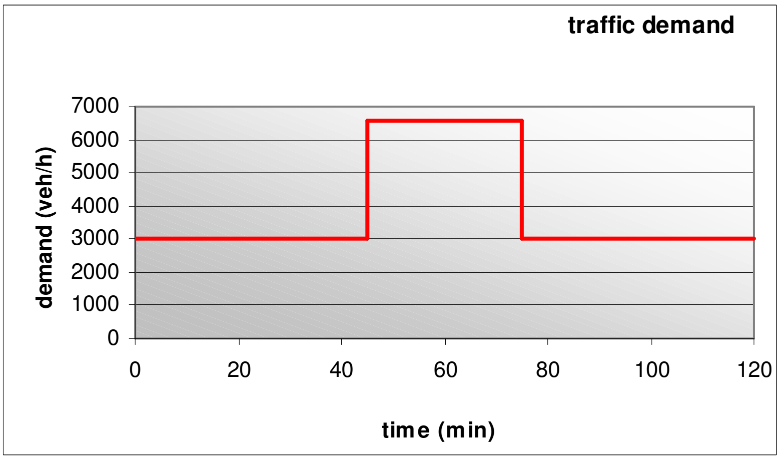
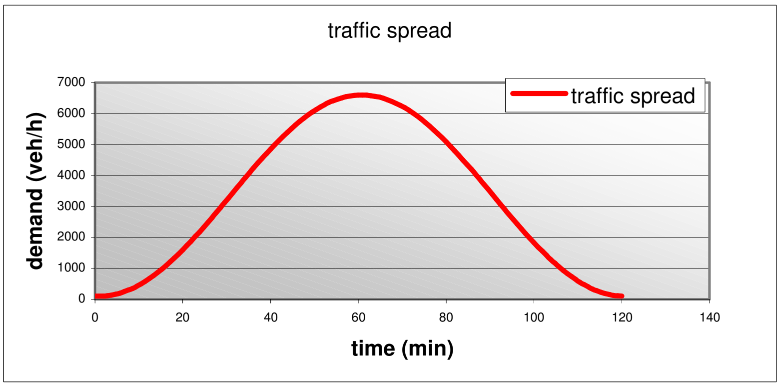


Figure 3-7 Traffic demand based on geometric function a basic and a peak demand

However in this case another option was chosen where the demand graph has the shape of a geometric function, this in order to simulate the real peak period better. *(Figure 3-7)*



The advantage of doing so is that there is no immediate transition from a low to a high demand, but a more smooth built up of traffic. Of course is in this case arguable whether the traffic in the off-peak is realistic enough, but to keep the demand function simple it is chosen to keep it as in *Figure 3-7.*
Because the capacities of the bottleneck and the normal link are respectively 2600 veh./h and 4000 veh./h, the traffic demand of 6600 in the peak equals the capacity. In that case congestion is to be expected when travellers don't choose according to the system optimum.

For the model this practically means that every new car that enters the model at the first node (Origin) has to compute the moment of entrance of its successor. That moment is based on the actual demand at the moment of entrance at A. At the maximum peak in the figure the demand (D) is 6600 vehicles per hour, which means an interval time of 0.54 seconds according to equation *(3-1*). So every second almost 2 vehicles enter the network.

$$r(s/veh) = 3600(s/h)/D(veh/h) \qquad (\ 3\text{-}1)$$

Furthermore at the moment of entering a vehicle gets some other characteristics as well. For every sequence of runs, every vehicle will keep these characteristics; so changing vehicles characteristics cannot be of influence on the results. For the route guidance system that works as such, that once a vehicle has a route guidance system it will keep that. When the percentage of route guidance systems will increase, more vehicles will get a route guidance device, but those who had it already will keep it.

The other parameters that will be assigned at the moment of traffic generation are:

- For every vehicle the origin and destination will be determined. This will be done based on an Origin Destination matrix. In case of a 2-links system that seem rather trivial but of course when more origins and destinations are involved it is required.

- Every vehicle gets its initial route, determining which route it would take without any knowledge about the traffic state (the influence of that will be explained afterwards in section 3.3)
- For every vehicle it will be determined whether or not it has a route guidance system, this will be done by drawing a random number from a normal distribution (which will then be compared to the penetration rate considered. (That will be more elaborated in section 3.3 concerning route choice and appendix A.2.)
- For every vehicle the characteristics will be determined. Based on the set percentages of users (further more explained in section 3.6 concerning the compliance) every vehicle will be assigned to such a group.

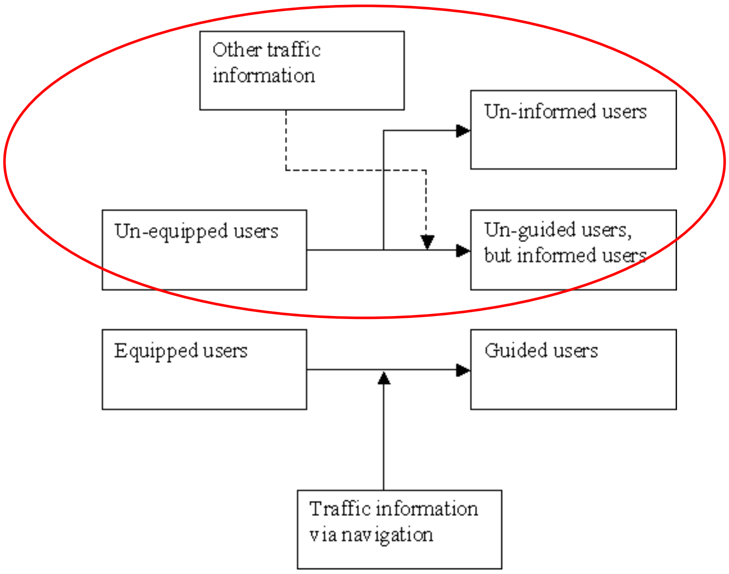
3.3 Route choice

One of the most important aspects that should be implemented is the way the model deals with route choice. This implies that for all the vehicles, the route that they will eventually take needs to be computed. Of course both the equipped and un-equipped user have different algorithms, on which they base their choice. In the model the route choice process takes place at all nodes, as that is the place where one or more links come together. However when a link has only one succeeding link no real choice has to be made. The exact movement of vehicles on the nodes will be explained in section 3.4, however in this section the elaboration of the route choice itself will be explained.
In the theoretical model (with only 2 links) there is only one route choice moment, at A (the origin). At all intermediate sub-nodes no route choice has to be made, as there are no alternatives there. In this simple case there are two alternatives that need to be considered in the route choice algorithms. Of course when the network gets more complex more alternatives become available.

3.3.1. Unequipped vehicles.

The group of unequipped vehicles can, as mentioned in the theory, actually be subdivided in a group that has no information about the traffic state at all and a group that receives descriptive information, for instance via radio messages as shown in *Figure 3-8*.

Figure 3-8 group of unequipped travellers



To get results that are as close as possible to realty, the unguided users should be divided in informed and un-informed users as well, as it is proven that informing travellers is beneficial to a traffic situation. However as this study concerns the influence of the dynamic route guidance systems it is chosen to model “the rest of the world” as simple as possible. Therefore it chosen to make one group of unguided travellers, that in this case doesn't receive traffic information. So when a comparison is made between both groups it should be taken care of that the performance of the unguided users might be underestimated, because the can in real life somehow acquire traffic information and adjust their route according to it.

The result of modelling the unguided travellers as such is that they have to base their route choice on something else than traffic information. This will be the initial free flow travel time. It is chosen the base of the route choice of the unequipped travellers is the initial free flow travel time, as that is a criterion that is often used when travellers depart for a trip. However to simulate the effect that not all users are informed well about the initial free flow state, a probability function is added to the modelling of that route choice. Travellers have a chance to take that initial shortest route or not.

To do so, for every vehicle an initial route is set at the moment it is created, based on that the unguided vehicle will travel through the network. To determine that initial route a logit-function used, as it is a very simple let travellers make a route choice. For the 2-link system this works fine as there are no overlapping routes. However in case of overlapping routes the logit-model is not so accurate, therefore one might consider using a probit-model to determine the travellers' routes. Nevertheless, as there are in the network case not so many overlapping routes and as it questionable whether travellers do consider the overlap of routes in their choice for an initial route, it is still chosen to use the logit-model.

In the case of the theoretical model a traveller has than a probability to take route 1, via link 1, or route 2 via link 2. *(3-2)*

$$\begin{aligned} P(R1) &= \frac{\exp(t_2)}{(\exp(t_2)+\exp(t_2))} \\ P(R2) &= \frac{\exp(t_1)}{(\exp(t_2)+\exp(t_2))} \end{aligned} \tag{3-2}$$

Where:

$P(R1)\,\&\,P(R2)$ = Probability for taking route 1 or 2
$t_1\,\&\,t_2$ = Free flow travel time of route 1 and 2

To actually let a vehicle make a choice for a certain route a random number from a normal distribution is drawn and compared to the probabilities P(R1) en P(R2) which can then provide the vehicles initial route. For different runs with different random seeds, this leads to a different initial route for every traveller.

3.3.2. Equipped vehicles

For the equipped travellers a different algorithm is applied, as they get a prescriptive route advice. In the first scenario of the theoretical model the compliance rate is set to 100%, which means that the travellers do follow the advice of the route guidance system. (Compliance itself, which implies that not all equipped vehicles do follow the advice, is elaborated in section 6)

Also the equipped travellers get the initial travel time as presented in the previous section, however these travellers get the extra information by their DRGS.

Measuring travel time

To generate an advice from the route guidance system, somehow the route guidance system needs traffic measurements to base its advice on. So in the model some sort of traffic measurement is inserted. When a vehicle leaves a link its travel time over that link is set to be the *measured* link travel time. So at every moment a vehicle leaves a sub-link a new measured travel time for that link is obtained. When this is done for all links the realized travel times on all links can be generated and summarized that provides a travel time for the full route.

To add the influence of computation time and time for collecting the data, a time slag (t_s), is added to the moment of the measured travel time. (Which is 180 s. in the first scenario) That means at the current moment (t) the measured travel time will set be the measured time of the moment $t - t_s$.

$$tt_{measuered}(t) = tt_{measuered}(t - t_s) \tag{3-3}$$

Route guidance system

When for all sub-links (L) these measured travel times (equation *(3-3)* are summarized, the measured travel times for a route (R) can be computed *(3-4)* and of course the route choice advice at location A will be the route that has the shortest (measured) travel time *(3-5)*.

$$tt^{R}_{measuered}(t) = \sum_{i=1}^{L} tt^{l}_{measuered} \tag{3-4}$$

$$R_{advice} = \min(R_1, R_2) \tag{3-5}$$

Of course this will result in a direct switch from one route to another when the measured travel time on one route is slightly improved compared to the other. Normally a traveller would not immediately react and change routes due to such a small change, however as the route guidance system doesn't act as a human being it is likely that it will immediately change to the other route when that is measured to be a shorter one.

3.4 Movement of the vehicles

As mentioned before, the movement of vehicles in the model consists in general of three procedures that a vehicle has to go through. First there are the nodes, on which the route choice mentioned in section 3.3 is performed. Generally that can be done within a split second, so passing a node doesn't take any time. Second there is the movement along the links where the vehicles encounter the real travel times, depending on the busyness on that link. To be able to cope with the existence of queues building up on a link and eventually even spillbacks to other links a kind of extra link at the end of a link (called *endlink*) is modelled. Here the vehicles on a link can be stored when they cannot leave that link because the next link is still occupied. *Figure 3-9* shows this sequence, which a vehicle has to take. It shows that the process of moving on a link is subdivided in moving on a link itself and moving on the endlink. Within the next sub-sections these processes will be described in more detail.

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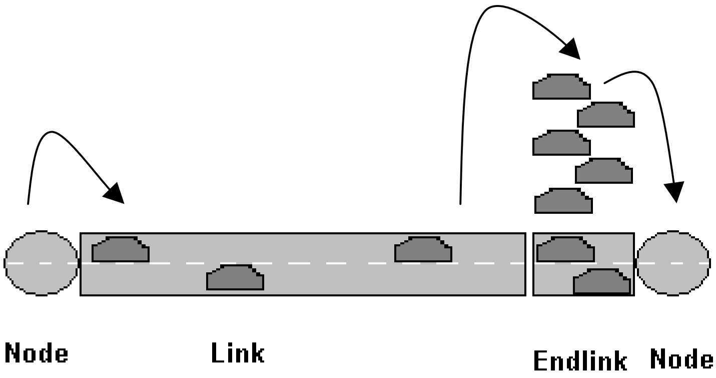
Figure 3-9 3 procedures for vehicle movement (node, link and endlink)



3.4.1. Movement on a node

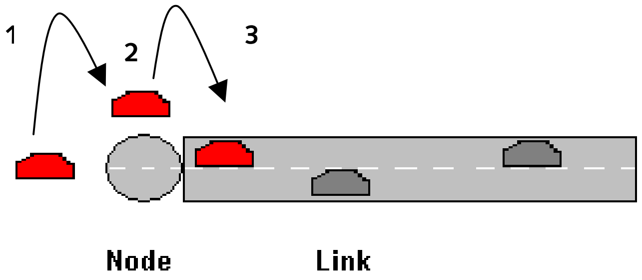
At the nodes the route choice algorithms, as presented in the previous section, are performed. Based on the node that a vehicle has entered and the destination of a vehicle, a shortest route (or initial route, in case of an unequipped vehicle) will be followed.

When the route choice is made the vehicle should be moved towards the next link on that route. However in case there is no space on that next link, the vehicle should wait at the node before it can be moved to the next link. That implies that the node is physically blocked and no car can pass the waiting vehicle on the node. Moreover that means that a possible queue on the next link, will spillback though the node.

For the model this means that a vehicle can practically pass a node in two ways:

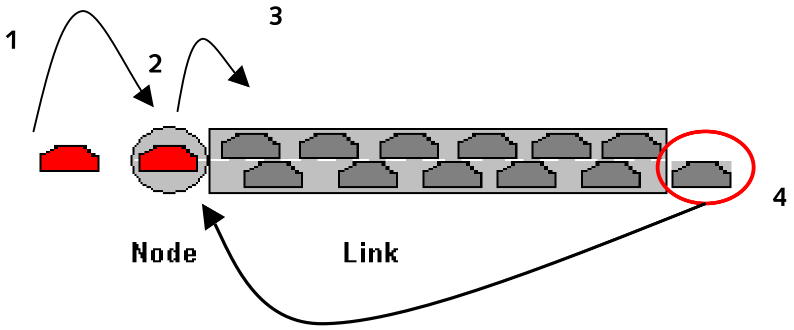
- First option: a vehicle can enter the node (1), make a route choice (2), leave the node (3) and will be set to enter the link at a certain time. Thereby it is checked that there is enough space on the following link. (*Figure 3-10)*

Figure 3-10 *movement along a node in case of a free link*



- Second option: a vehicle can enter the node (1), make a route choice (2) and can be blocked by an occupied next link (3) implying that it has to wait until there is space on that next link. The moment there is space again is determined by the first vehicle leaving the considered link (4) See *Figure 3-11*

Figure 3-11 *movement along a node in case of an occupied link*



- *In Figure 3-10 and Figure 3-11 the endlinks are not shown. Within the check whether there is enough space on the next link the endlink is considered, however to keep the figure as simple as possible it is not shown.*

That last possibility, when a link is already occupied, is more difficult to cope with in an event (or vehicle) driven model, as it cannot be predicted when there will be enough space for the entering vehicle on that next link. So it should either be checked every second whether there is space on the next link, or the movement of the vehicle from the node to the link should be triggered by the moment of a vehicle leaving from that next link. (As shown in Figure 3-11) The first option takes a lot of computation time as it means that an extra event has to be inserted every second. (Or at some other set time interval) For the second option an extra loop, which checks whether there is a vehicle waiting at a previous node whenever a vehicle leaves a link, has to be implemented. Although more complex, for that last option is chosen.

In Appendix A.3 the exact layout of a node is described in the way it is used in the model. As it becomes more complex when more, especially bi-directional, links come together, a more detailed description of the nodes is needed, however the main principles as shown above are still being used. That is all described in appendix A.3

3.4.2. Movement on link

Most straightforward of these three processes from *Figure 3-9* is the travelling along a link. When the choice for a certain route is made (movement at a node (1.4.1)) and a vehicle is moved to the next link on that route, the vehicle will be moved along that next link. Most time driven models would then let the vehicle move along the link based on the time steps that the model uses. *(3-6)*

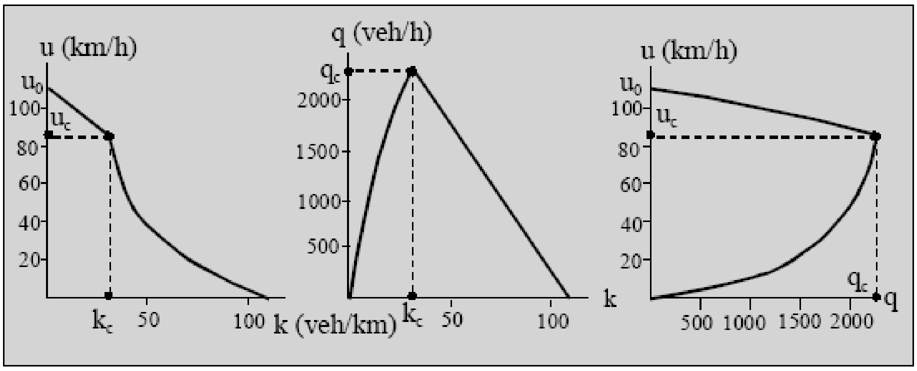
$$x_{t+\partial t} = x_t + u_* * \Delta t \tag{3-6}$$

The average speed (u_*) of the vehicle is determined by the state of the network. Traffic flow theory [24] shows that there is an interaction between the traffic density (k), traffic flow (q) and the instantaneous speed (u) *(3-7)*

$$q = k * u \tag{3-7}$$

Another way to graphically represent that interaction is the fundamental diagram, where the relation between the three interaction parameters is shown in three graphs. *Figure 3-12* shows these relations in Smulders' fundamental diagram. [24]

Figure 3-12 Smulders fundamental diagram [24]



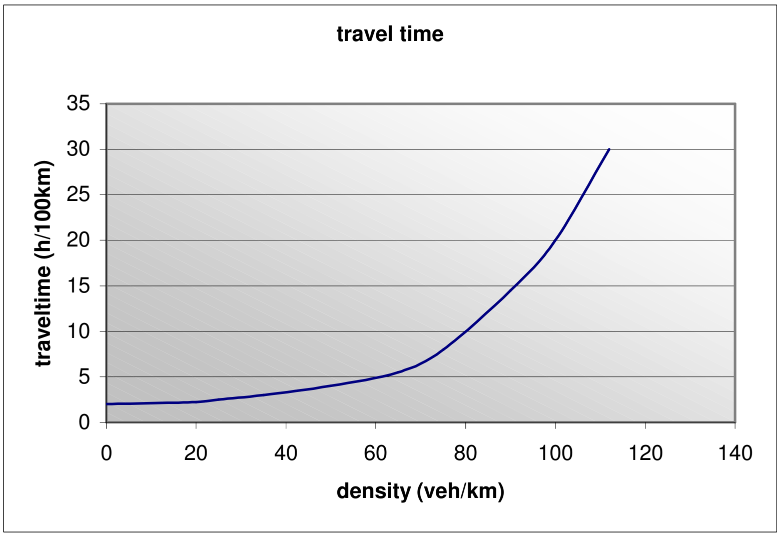
From these relations the average speed (u_*) for every vehicle can be computed and thereby the movement of the vehicle in one time step *(3-6)* is determined.

On the contrary to such a time driven model, (it bases computations on time steps (Δt)) the model used for this study does not compute (predict) the location of a vehicle at the next time interval, but it computes the needed travel time to reach the next location. (The end of the considered link) In general equation *(3-8)* is applicable for that.

$$t_{i-j} = \frac{x_{i-j}}{u_*} \tag{3-8}$$

This function is the inverse function of the (u-k) graph from *Figure 3-12* as the density on the road in this case determines travel time. Graphically this can be represented as shown in *Figure 3-13* where an increasing density on a certain road section will make the travel time increase as well. [24]

Figure 3-13 Travel time function based on the Smulders fundamental diagram



The problem with using average speeds for determining the density, and eventually travel times, is that the computation of average speeds is rather inaccurate due to the large time intervals used. Therefore in this model al link performance function (Bureau of Public Roads (BPR) function [26]) is used that bases the travel time on the actual flow of vehicles, the capacity and the free-flow travel time.

$$t_a(q_a) = t_a^0 \left(1 + \alpha \left(\frac{q_a}{C_a} \right)^\beta \right) \tag{3-9}$$

Whereby:

t_a = (Congested) travel time on a link a

q_a = Flow on a link a

t_a^0 = Free-flow travel time on link a

C_a = Capacity of the link a

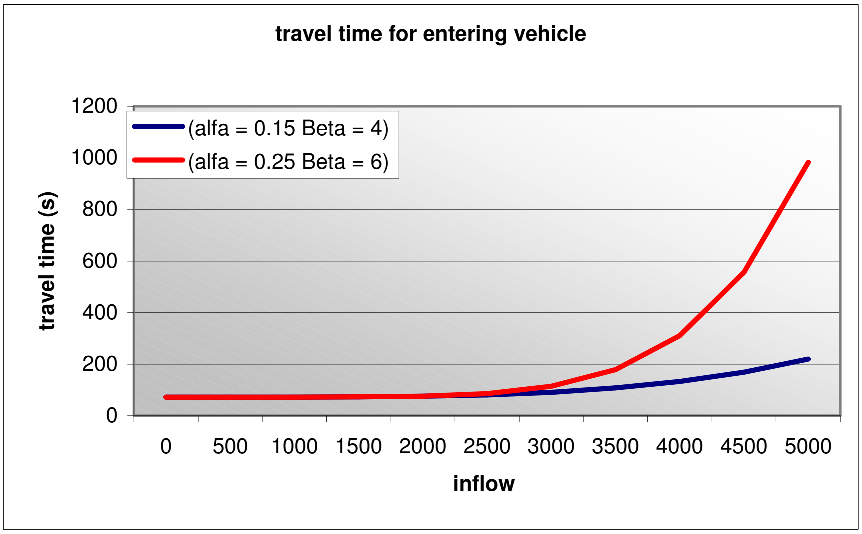
α, β Are parameters (0.15 and 6 in this case)

Theory suggests values for Alfa and Beta in the range of Alfa=0.15 and Beta=4. [25] In order to make the travel times a bit more realistic, especially in case of congestion the steepness of the curve is increased by using Alfa = 0.25 Beta = 6.

By using equation *(3-9)* the travel time is then computed for the entering vehicle on the link, based on the number of vehicles that entered on that link in the time period before (q_a).

For the sub-links of the theoretical model where the free flow travel time is 72 s. that leads to *Figure 3-14*. Of course when the values for inflow moves towards the capacity or even exceed it the travel times should start to increase rapidly. It can be seen that in case of the higher Alfa and Beta that is what happens.

Figure 3-14 travel times for the entering vehicles on a link



By using the inflow (q_a) for the BPR function a couple of problems can occur.

1. In case of a bottleneck a certain road section can become fully occupied, which will limit the inflow on that link. A decreasing inflow will result in a decreasing travel time, according to *Figure 3-14* and that is not according to reality. The travel times however should be more or less constant in case of a fully occupied link. To protect the model for such a decrement in travel times, a limit has been inserted such, that in case of an occupied road, travel times cannot decrease compared to the preceding vehicles (First in first out principle)
2. In line with that there is a problem with the outflow in case of high inflow ratios. A high inflow will result in longer travel times. However it does not necessarily result in a smaller outflow, al lot of vehicles can get the same high travel time and that can violate with the capacity principles. Therefore an algorithm is introduced that takes care of an interval-time that corresponds to the capacity and thereby the possible outflow.

3. On the other hand the inflow on a certain link can be much higher then the capacity of that link. (As the capacity on the upstream link and thereby its outflow can be much higher) That could lead to very high travel times and the results as such should be verified to reality. (The same as for the Alfa and Beta validation)

To solve these problems it is chosen to a simpler version of the link performance in case of congested links. It is stated that no more vehicles can pass then the capacity allows and all vehicles will pas at capacity outflow. So the travel time then will be a free flow part plus the extra time it takes for al predecessors to leave the link.

$$t_{i-j} = t_0^a + \frac{n}{C_a} \qquad (3\text{-}10)$$

In appendix A.4 the exact program code for travel time computation are presented.

3.4.3. Movement along the end of a link

Two problems can occur in case of using only the link travel times from the BPR-function. *(3-9)* First there is the problem that actually that way of modelling (vehicles a stored more or less vertically on a link) implies that there is an infinite space to store vehicles on a link. When all vehicles are vertically stored there is no problem with space for the cars. However in real life, when vehicles are stored horizontally (in a queue) it can turn out that there is not enough space on the considered link.

Related to that, there is the spillback of those queues along other links. As mentioned before the vehicles are moved over a link in one step, so they cannot predict the traffic situation at the moment of arrival at the end of the link.

When entering a link the travel time for that link is computed based on the inflow. The assumption thereby is that all vehicles that are on the link, and thus ahead of the entering vehicle, can actually leave the link before the considered vehicle, that is not necessarily true as a queue on the downstream link can start to block the outflow. As the next node probably won't allow the vehicles to enter a fully occupied next link vehicles should remain on their current link. These problems can predominantly occur when 2 links come together (*Figure 3-15*) or when the downstream link has less capacity. (*Figure 3-16*)

Figure 3-15 two links merging can cause queue spillback

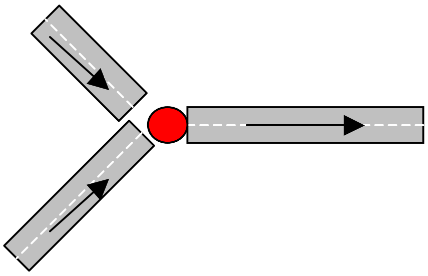
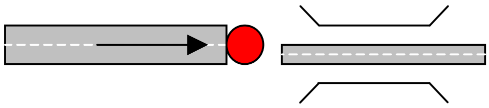


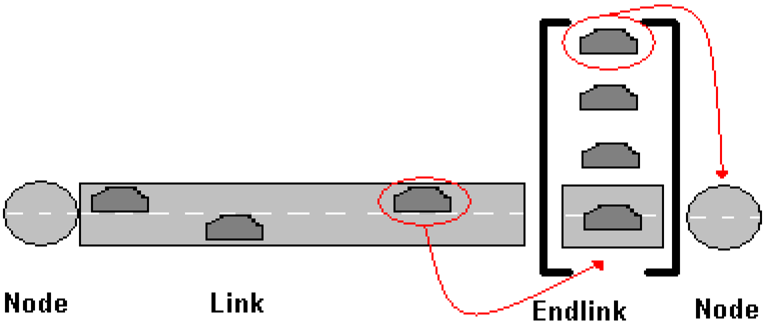
Figure 3-16 reduced capacity at downstream link can cause queue spillback



In general this means that not all vehicles, that actually want to exit the first link, can enter the next node (and thereby the next link) at the same time. So it should not only been taken into account how long it takes for a vehicle to travel along link it enters, but also whether it is possible to leave the link when it arrives at the end. As it is difficult to compute that last aspect at the moment of entering the link, the *"endlink"* has been added which makes it possible for vehicles to wait at the end of the link. Basically the *"endlink"* is a kind of parking lot where vehicles can be stored when the next node is occupied.

When a vehicle is about to leave the normal link it is moved into the storage space of the *"endlink"*. When there are no vehicles waiting on that *"endlink"* and the next node is free the vehicle will be moved towards the next node. When there is no space on the next node the vehicle will be stored on the *"endlink"*. So basically the *"endlink"* can be seen as a location where vehicles are stored and served in according to a first in first out principle. See *Figure 3-17*

Figure 3-17 principle of storing vehicles on an endlink



Then there is the problem how to determine the moment of leaving the *"endlink"*. (Like the moment for leaving in node in case of an occupied link, (*Figure 3-11*)). When the node is already free there is no problem, the first vehicle in line can than enter the node without any problem, however when the node is occupied the moment for leaving the *"endlink"* needs to be determined. Therefore the moment that a vehicle leaves the node should trigger the moment that a vehicle can leave from the *"endlink"* towards the desired node. Here the same consideration as used for the leaving of a node is applied. Appendix A.5 shows the actual program code for this process.

By using this endlink combined with to process of the node the process of a queue spillback is secured. The endlink prevents vehicles from leaving a link in case a next node is blocked. On the other hand the nodes themselves are programmed such that vehicles cannot pass unless the next link is free. Combining these two processes allows queues to spill back over several sub-links.

2-side inflow
In case of only a bottleneck (*Figure 3-16*) this "*endlink*"-procedure works fine, however in case of a 2-side inflow, like in *Figure 3-15* it is not clear which of the 2 upstream links gets priority to flow out on the next link. An extra algorithm is inserted that checks both links on a 50% ratio in order to get a good distribution between both upstream links.
That processes, where more links come together is furthermore elaborated in appendix A.5 concerning the node layout.

3.5 Arrival

The last process of figure *Figure 3-4* is the arrival of the vehicles at the destination. When a vehicle arrives there, the data collected during the trip should be stored so that results for all trips can be generated. Of course in a more detailed network these measurements can also be done for important intermediate links or nodes. Based on the criteria mentioned in chapter 2 *(Figure 3-18*) the required output data needs to be determined.

Figure 3-18 Main performance criteria mentioned in chapter 2

- Vehicle delay time
- Distance traveled
- Profit (time savings)
- Choices
- Length of jams
- Effects on different links
- Effects of different penetration rates
- Effects for users and non-users
- Effects of and on compliance

All these performance criteria from *Figure 3-18* can be computed within the model. Therefore a few basic computations have to be made to determine output values. Within the model a data storage algorithm is inserted, which can at certain time intervals (30 seconds) store values for all the counters within the model such that in the end those outcomes can (graphically) be represented.

Vehicle delay time
To compute the delay time for the vehicles, the travel time of every vehicle needs to be computed. For every vehicle the starting-time and the end-time are logged, from these 2 the travel time can be computed. *(Equation 3-11)* To compute the delay for a vehicle, this travel time needs to be compared with the possible travel time in case of a free flow. *(Equation 3-12)* Eventually, to compute the total vehicle delay time and the average vehicle delay time, this value has to be

summarized over all vehicles (n) *(Equation 3-13)* and divided by the total number of vehicles. *(Equation 3-14)*

$$t_{travel} = t_{end} - t_{start}$$ *(Equation 3-11)*

$$t_{delay} = t_{travel} - t_{free\_flow}$$ *(Equation 3-12)*

$$\sum_{i=n}^{N} t^{n}_{delay}$$ *(Equation 3-13)*

$$\frac{1}{N} * \sum_{i=n}^{N} t^{n}_{delay}$$ *(Equation 3-14)*

Distance travelled
A same computation can be made for the travelled distance. When a vehicle reaches the destination the total distance travelled over all links can be computed and also summarized for all vehicles. Of course as the links on the theoretical network have the same length that the result is the same for all vehicles.

Profit
Another interesting parameter that gives a good insight in the efficiency is the total profit. So, first a referential situation has to be determined, which is a situation without any route guidance systems at all. When dynamic route guidance systems are then assigned, the difference to the referential state can be determined. Then for all vehicles their individual benefit compared to that referential travel time could be computed.

$$tt^{n}_{profit} = tt^{n}_{measured} - tt^{n}_{referemce}$$ *(3-15)*

To get a total and an average benefit, this outcome of *(3-15)* can be summarized and averaged. *(Equation(* **3-16** *and(3-17)*

$$\sum_{i=n}^{N} tt^{n}_{profit}$$ *(3-16)*

$$\frac{1}{N} * \sum_{i=n}^{N} tt^{n}_{profit}$$ *(3-17)*

Route changes
Every time a vehicle has to change its route (taking another route than planned in the time step before) can be counted for every single vehicle and again also for the total number of vehicles. The sum and the average of that parameter are a rate for the efficiency of the system

Reliability of route choices
It can be computed whether the route choices, which the vehicles make, are correct or not. It is mentioned in chapter 2 that there can be a significant difference between measured travel time on which the route advice is based and the computed travel time by the BPR function. That difference can be seen as a rate for on the correctness of the route choice.
To make that influence clear a graph can be made that represents the difference between measured travel times and the computed travel times according to the BPR or capacity function.

Length of jams
The length of the queue that built up over time is a common used criteria to value the traffic state. Moreover it is good way to value whether the queue-spillback algorithm as presented in section 3.4.3 works properly. The length of these queues can be computed by comparing the number of vehicles on the link to the critical density.

Effects on different links
In the basic theoretical all links have the same properties, so there are no impacts for different types of links. However in case of a more developed network the results can be compared for different types of links. In case of the Rotterdam network a can difference be made between inner city roads and the ring roads.

Effects for different user groups
Of course for all groups, users and non-users but also different compliance groups the results can be split up per group when preferable.

3.6 Compliance

For all the aspects in the model, until now it didn't matter how the people reacted to the traffic information. It was assumed that all travellers act according to their route guidance system if they have one. In reality the way travellers react to the information and traffic situations they encounter is different. From the theoretical review in chapter 2 it becomes clear that there are mainly 3 directions of interest, which determine the way people react to information. It depends on the different types of information a traveller gets, the travellers' characteristics and the travellers' experience with the route guidance device how a traveller will react to the route guidance given by a dynamic route guidance system. This process is again shown in the figure below. *(Figure 3-19)*

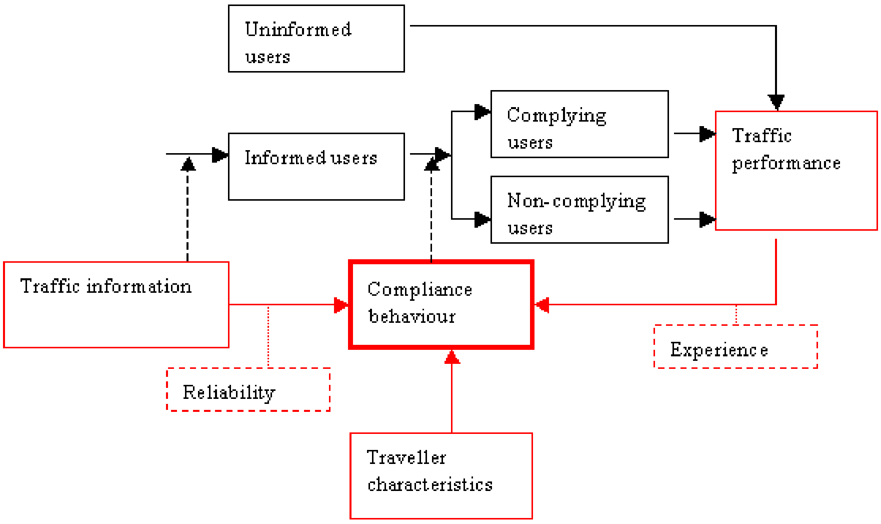


Figure 3-19 overview of the compliance process

Both this picture and the theory in chapter 2 show already that this is a complex world where a lot of variables interact.
From the perspective of traffic information it can be stated that more forms of information are preferable like radio messages etc. to be able to validate the information of the dynamic route guidance device.
From the side of the personal characteristics it would be preferable to view the impact of parameters like age, gender, transportation motivation, etc. to get a wide variety of users.
Finally from the point of experience one would expect the traveller to value the advice based on possible experiences in the past.
Modelling this in all its details will make the model big and slow and might even lead to a fake perception accuracy. However when assigning only a fixed percentage of people to comply with the route guidance advices, the result would be nothing more then a masked extension of the penetration rates. So one (or more) parameter(s) are preferred to show the interaction between travellers and travel advice.

3.6.1. Criteria for compliance

In general it can be stated that both traffic information and travellers experience are input variables on which the travellers make their decisions based on their characteristic. In order to determine criteria as such Adler [25] gives a couple of good parameters to verify the performance of route guidance.

- Arriving in the desired arrival window
- Minimize travel time
- Number of (red) traffic lights encountered
- Number of road changes
- Minimal trip distance

All of these criteria can be very useful to measure the impact of the travel advices for the users. Only the last two criteria are doubtful to be used, as their influence is only applicable to one specific route. Because

the used network of Rotterdam is very much simplified, there is only one route that has traffic lights on it and is also in general the shortest (measured in distance) these criteria would only be applicable to one route.
The difficulty of these criteria is that they can only be measured after a trip is made and so the influence can only be used in a possible next run. That means that these criteria become more or less already an experience, unless an iterative process is used to optimise the choices of the travellers. As that is something a traveller doesn't do in real life as well that won't be modelled here as well. Of course several runs for a similar scenario's can be made to provide travellers with experience on their choices.
For the model used this leads to a translation these five criteria from, plus one extra to model real experience over several runs [25].

Arriving at the predicted arrival window
The first criterion is based on the desired arrival time. Every traveller has a desired arrival time. However the choices to be made on this subject are more related to departure time choice then route choice. (See chapter 2) To incorporate this criterion and make it useful for this study the criteria will not value on the desired arrival time but on the predicted arrival time at the start of a trip. It seems logical that a traveller prefers to arrive at the initial indicated travel time. When the margin with that estimation is to high a negative result on this criterion is to be experienced.

Minimization of travel times
When using this criterion as en evaluation tool it can be stated that if the chosen route in the end was the shortest the possible travel time is minimized. On the contrary if the travel time on the chosen route was not the shortest (thus a shorter route was available) the traveller should have chosen different. In that last case the experience on this parameter will be negative.

Minimizing route changes
As mentioned in the theoretical approach travellers prefer staying on their initial route and consider route changes as a negative value. This is closely related to the criterion mentioned above that concerns road changes. The more a traveller is re-routed the worse the experience becomes, especially because a traveller then knows that the previous advice was wrong. However as there are only a few routes in this network, the number possible changes are also limited and therefore this criterion could be underestimated compared to real life.

Experience on previous runs
The fourth criterion used, which is not included in the Adler report, is the comparison to previous trips. When a traveller encounters a more beneficial travel time than before the current advice will be valued as positive, or the other way around, when the advice results in a worse travel time the traveller will consider the current advice as wrong.

Distance travelled
Another parameter that is be used is the distance travelled. Of course the more kilometres a driver has to travel the less he will be willing to comply the system. This can simply been computed by summarizing al the lengths of al links that a vehicle has travelled.

Traffic lights encountered
Also the number of traffic lights is parameter that is used. That can be computed the same as has been done for the travelled distances, by summarizing the number of traffic lights over all travelled links.

3.6.2. Travellers characteristics

There are in general two ways to translate the criteria as mentioned above to traveller's reactions. This can be done hypothetically, matching the traveller's characteristics to the mentioned criteria, or more realistic matching the criteria to existing travellers profiles like commuters and business travellers

Hypothetical
To integrate the traveller's reaction on these criteria in the model, the characteristics mentioned in section 3.6.1 should be coupled to these criteria mentioned above. Therefore the group of all travellers is divided into 5 subgroups of travellers, which eventually can be compared to the in the theoretical approach mentioned travellers characteristics.
The five different types of travellers are:

- All accepting travellers
- Easy travellers
- Normal travellers
- Critical travellers
- All neglecting travellers

All accepting travellers have the willingness to accept every advice and thus comply with every given advice no matter how wrong the results for the criteria are. On the other side will all travellers in the group of neglecting travellers decline every advice and maintain their initial travel strategy regardless of their experience. *Table 3-2* shows the reaction of the travellers as a function of the criteria mentioned in the previous section.

Table 3-2 types of users and their response in a hypothetical way

criteria / Type traveler	all positive	5 positive	4 positive	3 positive	2 positive	only 1 positive	all negative
All accepting	C	C	C	C	C	C	C
Easy	C	C	C	C	C	N	N
Normal	C	C	N	N	N	N	N
Critical	C	C	N	N	N	N	N
All neglecting	N	N	N	N	N	N	N

C = complying N = Neglecting

Realistic

A bit more complicated way to model this compliance behaviour is to use the common division for travellers as mentioned in chapter 2.

- Commuters
- Business travellers
- Long distance (freight) travellers
- Holliday travellers

The question then would be how to match the criteria mentioned above to these groups. Every group should have a different reaction to the criteria mentioned above. It is likely that commuters value arriving at the desired arrival window more important then minimizing travel time or travelled distance, whereas holiday travellers are not so concerned about those criteria but weigh more value to taking a route without changing it all the time.

To implement this for all 4 groups the rating to the criteria should be measured. As that is rather arbitrary it is assumed that for all groups only 3 criteria play a role. These will be ordered based on importance.

Table 3-3 importance of criteria for different traveller types

criteria Type traveler	Arriving in time	Minimize traveltime	Minimize route changes	Previous	distance travelled	traffic lights
Commuter	1	2	3	-	-	-
Business	3	1	-	2	-	-
Long distance	3	1	-	-	2	-
Holliday	-	2	1	-	-	3

Eventually when the travellers choices are made (within the model) they base their choice on there experience with these criteria. Therefore somehow the reaction on these three criteria should be computed. Using percentages on which the compliance is based can do that. However as there are only three criteria per user group, the scheme of the table below is be used. (*Table 3-4*)

Table 3-4 reactions on the order of criteria of table 3.2

Criteria 1	 2	 3	reaction
P	P	P	comply
P	P	N	comply
P	N	P	comply
P	N	N	no comply
N	P	P	comply
N	P	N	no comply
N	N	P	no comply
N	N	N	no comply

N=negative experience P = positive experience

So as the type of user is now coupled to a reaction on his experience with the DRGS, the individual effects can be computed. However for the total influence it is then of course important to determine the size of the different user classes. As the test case of the Rotterdam network is typically a case where most traveller are commuters, the distribution of travellers over the groups is chosen as in *Table 3-5*.

Table 3-5 distribution of user groups

Group	percentage
Commuters	55%
Business	15%
Long Distance	15%
Incidental	15%

Thereafter there is one important step to be implemented, namely what should happen in case a DRGS-users decides to neglect the advice. In the model it is chosen the let these travellers follow their initial route according to the logit-model presented in section 3.3.

Of course this approach of coupling the reaction of the different users to these criteria is very arbitrary, so it needs to be verified what is the influence of changing for instance the sequence of these criteria per user of adapting the size of the user groups. This is shown in a sensitivity analyses in chapter 5.

4. Model verification and calibration

In this chapter the results, generated by the model, will be validated. In general two checks will be performed here. First it will be checked whether the results are reliable. As there is randomness within the model, the outcomes of the model differ per run. When the differences between the runs are too big, the results are more unreliable, or the other way around, when the variation between the outcomes is small enough they can considered to be reliable. Thereafter a check will be performed that deals with the way the traffic itself is modelled. It will be investigated if the model performs well, compared to a real situation, to see whether the model is "realistic" or not.

4.1 Reliability of the results

In general 2 approaches can be made to test the reliability of outcomes of the model. It can be estimated how many runs are necessary to get reliable results. Or the other way around, it can be checked how reliable the results are, based on a fixed set of runs. In this case for that last option is chosen.

To do so the method of computing the confidence intervals of the mean is used. [27] This method will be applied on the results for the average travel time profit, which is one of the main outcomes of the model. (The results themselves will be shown in the next chapter) As all other result are closely related to these outcomes, it assumed that if results on the average travel time profit are reliable, that holds for the whole model and thus all other results are reliable as well.

To perform this test, it is assumed that the results of the model are normal distributed. By using the method mentioned, the results of the model can be compared to a standardized normal distribution and the reliability can then be computed by using the mean (or average) of the sample, the standard deviation and the sample size. Equation *(4-1)* shows this. That results in an upper and lower bound limit between which the real mean will lay with a 95% confidence in this case.

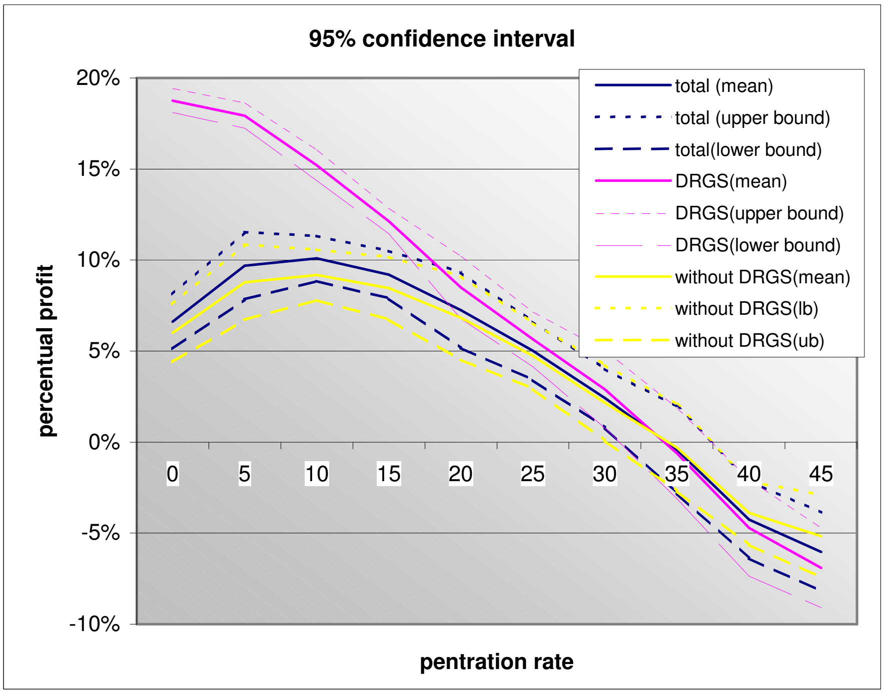
$$\left(\bar{x}_n - 1.96 * \frac{\sigma}{\sqrt{n}}, \bar{x}_n + 1.96 * \frac{\sigma}{\sqrt{n}} \right) \tag{4-1}$$

This test has been performed for the situation with 100% compliance and the results are presented in *Table 4-1*. For all penetration rates 10 independent runs are performed (n=10). The average outcome is computed by the mean. ($\bar{x}_n$) The standard deviation is the average deviation of the mean (σ). For all three results (total, DRGS-users and the non-DRGS-users) the lower and upper bound represent the 95% confidence interval. The results presented in *Table 4-1* can graphically be shown as in *Figure 4-1*

Table 4-1 *Upper and lower bound for the 95% confidence interval*

	Total		with DRGS		without DRGS	
Pen. Rate	upper	lower	upper	lower	upper	lower
0	2.70%	-2.03%	0.0%	0.0%	2.7%	-2.0%
5	8.12%	5.12%	19.4%	18.1%	7.6%	4.4%
10	11.53%	7.84%	18.6%	17.2%	10.8%	6.7%
15	11.33%	8.85%	16.0%	14.4%	10.6%	7.8%
20	10.50%	7.90%	12.8%	11.4%	10.2%	6.7%
25	9.33%	5.17%	10.2%	6.8%	9.1%	4.5%
30	6.61%	3.41%	7.1%	4.1%	6.5%	2.9%
35	4.02%	0.80%	5.0%	0.8%	4.2%	0.1%
40	1.95%	-2.80%	1.9%	-3.1%	2.1%	-2.7%
45	-2.14%	-6.37%	-2.1%	-7.4%	-2.1%	-5.6%
50	-3.87%	-8.19%	-4.7%	-9.1%	-2.9%	-7.4%
60	-10.04%	-14.06%	-10.6%	-14.6%	-9.0%	-13.4%
70	-15.99%	-27.38%	-16.5%	-28.8%	-14.7%	-24.1%
80	-29.45%	-37.19%	-30.1%	-38.2%	-26.6%	-33.5%
90	-46.59%	-51.07%	-47.2%	-51.8%	-39.5%	-45.0%
100	-93.93%	-93.93%	-93.9%	-93.9%	0.0%	0.0%

Figure 4-1 *graphical representation of the 95% confidence interval*

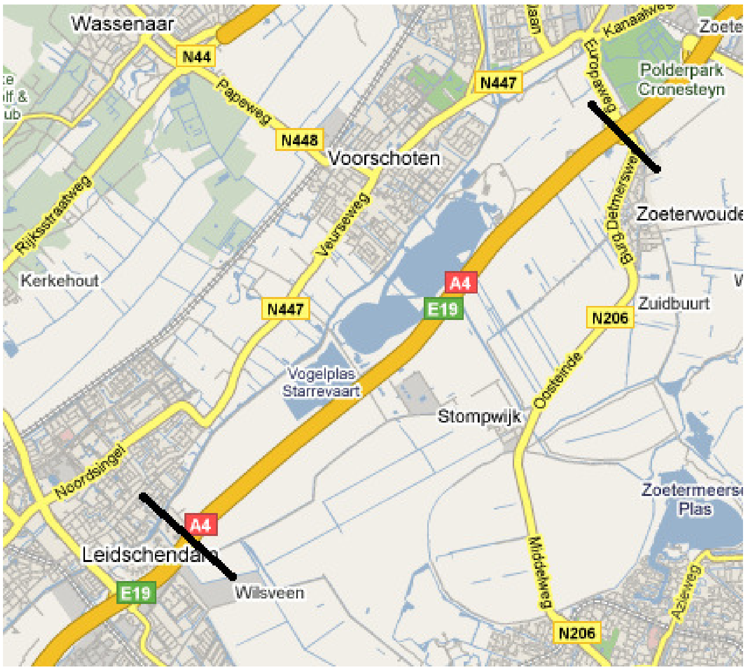


From *Table 4-1* and *Figure 4-1* it becomes clear that the results presented are rather accurate. Only at the higher penetration rates the results are a bit more uncertain as the range of the 95% confidence interval exceeds the 10%. (At 70% penetration rate) That can be explained be the oscillation effect of the traffic at higher penetration rates. (In chapter 6 that will be described more in detail)

4.2 Reliability compared to a real situation

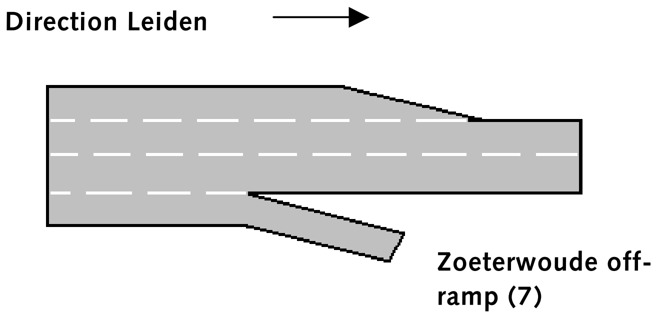
It is worthwhile to see whether a traffic situation computed by the traffic model is more or less comparable to a real traffic situation. Doing so gives a good view on the translation of results presented by the model to reality. As mentioned before the phenomena that are dealt with in this study are predominantly happening in dense traffic situations, so it is important to compare such a case to a real situation. So as the demand reaches the capacity and congestion occurs it is worthwhile to investigate on the performance of the model.
To do so, a real situation needs to be found where clearly congestion occurs due to an exceeding of the capacity. A location that is typically applicable for that is a bottleneck. Besides, it is practical to use a "long" stretch without any on or off ramps, such that growing queues can only spillback in one direction and no other influences have to be taken care of.
On of the most suitable locations is the A4 in northeast direction from The Hague to Leiden. On that part of the A4 there is a stretch of nearly 8 kilometre isolated road with a bottleneck in the end and there is nearly no influence of other roads on the network (See *Figure 4-2*)

Figure 4-2 Referential location- A4 The Hague- Leiden



Near exit 7 (Zoeterwoude) the A4 is reduced form 3 to 2 lanes. The only complicating circumstance is that just before that bottleneck the off-ramp for Zoeterwoude is situated and that will have an impact on the traffic situation. (See *Figure 4-3*.)

Figure 4-3 Schematic representation of the A4 bottleneck near Zoeterwoude



Modelling the off-ramp is hardly possible because there are no loop detectors on the off-ramp so the amount of traffic leaving the A4 is unknown, as it is not counted. This implies that the influence of the off-ramp (the amount of traffic leaving the A4 at Zoeterwoude) should somehow be incorporated in the throughput capacity of the bottleneck. Once the queue has spilled back over the off-ramp, the built-up of the queue should be more or less the same as if there where no off-ramp.

To compare the simulated situation to the real situation, the A4 road section has been divided in 17 pieces, which have exactly the length of the road sections between the loop detectors on the road. (As the loop detectors are in general placed at 500m from each other, the average length of a section is around 500m.) Via the data collection program Monica [28] the real measurements on the road are acquired and these need to be compared to the computed situation in the model.

Boundary conditions

There are three major variables that need to bee set order to compare the results of the model with reality; traffic demand, the bottleneck capacity and the number of vehicles that can be stored on every single road section.

The demand is computed by the flow measurements at the first road section. (Near The Hague) The bottleneck capacity is determined by the average throughput flow at the bottleneck, however it should be taken into account that a compensation has to be made for the Zoeterwoude off-ramp. The space on a road section is set to be around 35 veh./km according to literature. [24] In real congestion there can be more vehicles stored. So by doing so the length of the queues can be over estimated a bit.

Traffic speeds

The clearest result the Monica data presents from the real traffic situation is the speeds contour plot, where the speeds at every time and on every location are presented. This is shown for the real situation in *Figure 4-4*. Here it is shown that congestion starts in the bottleneck (35km) at 6 AM. Then a queue builds up upstream unto km 39-40. That queue then dissolves partially and after 7 AM it starts growing again. Eventually at 8:30 AM all congestion is dissolved and traffic is moving at normal speeds.

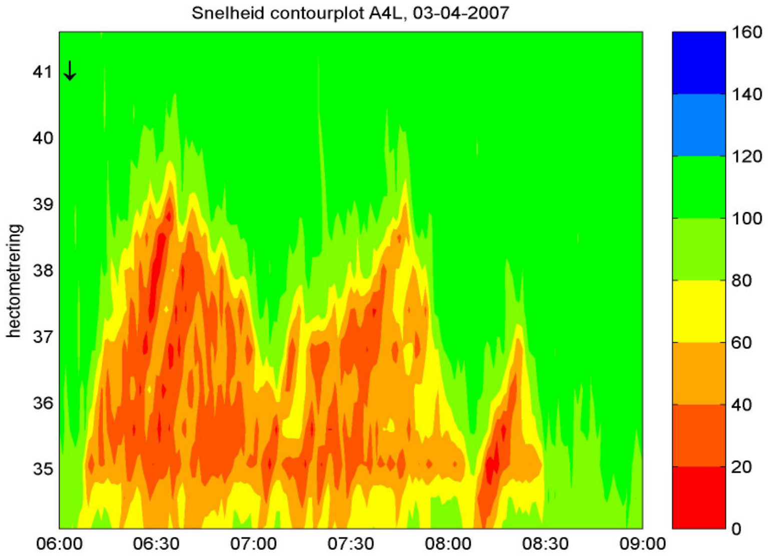
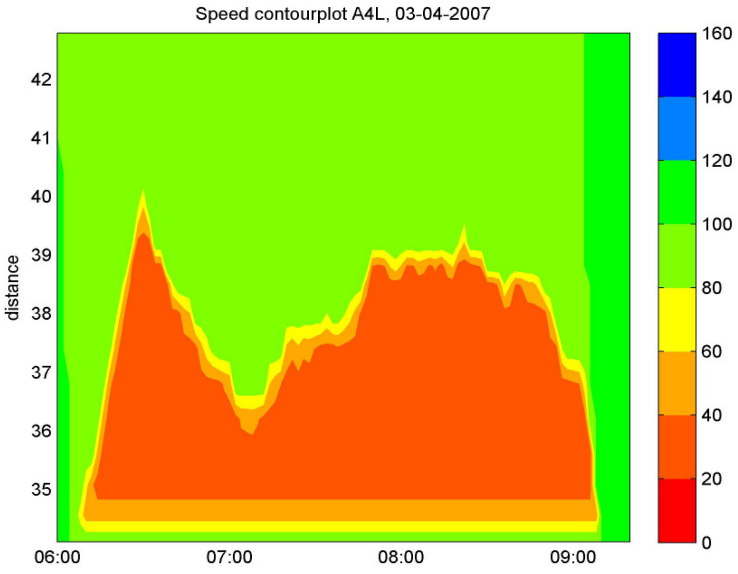


Figure 4-4 Real speed contour plot of A4 between The Hague and Leiden

The same drawing can be made based on the traffic situation in the model used for this study. It should however be mentioned that the speeds in the Monica data are instantaneous speeds measured at a fixed location. (Loop detector) The speeds measured in the model are average speeds on a road section and therefore won't fluctuate so much as the plot from *Figure 4-4*.

Figure 4-5 shows the speeds contour plot for the simulated situation. The two peaks can clearly be distinguished and the spillback of the queue is more or less the same. However the model cannot distinguish the third, smaller peak in the end of the congested period. This is because the congestion in the model seems to last a bit longer compared to the real situation. In the real situation the duration of congestion is dissolved half an hour earlier as in the modelled situation. That could however be explained be the fact that all traffic that normally is taking the off-ramp is now considered to cross the bottleneck.

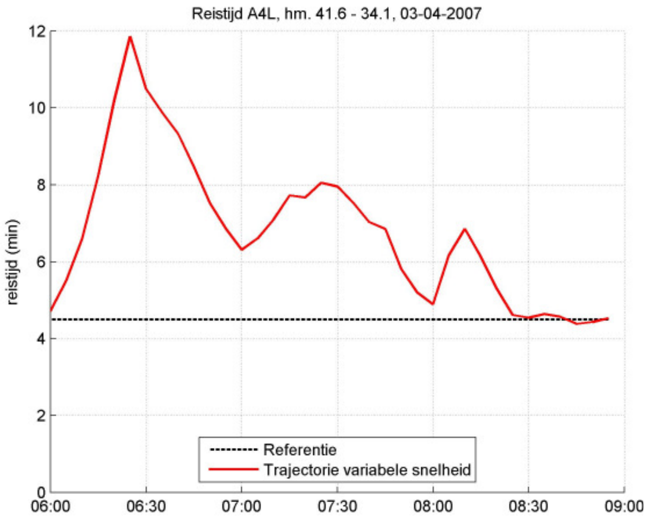
Figure 4-5 simulated speed contour plot of A4 between Th Hague and Leiden



Route travel times

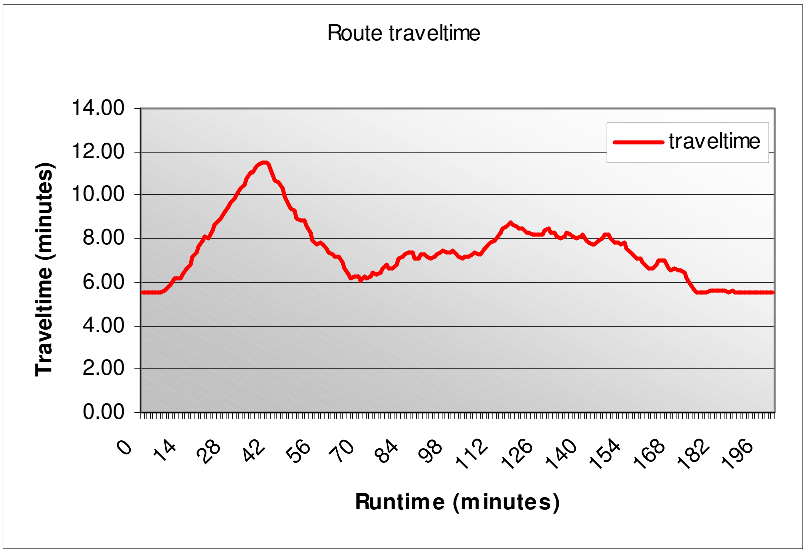
Another key figure that the Monica data provides is the route travel time. Based on the loop data also the route travel times can be computed. Doing so provides graph that represents the travel time on the route. The model also computes the travel times, however does that based on realized travel times. For the real situation that leads to Figure 4-5, where based on a free flow travel time of nearly 5 minutes, a maximum travel time of 12 minutes is distinguished.

Figure 4-6 Route travel times based on Monica data



The route travel times of the model (*Figure 4-7*) follow more or less the same pattern. As both graph are composed in different programs they are shown in 2 different figures. It should be mentioned that the road stretch in the model is a little longer and therefore the free flow travel time is nearly 6 minutes. The maximum travel time nearly reaches the 12 minutes and the top of the second peak is also close to 8 minutes. Due to the longer lasting of the congestion as mentioned before, the travel times in the last part of the run do exceed the travel times presented by the Monica data.

Figure 4-7 Route travel times based on the model



5. Results

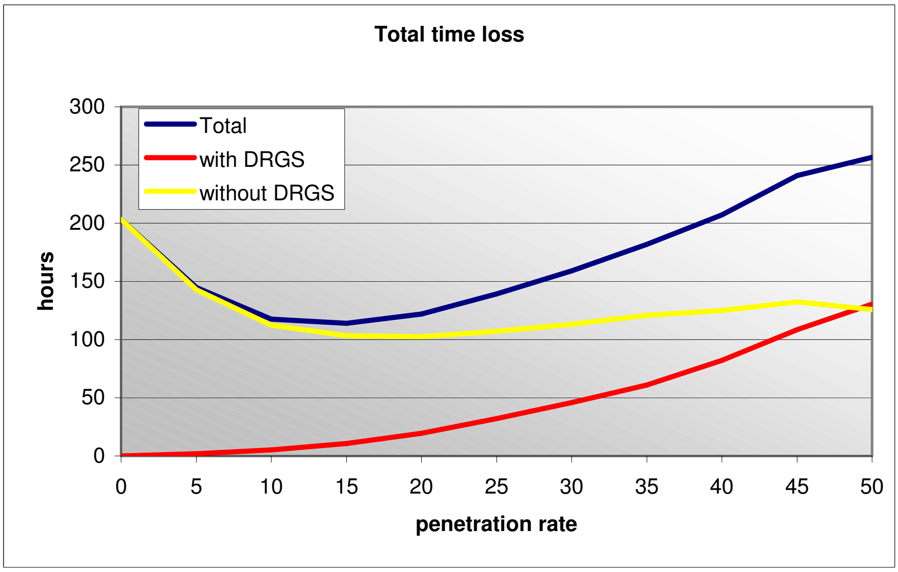
In this chapter the results of the model will be presented. It will be shown that in the theoretical 2-link case there is an optimal penetration rate and that eventually the situation can get worse than without dynamic route guidance systems. Furthermore the importance of accurate input data and the influence of travellers themselves on the system will be shown.
The results are divided in four sections, three concerning the major topics of the study, the penetration rate, the quality of information and the users reaction. The fourth section is about the distinction between the 2-link network and the Rotterdam case study. For this last section it is chosen to focus on the influence of penetration rates. Some small commands are made on the influence of the quality of information. As it would take much computation time it is chosen to not run the whole model for different sort of users reaction to the DRGS advice.
All results are presented for a penetration rate up to 50%, as that is the area, which is most likely to occur in the nearby future. Graphs for the full 0% to 100% penetration are presented in Appendix C.
It is chosen to present the results in line with the criteria that are mentioned in chapter 3, as most graphs are generated per criteria. Afterwards the results will be summarized for stakeholders. So RWS as representative of all travellers in general, the user of the DRGS and the non-users are distinguished. For some criteria only the results in general are presented and no distinction for stakeholders is made. That is because the model was not programmed to compute every criterion for all stakeholders separately.

5.1 Penetration rates on the 2-link system

The firsts major question of this study is concerning the influence of an increasing number of DRGS-users. The influence on all of the in chapter 2 given criteria will be given as a result of an increasing penetration rate. In this part the users of the DRGS are considered to comply with the route advice given. So the compliance is 100%.

Vehicle delay time
As mentioned, one of the most common criteria to value a traffic situation on is the total travel time loss ("voertuig verlies uren" in Dutch) of the system. In this model that is defined as the extra time a vehicle is in the system compared to its own free flow (or ideally) travel time. *Figure 5-1* (Figure C1 in appendix C) shows this for the total travel time loss, for all travellers together, and for the users and non-users of the DRGS separately.

Figure 5-1 total time loss



In *Figure 5-1* it can clearly be seen that there is a drop in the total hours all vehicles lose extra due to hindering while travelling. The optimal situation is around a penetration rate of 10%-15%. Furthermore it can be seen that when the penetration rates exceed the 35%-40%, the total time loss is more than the referential situation without any DRGS. The eventual reduction of travel time loses that can be achieved by equipping more travellers is around 40%. When almost half of the travellers is equipped also the total time loss for both groups is equal, so it makes no difference whether one is equipped or not anymore.

Because this figure represents the total time loss it is logical that the loss for DRGS-users increases. (While increasing the number of DRGS-users, their total travel time loss increases as well.) Remarkable is the more or less constant travel time loss for the non-users, although the absolute number of non-users is decreasing.

Influence on the total time loss:

DRGS-users:

- Increasing total travel time loss at an increasing penetration rate

Non-users:

- At around a 20% penetration rate the total travel time loss is minimized for non-users in minimized.

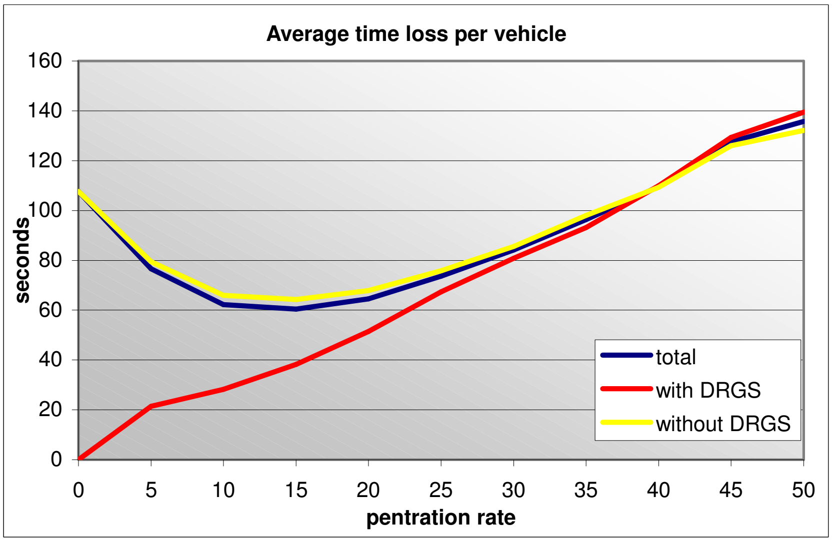
All users together:

- At around a 15% penetration rate the total travel time loss is minimized.
- At around a 40% penetration rate the total travel time loss is equal to a situation without DNS's.
- Equipping around 15% of the vehicles leads to a reduction 40% in total travel time loss.

Travel time loss per vehicle

To compensate for the fact that the number of DRGS and non-DRGS-users is not the same over the runs with different penetration rates, the average time loss per vehicle has been computed as well (*Figure 5-2*, full version is shown in appendix C 2)

Figure 5-2 Time loss per vehicle



In this figure it can also be seen that there is an optimal penetration rate at about 15% and after 35%-40% the situation gets worse than without DRGS's. Here it can be seen that also for the group of non-users the loss per vehicle is increasing after a penetration rate of 15%

Influence on average time loss per vehicle:

DRGS users:

- More or less constantly increasing travel time loss

Non-users:

- Have least travel time loss at around 15% penetration rate

All users together:

- At around a 15% penetration rate the total travel time loss per vehicle is minimized.
- At around a 40% penetration rate the total travel time loss is equal to a situation without DNS's

Distance travelled

As the lengths of both links in the theoretical 2-link system are the same, this criterion has no influence on the results. Every vehicle has the same trip length, so the total travelled distance will always be the same. (However in the network case this will of course have influence)

Influence on distance traveled:

- As the distance to travel on both links in the theoretical network is the same, the total distance traveled is of no influence.

Travel time savings

With this criterion the profit compared to the referential case where none of the travellers is equiped with a DRGS is presented. This has been done absolute in seconds of saved time (*Figure 5-3* and appedix C figure 3*)* and relative in a percentage of the total travel time per vehicle. (*Figure 5-4* and appedix C figure 4)

Figure 5-3 total travel time profit per vehicle

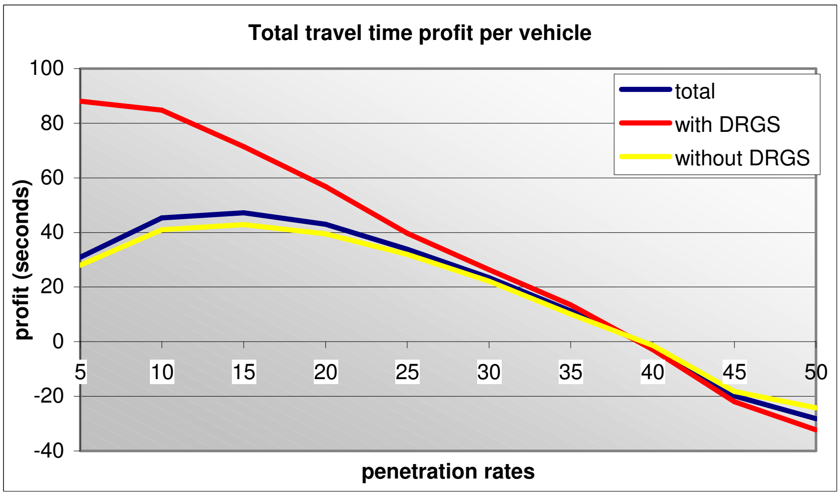
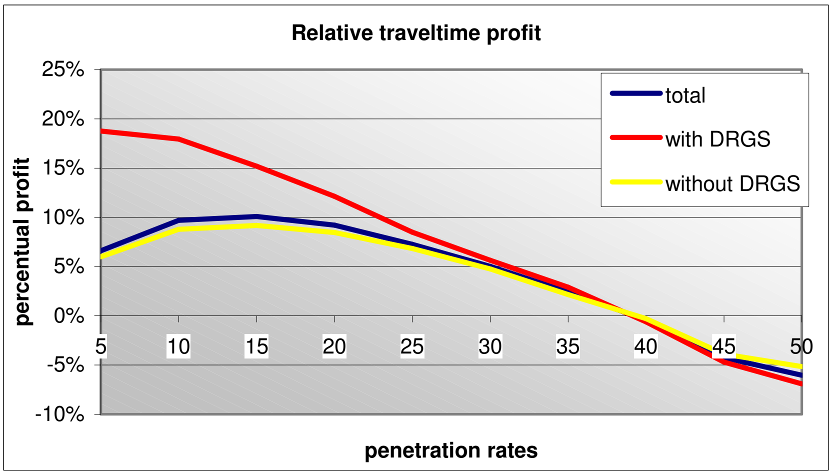


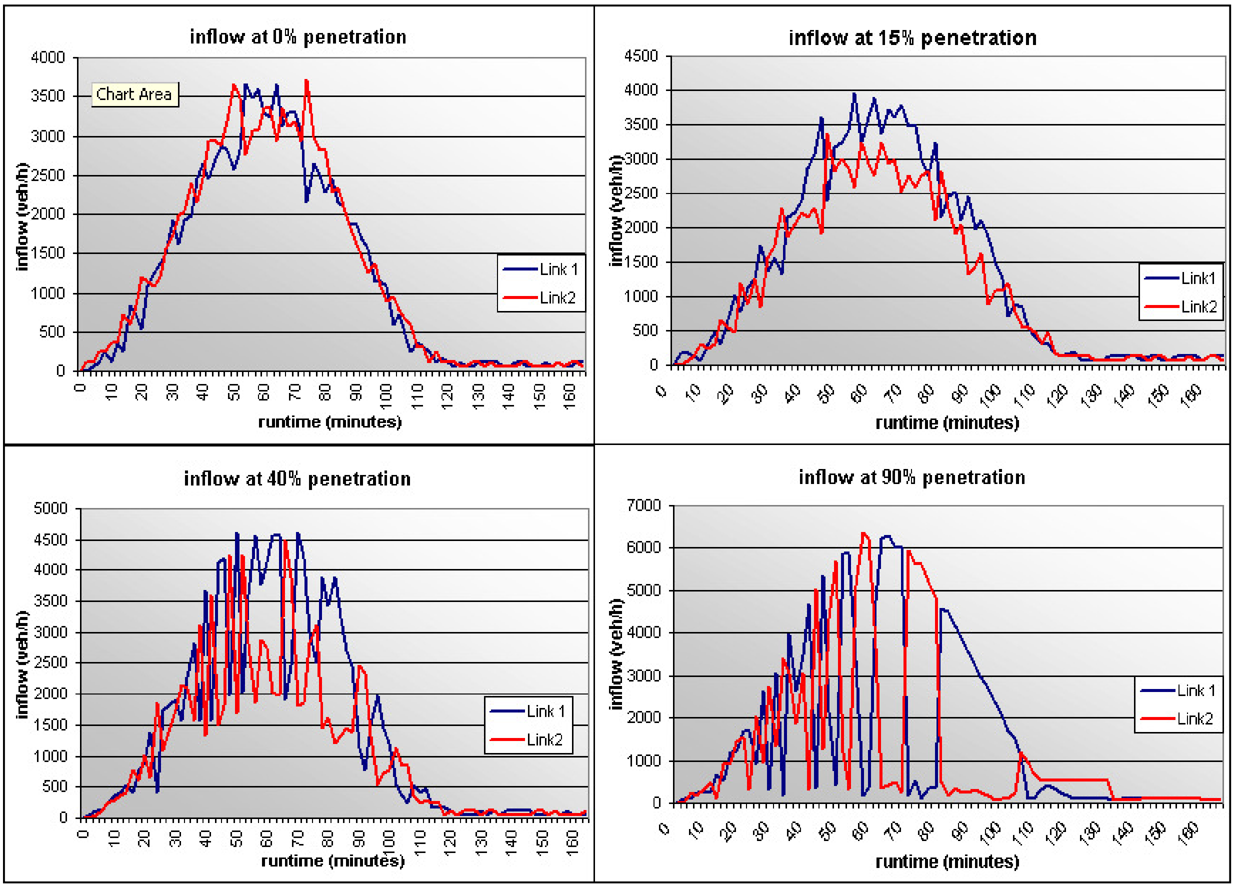
Figure 5-4 relative travel time profit



In these figures it can be seen again that there is an optimum around 15% of DRGS-users and yet again at a penetration rate over 40% the influence on the traffic situation worsens compared to a situation without DRGS's.

The drop of the benefit for the DRGS can be explained by the effect that more and more vehicles are rerouted at higher penetration rates at the same time. Therefore the traffic inflow at certain time intervals becomes so high that congestion starts occurring even at the link without the bottleneck. This shown in Figure 5-5 where for 4 penetration rates (0%, 15%, 40% and 90%) the inflow over time on the 2 links is represented.

Figure 5-5 inflow at 4 different penetration rates



It can be seen that at 0% penetration, the inflow on both links is more or less equal over time, which is logical as both routes have the same free flow travel time. In the second graph (15% penetration) link 1 has significant more inflow, due to the fact that the DRGS reroutes traffic to link 1. (Because of congestion in the bottleneck.) Although some oscillating is already visible, the inflow never exceeds the capacity of link 1 so no problems occur yet. In the third graph (40% penetration) there is so much traffic assigned to link 1 that it exceeds the capacity (4000 veh./h) on link 1 as well and the system starts oscillating heavily. In the final graph (90% penetration) the system assigns traffic almost as in an all or nothing assignment, which is very inefficient, as the inflow exceeds the capacity significantly at almost every moment.

Graphically in this 90% situation the contours of the demand graph, which is presented in chapter 3, can be seen again)

Influence on total and relative travel time profit:

DRGS users:
- A DRGS is profitable until 40% penetration
- The benefit for the DRGS user is decreasing as more and more travelers are equipped
- Over 40% equipped users, their distribution starts oscillating.

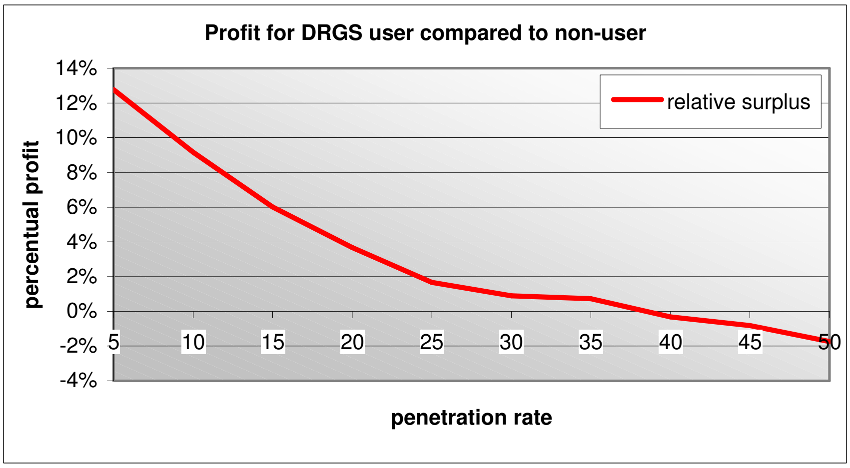
Non-users:
- Also the non-users of the system benefit a lot from the DRGS
- Also non-users encounter negative consequences of oscillations.

All users together:
- The benefit for the whole society is maximized at around 15%
- Total benefit is equal to a system without DRGS at around 40% penetration

Economical review of travel time savings

From the figures before (*Figure 5-3* and *Figure 5-4*) it becomes clear that user, as well as non-users, benefit from the DRGS until a certain penetration rate. However, the DRGS user has to make some effort in acquiring the DRGS itself and buying the traffic information for the DRGS. Therefore from an economical perspective their benefit might be less than concluded before. Moreover as also the non-users benefit, the relative benefit for the DRGS-user is only the difference between the profit of the user and the non-user. In *Figure 5-6* (figure C5 in appendix C) the difference between the benefit of both the user and non-user of the DRGS is presented. It can be seen that the surplus value for the DRGS decreases far more rapidly compared to the general profit from *Figure 5-3* and *Figure 5-4* . Over penetration rates of 50% it shows a more or less steady small "disadvantage" for the DRGS.

Figure 5-6 Profit for a DRGS user compared to the profit of a non-user



The result from *Figure 5-3* and *Figure 5-4* can also be extended in more economical detail using some key values of the CBS (Central Buro of Statistics) [28] *Table 5-1* presents these CBS records together with the costs of a route guidance system on a monthly basis, which are used to make the economical review.

Table 5-1 used CBS-key values

Record	Value	Unit
Average time travelling per day	60	Minutes
Value of time	11,20	Euro
Working days per month	20	Days
Monthly cost	10	Euro
purchace cost	200	Euro

Using these records leads to *Figure 5-7* where on a monthly base the profit of a DRGS is compared to its cost. Also the benefits for the non-users are shown.

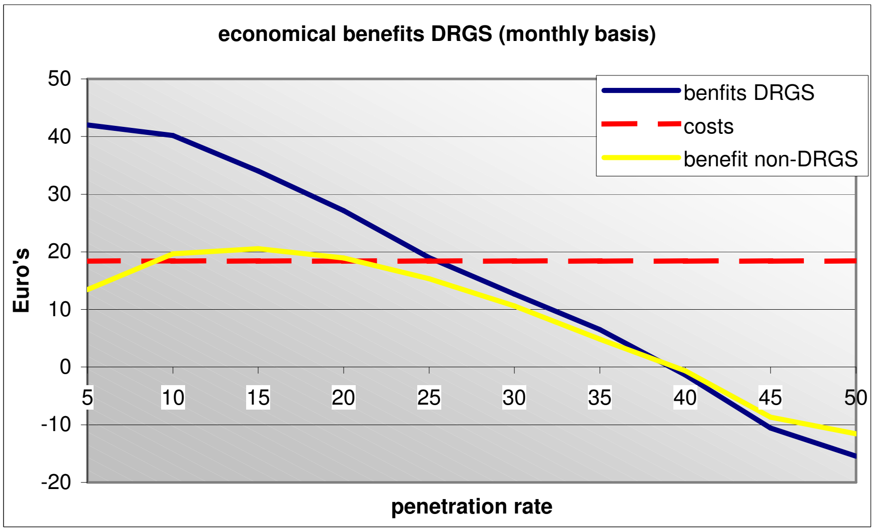


Figure 5-7 economical benefits of DRGS

Here again a comparison can be made between users of the DRGS and non-users. *Figure 5-8* shows the economical surplus value of a DRGS compared to the costs of the system.

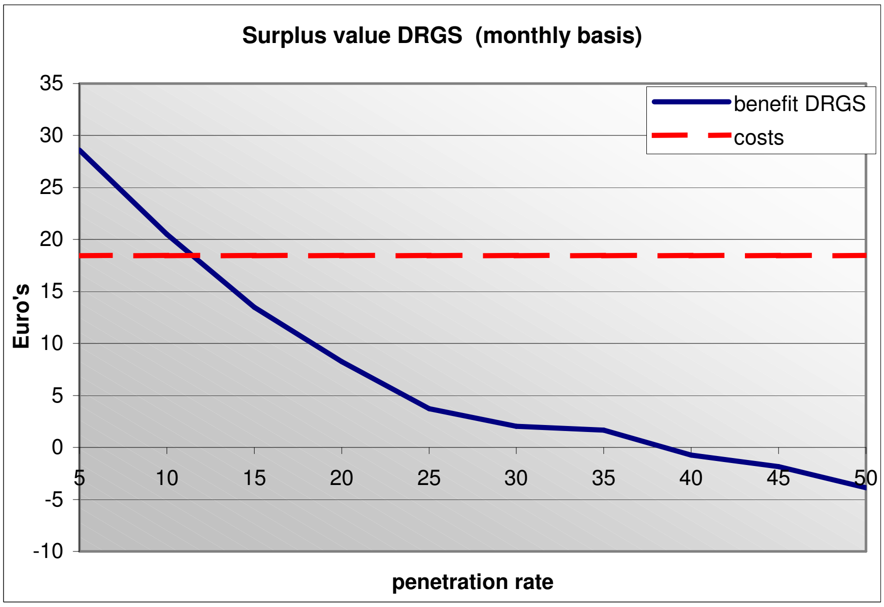


Figure 5-8 Economical surplus of DRGS

So again the benefit of a non-user is subtracted from the benefit of a DRGS-user and it can be seen that at a 10% penetration rate it is more profitable to " not-buy" a DRGS then to buy it.

Economical review on increasing number of DRGS-users:

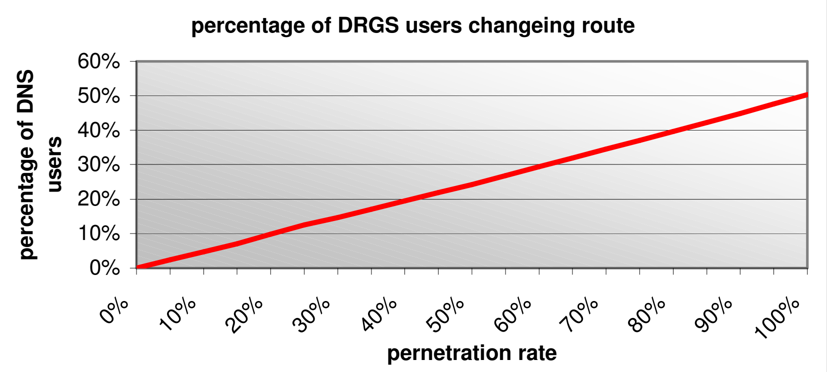
DRGS-users:
- Buying a DRGS is beneficial until 10% penetration rate

Non-users
- The advantage of not buying a DRGS is significant

All users together:
- Doubtful whether the optimal situation at around 15% penetration would be achieved

Route changes.
The 4th criterion, as mentioned in chapter 2, is more a criterion on which the users could weight effect of the DRGS, the more changes they are advised to make the less the will probably rely on the system. However, it can also be seen as a criterion to value the efficiency of the DRGS. The more travellers it can provide with a different route, the better it performs.
To measure this, for all equipped travellers it is checked whether they have changed their route according to the DRGS advice. The results of that are presented in *Figure 5-9*. As the process of assigning a DRGS is random it is obvious that more or less half of the users is already on the shortest route in case of the 2-link system. Therefore only the other half of the DRGS-users is likely to be rerouted to the link without congestion. Thus is the percentage of rerouted travellers more or half of the percentage of equipped travellers.

Figure 5-9 percentage of DRGS-users changing route



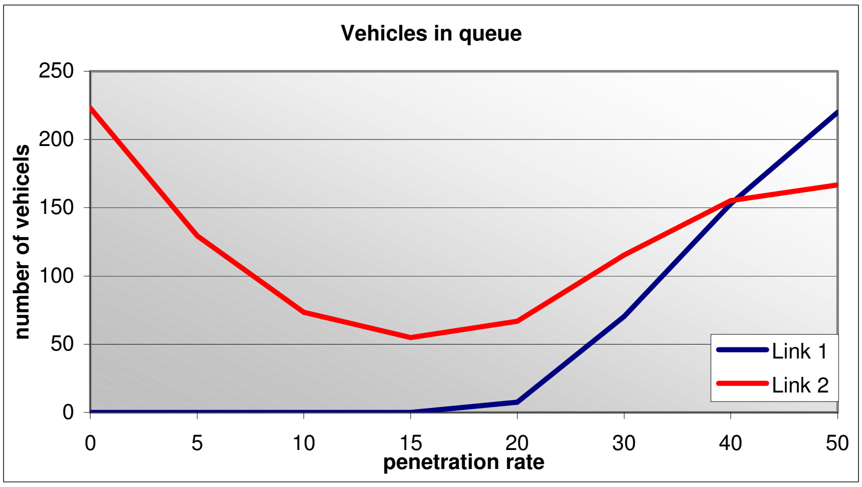
Influence on the number of route changes:
- Route changes are more or less a constantly increasing value at an increasing penetration rate in the 2-link system.

Length of the congestion in the network

This criterion is probably the most interesting for most travellers as that is the information they commonly get. However in this model the queue lengths are very depending on the way the network and separate links are designed. Generally in the model the queues built up from the bottleneck on the second link.

On the other hand when the penetration rates start increasing, the inflow on the entrance links can exceed the capacity on those entrance links. So the entrance links themselves then become a bottleneck. *Figure 5-10* shows the amount of cars that are waiting on all sub-links of link 1 and link 2. (The vehicles are waiting on the "endlinks" according to chapter 3.) For the queues on the entrance links the amount of vehicles present on the links is compared to the maximum throughput at a capacity flow. (No real queues can occur on the entrance links, as the vehicles then can be blocked while entering the system, therefore there is infinite space on the entrance links.)

Figure 5-10 vehicles in queue on link 1 and 2



In general the same conclusion can be draw as from the previous criteria. The influence of the DRGS is best in case that 15% of the travellers being equipped. After that queues on both links start increasing and thus even the un-congested link 1 is influenced.

Influence on the queue lengths:

- Congestion is decreasing until 15% of the travelers become equipped with the DRGS.
- When the penetration rate exceeds 15% also the link without congestion, becomes congested.
- Also after 15% penetration the congestion on link 2 starts increasing again.

Influence on different type of links

This criterion was originally chosen investigate on the difference between different levels of roads. For instance the difference between an urban road and a motorway could so be investigated on. Additionally to that, a distinction can be made between the road with and without the bottleneck. Based on the number of vehicles being in a queue, (*Figure 5-10*) it can be seen that for travellers on link 2 even at a 50% penetration rate the situation is better as in the situation without DRGS's. However for the travellers on link 1 the situation starts worsening at 20% already. So captive travellers of route 1 will encounter only negative influence of the system and captive travellers of link 2 will benefit from it to much higher penetration rates.

Influence on different types of links:

- Congestion is spread out over both links, even at penetration rates around 50% the situation is more or less equal to a situation without DRGS's
- Different consequences for users of both links.

5.2 Impacts of information quality on the 2-link system

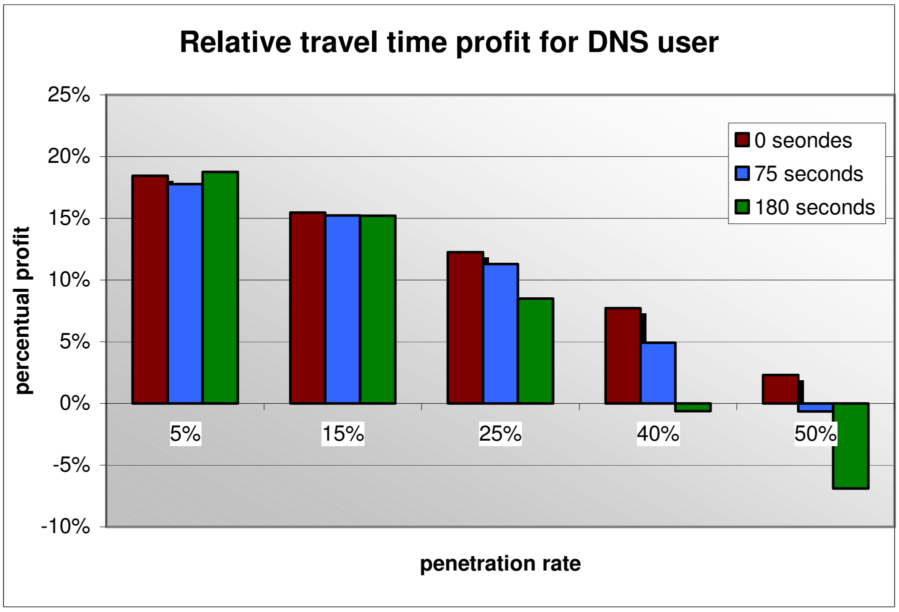
The second matter of investigation is the quality of the information used to guide the travellers with. In the results described in the previous section, the time for acquiring and processing the traffic data is considered to be 3 minutes as mentioned in theory. So a delay of 3 minutes is added to the measured travel times on the links. In the near future it is likely that this process time will be shortened and therefore a test case of 75 seconds is implemented. Eventually one would prefer to see what is the influence of immediately returning the measured travel times to the system as well. Therefore the instantaneous travel times, with a 0 seconds delay are used.

So 3 scenarios are tested to see the influence of the quality of information. One situation with 180 seconds slag delay, one with 75 seconds slag delay and one without any delay in providing measured travel times to the DRGS's, is tested.

For these three scenarios' the same plots of section 5.1 could be made. (Actually section 5.1 is the first scenario, where the slag delay is 180 seconds.) Doing so would lead to the same set of graphs as in the previous section, but then three times. In order to keep the results comprehensible it is chosen to compare the results for the information quality only by the outcomes for the relative travel time profit.

Figure 5-11 shows the relative travel time profit for the DRGS-users at five different penetration rates. When there are not so many travellers equipped, the impact of reducing the processing time is not so large. However from 25% penetration rate on it can be seen that the profit of reducing the processing time is significant. Moreover the moment when the impact of the DRGS's becomes negative for the system is delayed from 40% to a penetration rate of over 50% in case of a reduced process time.

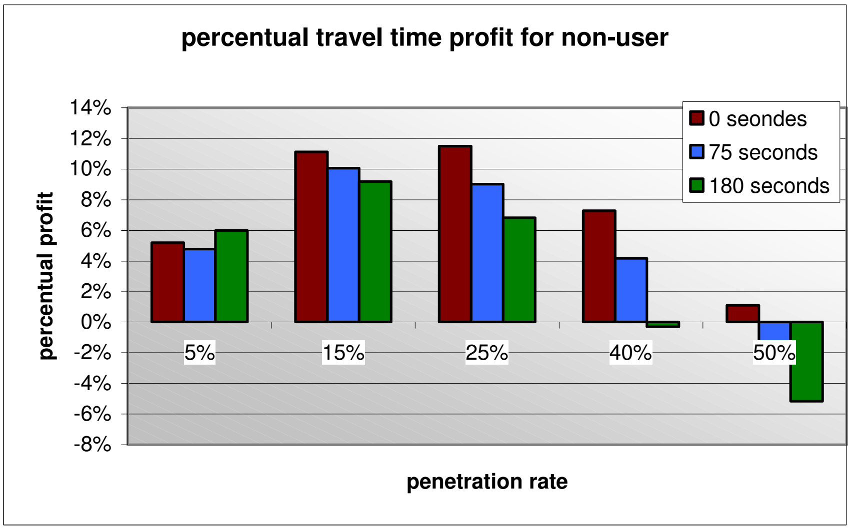
Figure 5-11 relative travel time profit for DRGS-user in case of reduced slag delay



In general it can be stated that increasing the quality of the information for the DRGS, doesn't increase the relative profit for the users at low penetration rates, but it does extend the profitability.

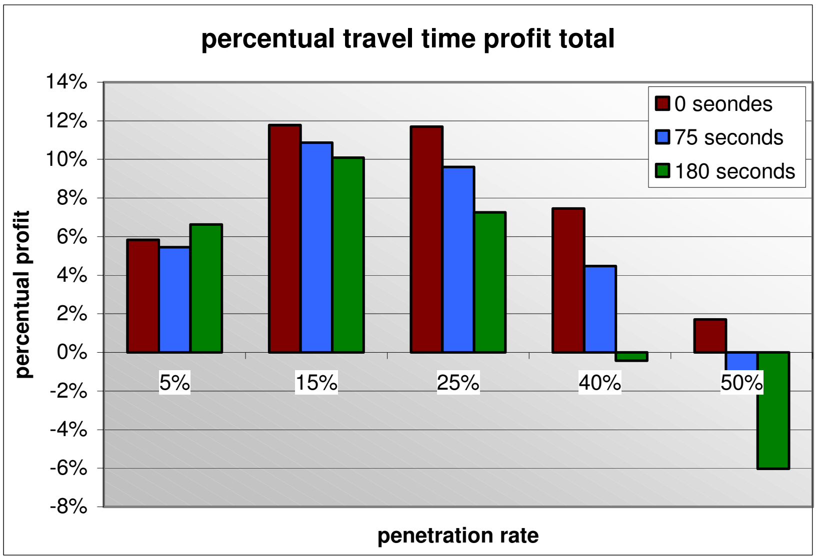
In *Figure 5-12* the same graph has been made for the non-users. As mentioned in the section before it can be seen that for the non-users the DRGS is most profitable at around 15% (in the scenario with a 180 seconds delay). However when that delay is reduced to 0 seconds, it is shown in *Figure 5-12*, that the benefit for the non-users is higher and their optimum is at around 25%. So it can be stated that, when the delay time is of the DRGS reduced, the profit of the non-users is higher and also their optimal penetration rate is at a higher rate.

Figure 5-12 relative travel time profit for non-DRGS-user in case of reduced slag delay



Finally the same graph has been made for the two combined: the total profit. Of course at the lower penetration rates the influence of the non-user is far larger compared to the group of DRGS-users. So the form *Figure 5-13* is more or less the same as *Figure 5-12*. In general it can be concluded that reducing the processing time leads to a larger profit and the DRGS is profitable at higher penetration rates.

Figure 5-13 relative travel time profit for all users in case of reduced slag delay



Influence on relative travel time reduction by improving the quality of traffic information:

DRGS-users

- Improving the information quality does extend the profitability of the DRGS
- Improving the information quality doesn't significantly improve the individual profit for the DRGS users

Non-users:

- Improving the information quality does extend the profitability for the non-users
- Improving the information quality does also improve the individual profit for the non-DRGS users

All together:

- Improving the information quality does extend the profitability for all users in general
- Improving the information quality does also improve the individual profit for all users in general
- Improving the quality of information is specifically noticeable at higher penetration rates

It can be seen that providing better information to the DRGS has especially a positive influence at higher penetration rates. The explanation for that can be found in the oscillations that do occur at these penetration rates. (See *Figure 5-5*)
In case of a low penetration rate the fact that the timing of system is running behind only leads to a wrong choice twice:

- Once when the queue builds up, then the DRGS reacts on average 180 s. late on the real situation. So travellers should have been rerouted 180 s. before.
- The second time is when the queue dissolves then the DRGS again observes the change of the traffic situation on average 180 s. late. Here again the DRGS could have reacted a 3 minutes before.

However in between these two moments the advices will be correct despite the fact that the information is 180 s. delayed.
On the contrary to that, when the system start oscillating, (over a 40% penetration rate) the queues are building up and dissolving at both links and not only once, but alternating. This results in more changes of the DRGS from one route to the other. Every time it does changes the advice is late and thus wrong for a while.
This phenomenon can be seen in *Figure 5-14* and *Figure 5-15* where the difference between the measured travel times and the actual travel times on all sub-links for both routes are compared. (Actual travel times are computed via the via link performance function.)
It should be mentioned that this method is not fully correct, as the travel time on an *endlink* cannot be computed in advance, but is included within the measurement. So in cases of congestion the computed travel times should be a little higher and therefore the peeks from *Figure 5-14* and *Figure 5-15* might be a little lower.

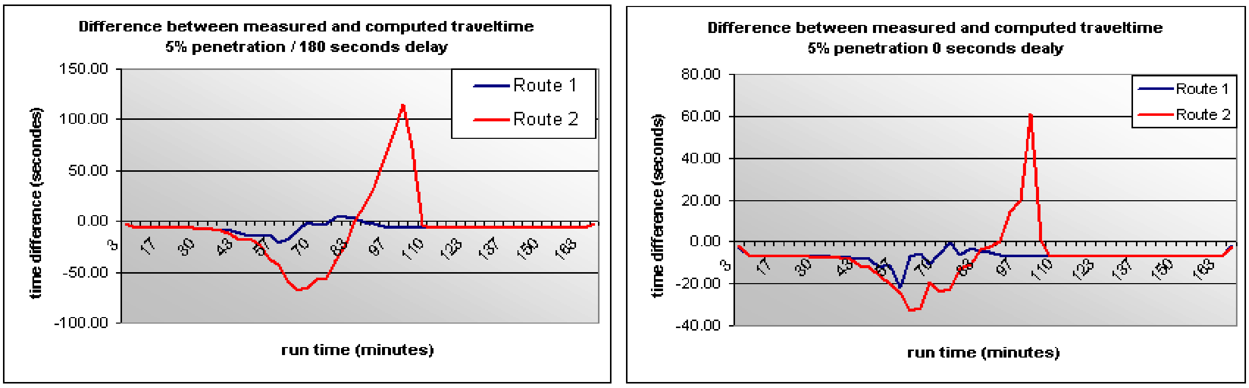


Figure 5-14 Difference between measured and computed travel times for a 5% penetration rate: right 0 s. delay left 180 s. delay.

Figure 5-14 shows this difference between the scenario with 180 s. delay (left) and 0s. delay (right) at a 5% penetration rate. It can clearly be seen that on route 2, first the DRGS underestimates the travel times, (The graph shows a negative value, which implies that the computed travel time is larger then the measured travel time) which is predominantly happening when a queue is building up. Afterwards when the demand starts to decrease, the DRGS overestimates the travel times (the measured travel time is larger then the computed travel time). It can be seen that in case of the reduced delay, the two peeks are significantly smaller, compared to the situation with a180 seconds delay. So the DRGS then performs better only the influence is not so big.

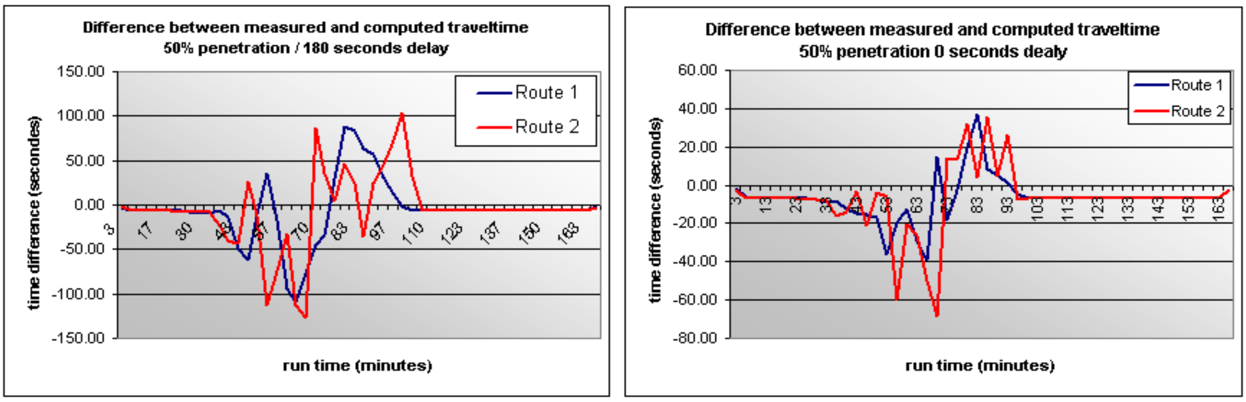


Figure 5-15 Difference between measured and computed travel times (50% penetration)

Figure 5-15 shows the same picture but then for a 50% penetration, it can be seen that in case of the scenario without delay the peeks are significantly smaller. Besides the peeks do not change so much over time as the peeks in case of the 180 seconds scenario. The facts that the fluctuations between measured and computed travel times are far less, in case of a reduced delay, can be seen as the cause for the fact that improving information has more benefit at higher penetration rates.

More detailed view on the improvement of the quality of traffic information:

- Improving the quality of the information is most beneficial at higher penetration rates

5.3 Users compliance on the 2-linksystem

Within the previous 2 sections the behaviour of the DRGS-users was modelled to be 100%. A traveller was considered to comply in any case with the advice of the DRGS. As mentioned in the theory of chapter 2 that is of course not always the case. In this section the reaction of the user will be investigated and the result on the profitability of the DRGS will be shown.

In *Figure 5-16* the equivalent graph of *Figure 5-4* is presented, it shows again the relative travel time profit. (Because the profitability of the DRGS's is extended to over a 50% penetration rate, *Figure 5-16* shows the full 100%.)

Figure 5-16 Relative profit with non-complying travellers

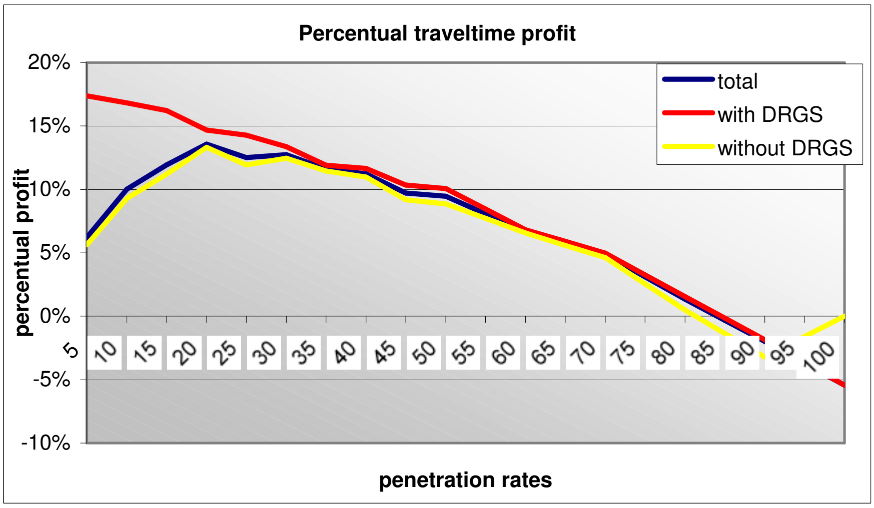


Figure 5-16 shows that the DRGS is still profitable up to an 85% penetration rate. So it turns out that in case not all travellers do comply with the DRGS the effective penetration rate is lower and thereby the positive result of the DRGS is stretched further, compared to the case where all travellers would comply with the advice.

Influence of users compliance on the relative travel time profit:

DRGS-user:

- Profit is more or less the same compared to the situation where they are obliged to follow the advice.
- The profit is stretched to higher penetration rates.

Non-user:

- Optimal point is shifted towards a penetration rate of around 20%-25%.
- The profit is stretched to higher penetration rates.

All together:

- The fact that not all travelers comply with the DRGS stretches the figure of the profitability and makes the DRGS profitable at higher penetration compared to the case where all travelers comply.

Of course these results are very much depending on the way the behaviour is modelled. As mentioned in chapter 3, there are 4 diverse types of users that react all different to the 6 different criteria described. The distribution of travellers over these 4 groups can then have large impact on the outcomes. For *Figure 5-16* above the distribution over groups is set as in *Table 5-2*.

Table 5-2 distribution of user groups

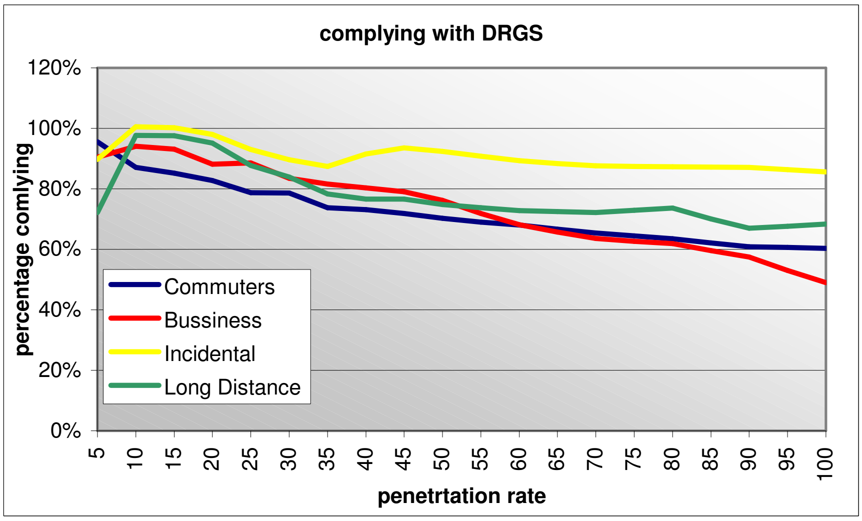
Group	percentage
Commuters	55%
Business	15%
Long Distance	15%
Incidental	15%

The compliance parameters themselves

In Figure 5-17 the compliance of the users is shown for the used groups. It can be seen that over 80% of the incidental travellers that are equipped with a DRGS, comply even at 100% penetration. So apparently their criteria (minimize travel time, minimize route change and avoid traffic lights) are not violated very often. In general it can also be seen that most travellers do comply at low penetration rates, but when more vehicles become equipped, their criteria are violated more often, and they lose their willingness to comply with the DRGS.

For 3 of the for groups a peak can be measured around 15%-20% penetration, which means the criteria on which the compliance are based perform best there, that implies that also the DRGS performs best at these penetration rates.

Figure 5-17 Complying of the travellers



For the total reaction of the travellers this results in *Table 5-3*, from which it can be seen that eventually even 63% does follow the advice of the DRGS at a 100% penetration rate. Logically the commuters generate the largest part of that 63% compliance, as they are the largest group. (55% according to table 5-2.)

Table 5-3 total complying travellers

Group	percentage	compliance at 100%	perc. of total
Commuters	55%	60%	33%
Business	15%	50%	8%
Long Distance	15%	68%	10%
Incidental	15%	83%	12%

Total complying percentage at 100% penetration 63%

So even case every traveller is equipped still 63% will follow the advice of the DRGS, of course under the assumptions made in chapter 4. This phenomenon looks a bit counterintuitive, as on might expect in case the traffic situation worsens, fewer users will follow the advice. However the fact that not all users do follow the advice of the DRGS advice, stretches more or less the profitability an thereby lets the criteria perform better and thus more travellers are willing to comply even at high penetration rates.

On the other hand it is interesting to see the influence of the different criteria on which the compliance is based. This is shown for the 4 criteria that are influencing the results in the 2-link system. (Traffic lights and travelled distance are not of any influence in that case, so they are not shown)
In *Figure 5-18* it is shown that the different criteria have a different impacts at different penetration rates. The influences of three of the four criteria are increasing when the penetration rate increases. So at low penetration rates only a small percentage of the DRGS-users encounters a bad experience on these criteria it is thus logical that a lot of the travellers still do comply with the advices.

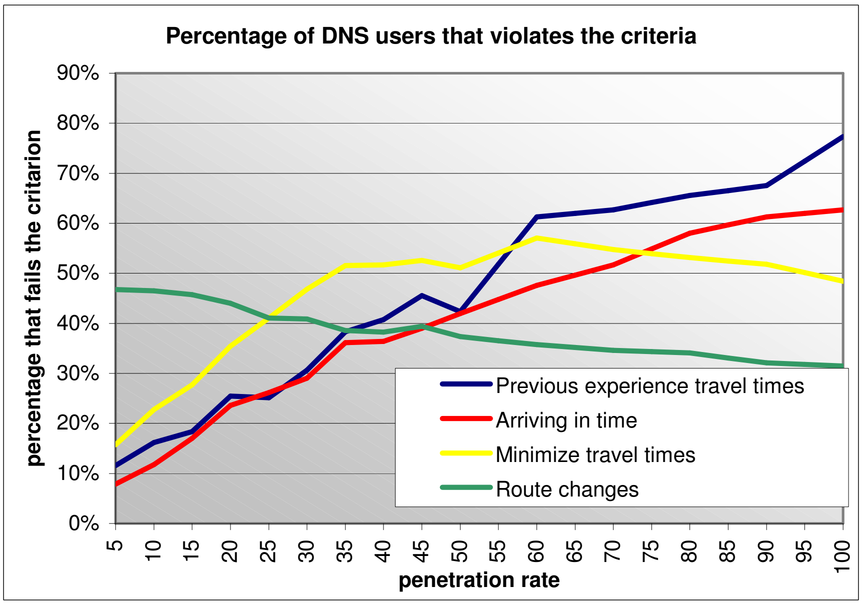


Figure 5-18 Influence of the compliance criteria on the users reaction

From *Figure 5-18* it can also be seen that the criterion that is violated most, is the one concerning the previous experienced travel times. This however only influences the behaviour of the business travellers. (See Table 3-3)

Influence of the compliance parameters themselves:

- As the penetration rate increases, the percentage of complying travelers is decreasing as well, implying that the criteria on which the compliance is based are violated more often
- Different criteria are influenced differently as the penetration rates increase.
- For this case, the experience with the previous travel times is most dominant

Sensitivity

To investigate on the sensitivity of the chosen parameters for the compliance, more runs with the model are performed. Therefore a scenario is used where most travellers have the experience of the previously encountered travel times as their major criterion in order to see whether that changes the results a lot. As that is the criterion that is violated most often in the original run, it is most interesting to see the influence in such an "extreme case"

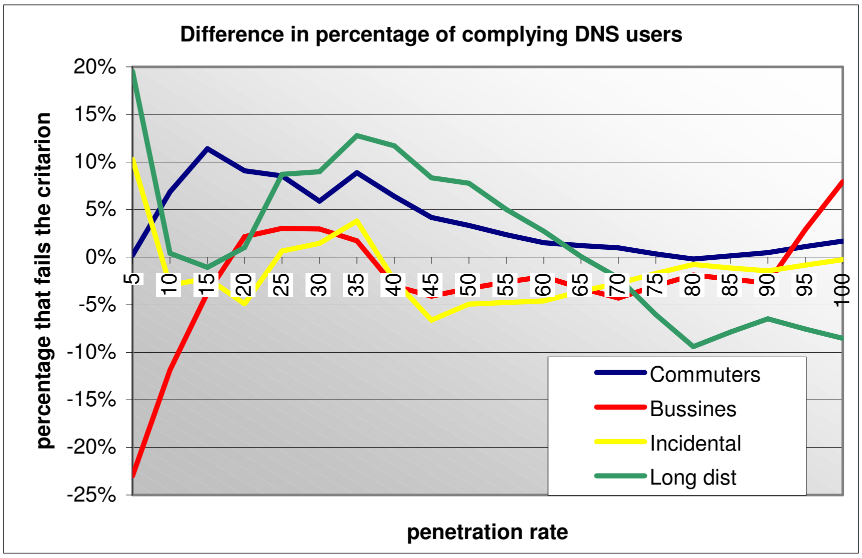
To do so Table 3-3 has been changed such that most travellers have the criterion of "the previous experienced travel times" as their main criterion (see *Table 5-4*)

Table 5-4 changed compliance behaviour for sensitivity analyses

criteria Type traveler	Arriving in time	Minimize traveltime	Minimize route changes	Previous	distance travelled	traffic lights
Commuter	**-**	2	3	**1**	-	-
Business	3	1	-	2	-	-
Long distance	3	**-**	-	**1**	2	-
Holliday	-	2	1	-	-	3

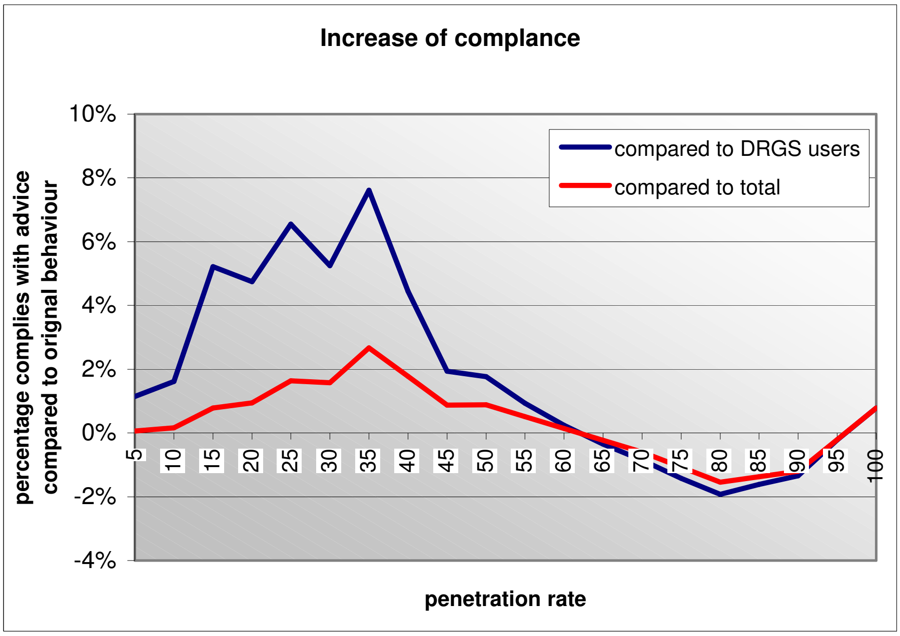
This change leads to more or less the same figure as *Figure 5-17* where the percentage of DRGS-users that complies with the criteria is shown. To see the difference, caused by changing the dependence on the different criteria, Figure 5-19 is shown. Here the difference between the original run and the run with the parameters of Table 5-4 is shown. It can be seen at lower penetration rates the compliance is higher compared to the original case and at higher penetration it is more or less the same.

Figure 5-19 Differences in compliance reaction for users groups.



On average that leads to *Figure 5-20*, where it can be seen that there is an increase in compliance for the number of DRGS-users. However when that is compared to the total number of vehicles involved the increase is far less as the penetration rates are low.

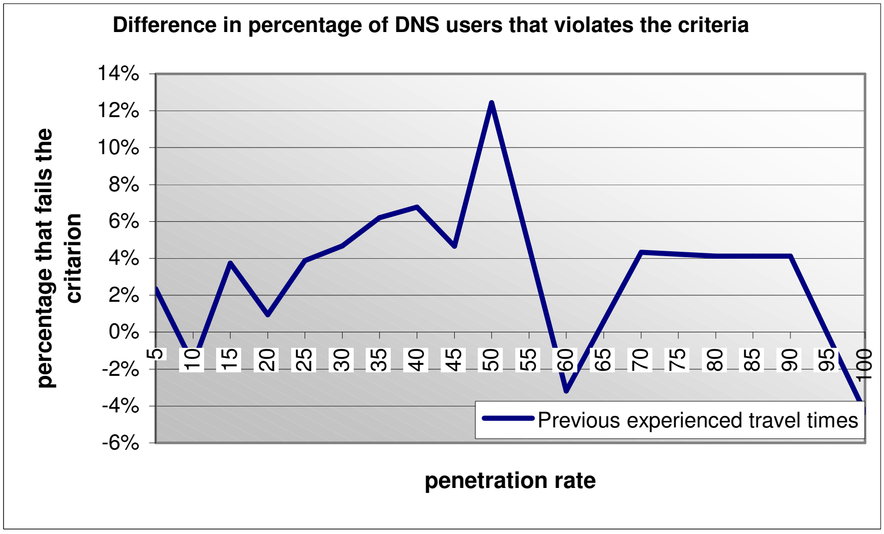
Figure 5-20 percentage of users that complies with the advice compared to original behaviour



So from these considerations it would be logical to conclude that changing the situation to a scenario where all travellers base their compliance on mainly one of the criteria leads to a higher compliance at low penetration rates and a lower compliance at higher penetration rates. More in detail it is interesting to investigate on the criterion used. Figure 5-21 shows the difference between the original run and this new situation. The result is a bit counterintuitive because there are, at low penetration rates, more travellers that have a negative experience.

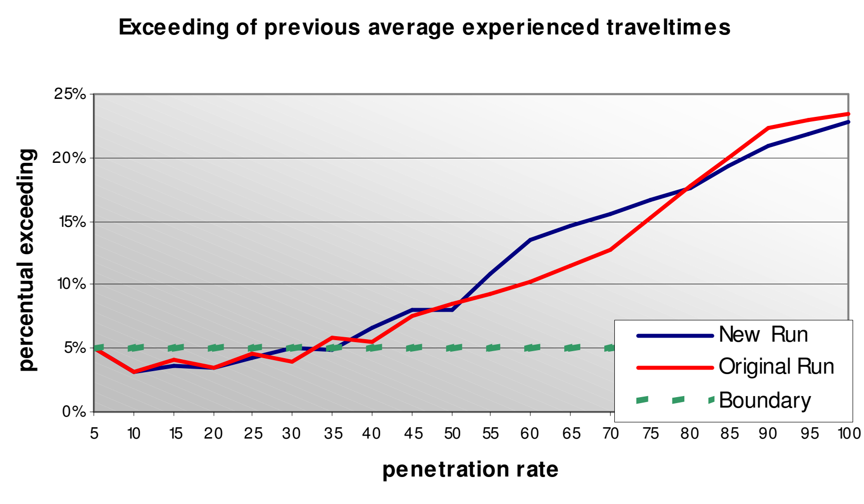
However the criteria is modelled such, that the there is a 5 % margin which has to be crossed in order to let the travellers reject the advice.

Figure 5-21 Difference in percentage of DRGS-users that violates the criterion " Previous experienced travel time" compared to original behaviour



To investigate on that in more detail the average difference between the current experienced travel time and the average of all previous runs is computed. Figure 5-22 shows this relation. It can be seen that on average the value of the difference is below that 5 % limit, so there is no extra influence of the fact that the this criteria is violated a bit more at low penetration rates. (So practically it is not violated) Besides that it can be seen (from *Figure 5-18*) that for low penetration rates the influence of the criterion concerning the previous experience is not so big.

Figure 5-22 Exceeding of the criterion "previously experienced travel time"



- Changing the parameters of compliance to an extreme scenario has influence on the outcomes. In this case it increases the compliance of DRGS's by nearly 8% (at most)
- As the change to an extreme case results is maximal 8% shift in compliance the general results are considered to remain valid.
- A more founded implantation of the users compliance is preferable.

5.4 Rotterdam network case study

The results of the previous sections are based on the theoretical 2-link network. The same computations can be performed on a network level. *Figure 5-23* shows the used network again. Appendix B shows all links that are used more in detail. As the computation time for running the same model on a network scale takes a lot more time it is chosen to only perform the simulations for the case where all travellers do comply with the DRGS and no further investigations have been made on the performance of the DRGS in case of users reaction. (That implies the results are comparable to the situation of section 5.1, but than on a network level)

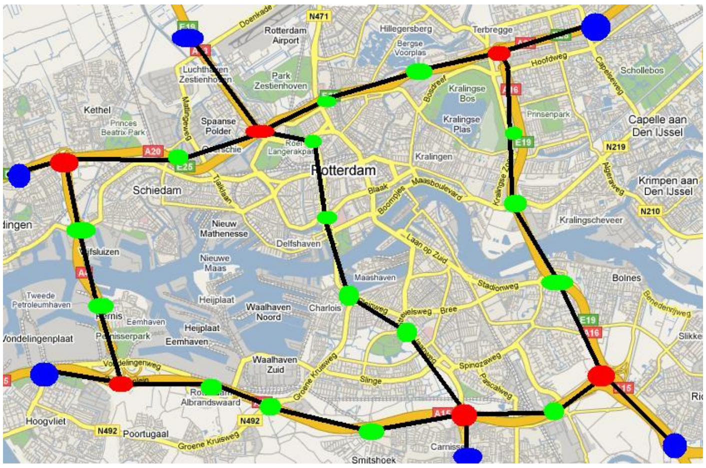


Figure 5-23 schematic representation of the network

To archive proper results in this network scenario, based on the Rotterdam network, it is important that the data that is used for the simulation does fit with the model. One could put a lot of effort in calibrating the model, such that it exactly fits the reality, however as the traffic model, which is used in for this study, is quite rough, it is questionable whether that would lead to more reliable results.

For the network only 6 origins and destinations are used (See the blue nodes in *Figure 5-23*.) Therefore it is very difficult to use a real OD-matrix to generate the right traffic, as that usually contains much more O-D pairs. For that reason it is chosen to have the same amount of traffic from all six nodes to another. So in that matter this network case is dissimilar from the real Rotterdam situation.

Furthermore it turns out that it is difficult to determine the critical amount of traffic for the modelled network. In case of the 2-link system it is easy to compute the capacity of the system and thus determine a traffic demand that is close to that. In case of this network scenario it is more difficult to determine a demand that is close to the capacity. Especially as at higher traffic input rates, the congestion starts also occurring at the entrance links. To solve that some adaptations had to be made to the link properties and thus also in that way the model doesn't fully represent the real Rotterdam case anymore.

Another problem that does occur when using the network as shown in *Figure 5-23*, is that a lot of travellers become captive of a certain route. It is obvious that if one is travelling from the direction Delft towards

Maassluis there is only one plausible alternative and that is via the A13-A20. In general it can be stated, that for a little more then 50% of the OD-pairs there is no decent alternative route. (16 of the 30 pairs are considered to have one route and thus no alternatives.) Compared to the 2-link system where all travellers have always one alternative route that will have some influence the results. It is therefore chosen to "implement" a new group of users to show the results for: the travellers that have a DRGS and also have the opportunity to actually change routes. This in order to make a distinction between the DRGS-users that do have a DRGS but cannot use it due to the fact that they have no alternative. In the general description of the results this group will be presented and the results of the whole group DRGS-users are in general performing a little worse.

Vehicle delay time
Figure 5-24 (appendix C6) shows the total time loss for the whole network. When comparing this to the 2-link case (*Figure 5-1*), it can be seen that for the total traffic situation the improvements are significantly less. Equipping around 25% percent of the vehicles with a DRGS leads in this case to a reduction 7% of lost hours.

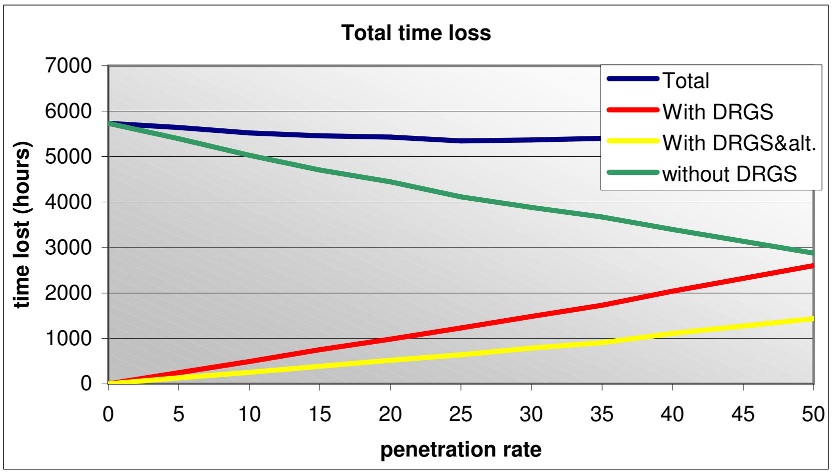


Figure 5-24 Total time loss for the network

Influence on total time loss in the network scenario

DGRS-users with alternative:

- Has an increasing influence, mainly because their number is increasing with the penetration rate

Non-users:

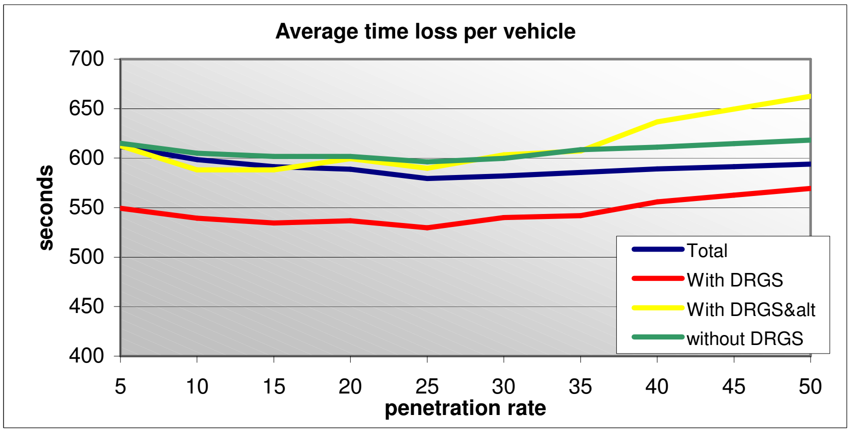
- This is the opposite influence of the influence on DRGS-users, mainly because their number is decreasing with the penetration rate.

All together:

- Equipping around 25% of the travelers with a DRSS leads to a reduction of the total travel time loss of nearly 7%

Vehicle delay time per vehicle
As mentioned it is also interesting to see these results based on an individual basis. This is done and in *Figure 5-25* this is shown.

Figure 5-25 Vehicle delay time per vehicle



Logically it can also from this figure be seen that the total profit of using a DRGS is around 7% for the whole system. Remarkable is the fact that, the group of users with a DRGS and an alternative route, seem to have the most delay per vehicle especially when the penetration rates exceed 30%. That could be explained because these are the travellers that do have an alternative, those are primarily the travellers with the longer routes and the delay is here the difference between the free flow travel time and the experienced travel time.

Influence on average time loss in the network scenario:

DGRS-users with alternative:

- The Individual delay for the group of users higher due to the fact that they have generally longer routes.
- Their average delay does decrease until 25%

Non-users:

- Have a small increase in delay, most efficient at 20%

All together:

- Total average delay has a minimum at around 25%-30% penetration rate

Distance travelled
The travelled distance is a good measure to see the influence of the DRGS. In this case this is only performed for the total group of travellers, which is shown in *Figure 5-26*. It can be seen that the more travellers become equipped with the DRGS, the lower the average travelled distance becomes. In this scenario the total distance travelled is reduced by 2%.

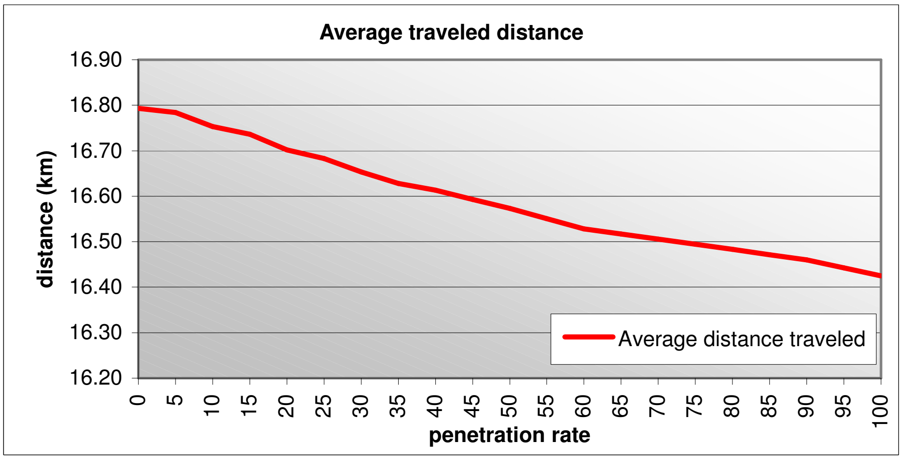


Figure 5-26 Average distances travelled in the network

The reasoning for this decrease can be twofold. On the one side it can be the case that more travellers are advised to take the shortcut through the city, because there are traffic "problems" on the other parts of the network. That matter has of course to do with providing a better route based on traffic information.

There is however another aspect that might play a role here, which is the fact that travellers have a chance of not having the most beneficial route in the beginning, according to the logit-model. In that case redirecting that traffic is not necessarily because the traffic information provides a better alternative route, but it can also be because the initial route was not set to be optimal. In that case the DRGS does act similar to a static route guidance system and the influence should not be contributed to the DRGS itself.

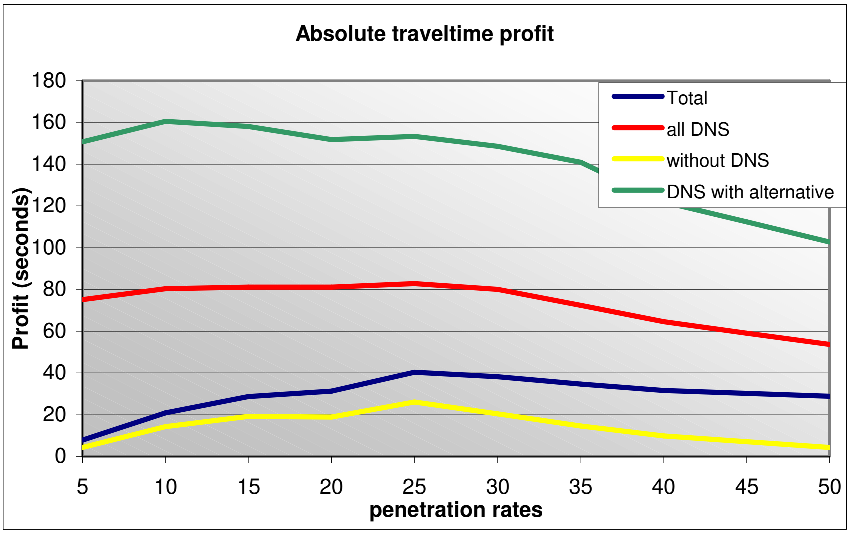
Influence on the traveled distance in the network scenario:

- The traveled distance can be reduced by 2% in a network case
- It is questionable whether this decrease could fully be attributed to the dynamic influence of the DRGS

Travel time savings

Figure 5-27 (appendix C8) shows the absolute travel time profit for al vehicles. It can be seen that for the DRGS-users, who do have alternative routes, there is significant profit. Especially the difference between the users and non-users is remarkable compared to the scenario of the 2-link system.

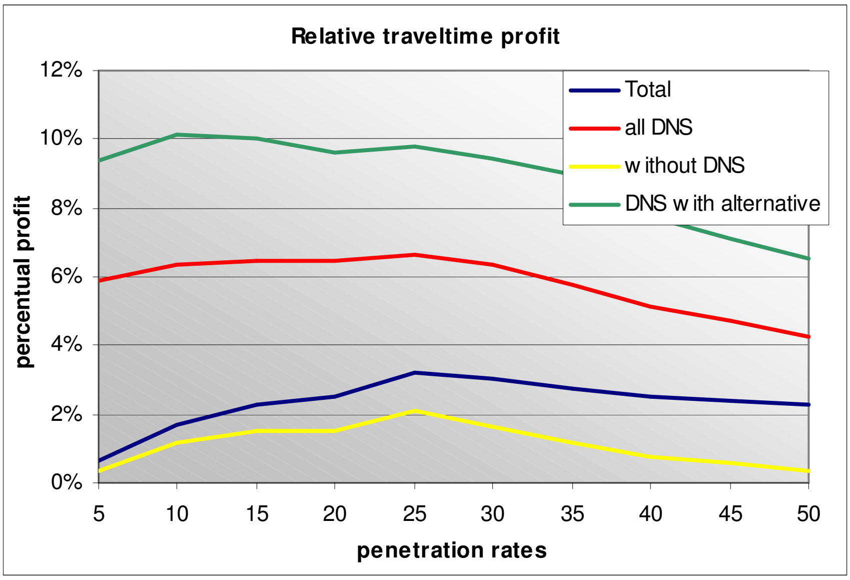
Figure 5-27 Absolute travel time profit



In *Figure 5-28* (Appendix C9) the same result is shown but than again for the relative profit. Compared to the 2-link case it is remarkable to see that the profit for the DRGS-users that do have an alternative route, the profit is only around 10% compared to the almost 20% in the 2-link case. Moreover the profit for the non-users is hardly visible compared to the 2-link system. It is in this case at most 2%.

It is also interesting to see that although the average profit seems to be less compared to the 2- link system the profitability is extended to higher penetration rates compared to that 2- link system. Also for that an explanation can be given. Because the fact that over 50 % of the travellers is "captive" of a route, the "effective" penetration of the DRGS's should be reduced by nearly 50% in order to get the same percentage of influenced travellers.

Figure 5-28 relative travel time profit



Influence of travel time profit in the network scenario:

DGRS-users with alternative:

- Profit for DRGS-users with an alternative is around 10%

Non-users:

- *Do benefit for maximal 2% in terms of travel time profit*

All together:

- The profitability for the system is extended to higher penetration rates due the fact that there are a lot of captives in the system.

Economically

As in section 5.1 the network case can also be reviewed in a more economical way. In *Figure 5-29* it can be seen that the difference between the user and non-user is larger as in the 2-link system and the DRGS is profitable at higher penetration rates.

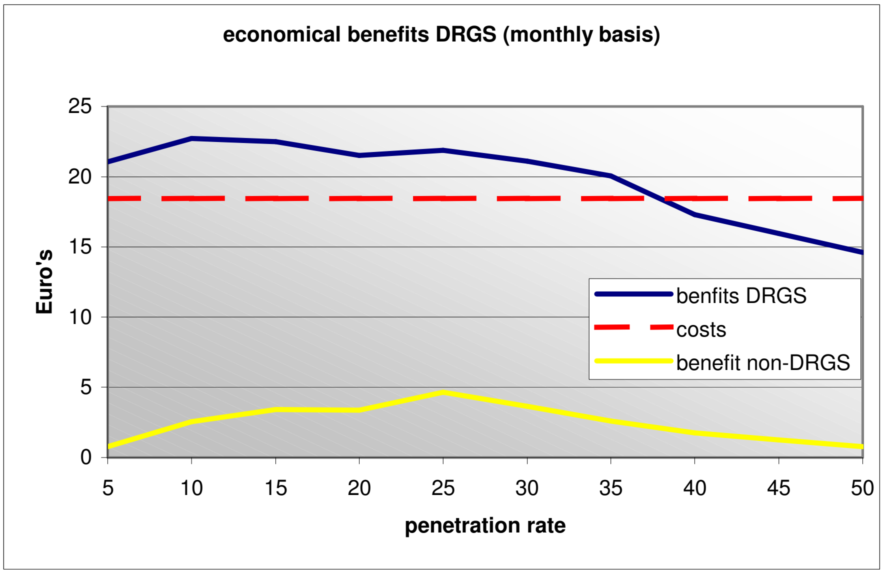
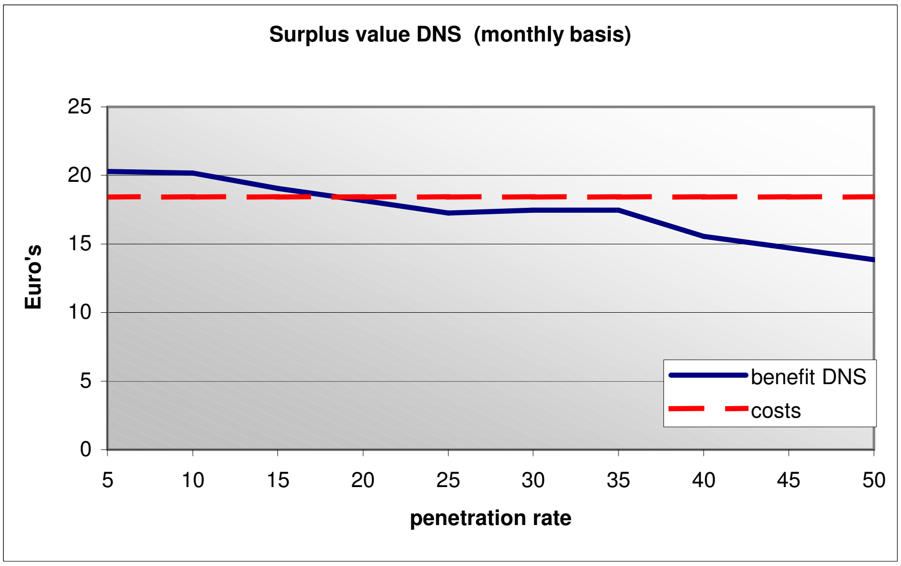


Figure 5-29 economical benefits in network case

From *Figure 5-30* it can be seen that when the difference between the profit of user with an alternative route and the non-user is plotted that the system is beneficial unto 15% penetration rate. Besides that the descent of that line less steep compared to the 2-link system, so when for instance the costs can be reduced the system might be profitable to a much longer extend.

Figure 5-30 Surplus value for DRGS in network case



Economical review of profitability in network scenario:

- Beneficial to 35%-40% compared to its purchase cost
- Beneficial to around 15% compared to profit of the non-users

Route choice

As mentioned in the beginning of this section, there are lots of travellers that are captive of a route (around 60%) Which implies that there are at most 40% travellers that have a real choice. That has of course consequences for the route choices to be made in the model. To investigate on that for every link it is checked what is the amount of DRGS's that use that link and that is compared to the number of DRGS's that actually has an alternative route. *Figure 5-31* shows the sum of that for all links.

Figure 5-31 Percentage of travellers that does have a "real" route choice measured per link

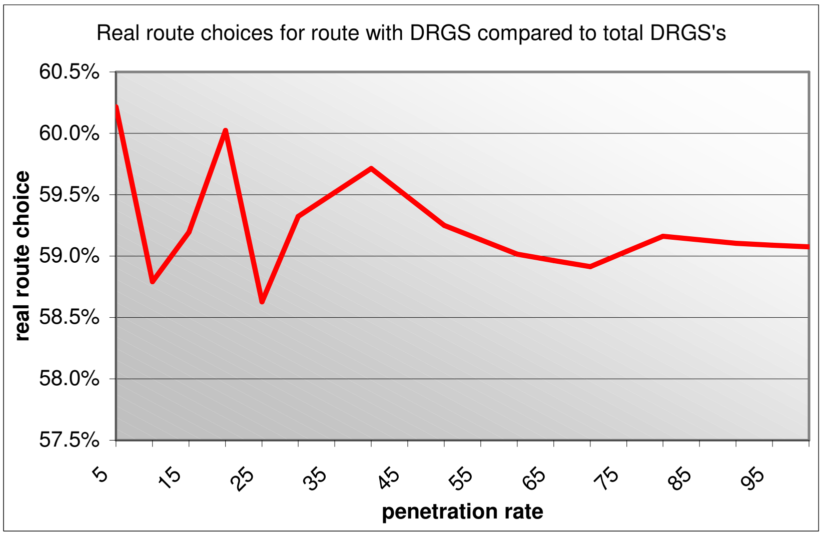


Figure 5-31 shows that this real number of travellers that have a route choice on a link is around 60%. That is different to the before-mentioned 40%, which was to be expected. The reason behind this difference is that predominantly the longer routes have one or more alternatives. Longer routes incorporate on average more links. So when the links are considered, the average number of vehicles that pass on a link and do have a route alternative is larger then when the vehicles themselves are considered.

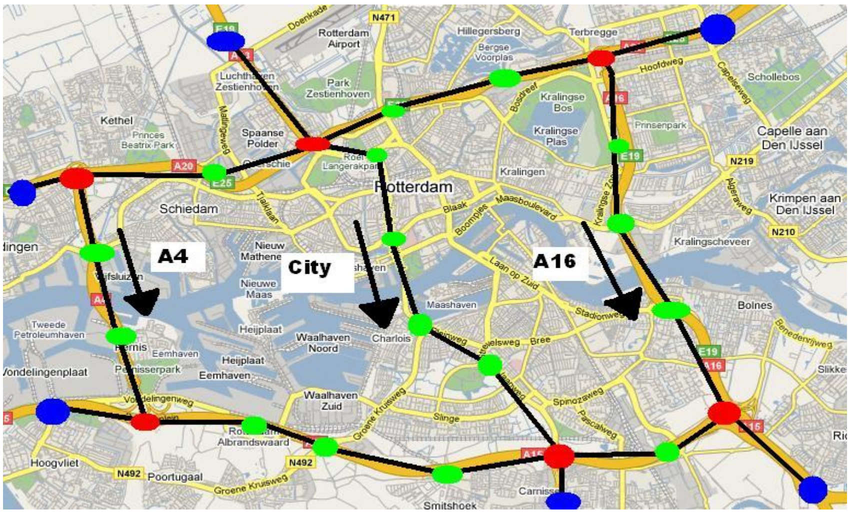
Influence of route choice in network scenario:

- There is a difference of around 20% when the route choice for the individual traveler is compared to the groups of travelers on a certain link.

Route changes

To get a better insight in the changes between different routes some routes need to be defined. In the 2-link system it was easy to determine 2 routes from origin to destination. However as there are in the network case several origins and destinations and thus more routes in between, it is chosen to investigate on the north-south relations. (See Figure 5-32)

Figure 5-32 different route for Rotterdam network case study

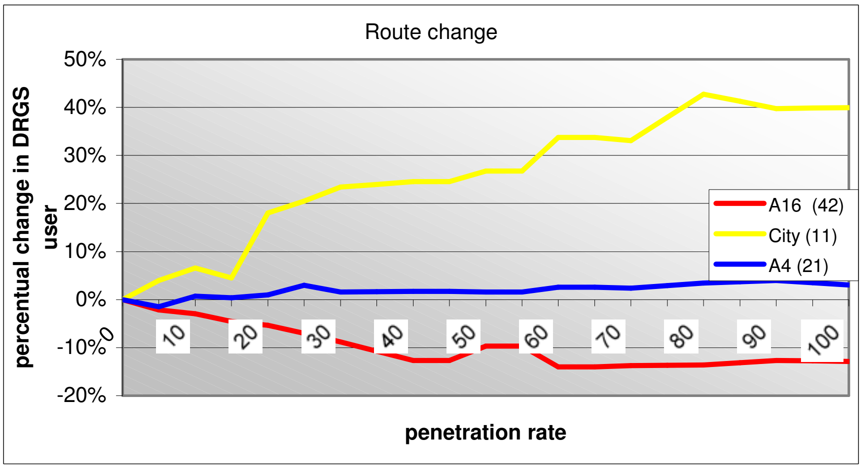


On one of the links of a route the total amount of traffic is counted. This is done on the following sections:

- A4 from Kethelplein to Beneluxplein
- A16 from Terbregseplein to Ridderster
- City road from Kleinpolderplein to Vaanplein.

In *Figure 5-33* the effect of the DRGS on the changes over these routes is shown. The number of vehicles compared to the initial situation is presented, it can be seen that around 40% extra traffic is rerouted over the inner city link compared to the situation without DRGS. In this case that leads to a reduction of traffic on the A16, whereas traffic on the A4 is more or less the same. Of course percentages on both motorways are less because of the initial amount of traffic that was on these roads is much more and thus the relative change is less.

Figure 5-33 Change in number of user on different routes

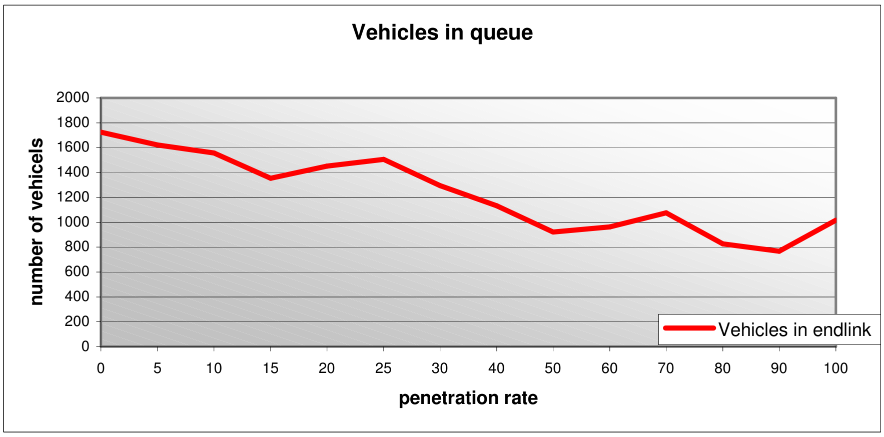


Influence on route changes in the network scenario:

- The shift from routes can be very different on different types of links in the network.

Length of congestion,
Another criterion used to verify the influence off DRGS's on is the influence on the total congestion in the system. Figure 5-34 shows this. It can be concluded that that the number of vehicles that is waiting on the "*endlink*" (which corresponds more or less to the number of vehicles that is in a traffic jam in a real situation) decreases at increasing penetration rates, and it shows more or less the same pattern as *Figure 5-25*

Figure 5-34 Queue lengths in the network



Influence on the length of congestion in the network case:

- Congestion is reduced at increasing penetration rates
- Optimal situation as again around a penetration rate of 85%
- A reduction almost 50% in congestion length could be achieved.

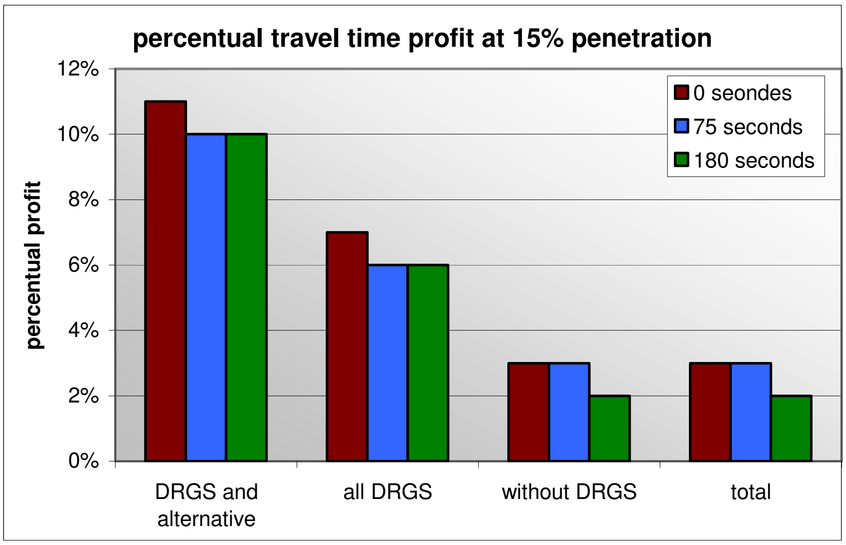
Influence of different types of links
In Figure 5-33 it already shown that the influence on different parts of the network can be quite opposing. It can be seen that there is a remarkable increase of DRGS-users through the city centre and a decrease on the motorway (A16). Due to the fact that the link is not so attractive in the initial state, where traffic is assigned by the logit-function (equation 3-2) and becomes more attractive when the traffic situation plays a role, this percentage can become so high (around 40%) In general this means that the impact on smaller low-capacity roads can be much higher than on a high capacity motorway.

Influence on different types of links in the network case:

- The impact on smaller, low-capacity links can big large because of its low capacity.

Influence of traffic information
As it would take too much running time to investigate the influence of the quality of information on all penetration rates it is chosen to that only at 15%. *Figure 5-35* shows these relations for all users groups. It can be seen the all users do benefit from these improvements, although it should be mentioned that the differences are quite small.

Figure 5-35 Influence of the quality of information in the network case



The influence of information quality in the network situation:

- For all groups a small profit is observable when the quality of information is improved

6. Conclusions and recommendations

In this chapter the conclusions and recommendations of the study will be presented. To do so it is worthwhile to pay some attention to the main goal as stated in the introduction: Determining the effects for travellers, who make different route choices, influenced by an increasing number of dynamic route guidance systems and present the consequences of that for RWS as the national road authority.

First briefly the results of chapter 5 will be summarized. Afterwards the consequences of those results and the suggestions how to cope with those consequences will be presented. This will be done for the dynamic route guidance system users (DRGS-users), the non-users and RWS as the representative of all users in general. This means RWS serve the general public interest, as a consequence that doesn't mean that their interest is beneficial for al, as the disutility of a few travellers might lead to a profitable situation for the majority of travellers. Finally a view on the possible future will be presented.

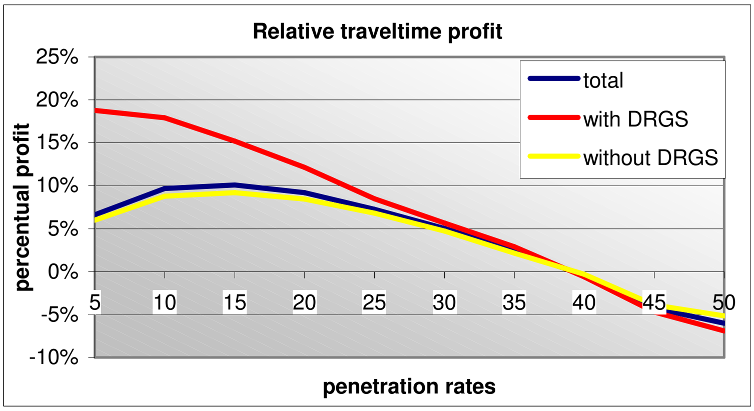
It should be mentioned that the results are depending on the assumptions made. It is likely that in case of a combination of a different network, a different composition of traffic and other changes in variables would lead to other optimal results.

6.1 Brief summary of results

Increment of penetration rates

Increasing the penetration rate of DRGS's in a traffic system leads to a travel time loss reduction for all users, compared to system without DRGS's. The profit for the individual user is highest at low penetration rates and is almost linearly decreasing. At around 15% penetration rate the profit for all users together is highest, at penetration rates above 15% this benefit is decreasing. When around 40% of the travellers are equipped with a DRGS the situation becomes worse than in case no travellers were equipped with DRGS's. These percentages hold more or less for all criteria used. Whether it is travel time loss, vehicle delay time or even queue lengths, in general the same optimal solutions are found. *Figure 6-1* again shows this development

Figure 6-1 general result for relative travel time profit



Improvement of information quality
Improving the quality of the traffic information leads in general to better route choices of the DRGS-users however the influences of that is only noticeable at higher penetration rates.
Over penetration rates of 25 % there is a clear advantage visible of using more accurate traffic information. This implies that the profitability of using DRGS's is extended to over 50%. (Compared to the before mentioned 40%) This advantage also holds for the non-users, who besides that also have a slightly larger profitability at low penetration rates. (Around 2% more travel time saving)

Influence of users compliance
When the influence of the travellers themselves is also taken into account the process becomes more complex. In general it can be stated, that due to the fact that not all travellers do comply with the advice of the DRGS, the results found in the situation where only penetration rates are investigated, are extended to higher penetration levels. When using compliance, the maximum profit for all users together is at around 25%-30%, whereas the moment that the situation gets worse compared to the situation without any DRGS's is shifted to around an 80%-90% penetration rate.

Effects on network scale
When applying the increment of DRGS's to a network case the problem arises that not all travellers do have route choices alternatives. Lots of travellers are captive of a certain route and that significantly influences the results. Therefore it is chosen to distinguish the users that do have an alternative route and a DRGS separately. It is shown that the maximum profit for the DRGS-users that do have an alternative is significantly lower in a network scenario compared to the theoretical 2-link system.

6.2 Conclusions for the stakeholders

For all different stakeholders the conclusions of the result of chapter 5 will be represented in the next three sections

6.2.1. Dynamic Route Guidance System users

Increment of penetration rates
Dynamic route guidance systems provide an advantage for the DRGS-users themselves. The travel times can be reduced by around 20%, at low penetration rates. This implies there is a considerable benefit for them and it is preferable to use such a system. However it is also shown, when the penetration rate increases the profit becomes less. At around 40% penetration rate there is no profitability at all and it is harmful to use a DRGS.
When the system exceeds a penetration rate of 40% it is shown that the assigning of traffic starts oscillating. This leads to a continuous over and under estimation of the travel times, which results in worse advices for the DRGS-users.

Economical influence
When the profit is compared to the cost of purchasing the system itself, and moreover to the benefit of the non-users as well, it seems not so evident that travellers will buy and use the DRGS until the before mentioned 40% penetration rate is achieved. (As this influence of the DRGS's becomes negative) Using that economical perspective leads to a conclusion that the penetration rate will never exceed 10% because afterwards it is not beneficial anymore.

Improvement of information quality
It is shown that improving the quality of the information for the DRGS is not increasing the profit of the individual user very much, especially not at low penetration rates. However as the penetration rises the influence of better information becomes more and more significant and it eventually delays the moment where the DRGS is not beneficial anymore from 40% to around 50% penetration rate. So especially when more travellers are equipped it is worthwhile to improve on the traffic information.

Influence of users compliance
The fact that not all travellers do comply with the advices of the DRGS does stretch the benefit of the DRGS to higher penetration rates. Making the advice of the DRGS better does increase the compliance, and increasing the compliance makes the benefit drop faster. This interaction leads in general to a system where the decrement of profit for the DRGS-user is less strong, compared to the situation where all travellers do comply with the advice and a system. By using compliance behaviour the profitability can be stretched to 80 to 90 percent penetration rate.

Effects on network scale
In case of a network, the profit of a DRGS is less, compared to the theoretical situation where only two links are considered. It is shown that only a profit of 10% in reduced travel time is possible. Another matter of importance is the fact that a lot of travellers have no (realistic) choice alternative within the network. Therefore the actual number of travellers that is influenced is far less compared to the theoretical case. This, “being captive of a certain route” leads to a system that, at higher penetration rates, still provides a beneficial traffic situation.

- DRGS-users benefit at most 20% in terms of travel time profit, in the 2-link situation when all travelers comply with the advice.
- Their individual benefit is decreasing and becomes negative, at penetration rates around 40%.
- At penetration rates over 40% the advices for the DRGS-users starts oscillating.
- Purchasing a DRGS seems profitable to around 10% penetration rate.
- Improving the traffic information does not increase the individual benefit of the DRGS user very much.
- Improving the traffic information does stretch the advantages of the DRGS to around 50% penetration rate.
- When not al travelers do comply with the advice of the DRGS the advantage for the DRGS-users is stretched to a penetration rate of around 85%.
- In case of a network approach the maximum profit is around 10 % in terms of travel time savings.
- Because not everybody has a realistic route alternative in the network scenario a lot of travelers are not influenced, although they do have a DRGS.

6.2.2. Non-users

Increment of penetration rates
Also the non-users encounter benefits, caused by the route changes of the DRGS-users. When only a few vehicles are equipped the non-users can save around 5% travel time. Moreover when more vehicles are being equipped with a DRGS the profit for the non-users increases to around 10%, when approximately 15% of the vehicles are equipped.

Economical influence
As the purchase of a DRGS is an extra investment for the user and the non-user also experiences an advantage of the DRGS, it would be unwise from an economical perspective, for a non-user to buy a DRGS at a penetration rate over 10%, as the cost then exceed the benefits. Therefore the non-users will never reach their most beneficial point, which is at around 15% penetration rate. The difference between the profit at 10% and 15% penetration is however not so big. (1%-2%)

Improvement of information quality
Providing more accurate traffic information to the DRGS results in a slightly higher profit for the non-users at low penetration rates. When the penetration rates increase the influence of the quality of information becomes more significant and eventually it stretches the profitability to a higher extend.

Influence of users compliance

When the users reaction is concerned, it is logical that the non-users don't change their behaviour, however they do experience the actions of the users. As not all users do comply with the advice anymore, a higher penetration rate is required to achieve the optimal situation for the non-users. That moment is shifted from around 15% penetration rate to nearly 30% penetration rate. However the negative consequence, namely the moment that the situation gets worse then without DRGS's is also shifted to around 85% penetration rate.

Effects on network scale

Also for the non-users the influence is less compared to the 2-link scenario. They save up to 2% travel time at a penetration rate of 25%. In line with the users of the DRGS's also the non-users profit is stretched too much higher penetration rate because of a lot of the DRGS-users are captive.

- When only 5% of the travelers are equipped the non-users can save up to 5% in terms of travel time savings.
- At a penetration of 10%-15% their profit is maximal. (10% travel time savings)
- At a penetration rate of around 40% also the benefit of the non-users becomes negative.
- Due to the fact that the economical optimum for the DRGS-users is at around 10% it is unlikely that the optimum for the non-users will be achieved without any public measures.
- Providing more accurate information results in a slightly higher profit for the non-users at low penetration rates.
- Providing more accurate information does stretch the advantages for the non-users to around 50%.
- For the non-users the optimal point moves to around 30% penetration rates when DRGS-users have the opportunity to neglected the advice.
- Very small benefit in case of the practical network situation.

6.2.3. Rijkswaterstaat

Increment of penetration rates

RWS is stated to be the representative of the public interest. At low penetration rates the non-users are the main group of interest as they contain most travellers, so their profit has most influence on the total profit. As there are a few vehicles that do benefit a lot and the rest of them befits a bit from that as well, there is nothing to worry about as the total situation improves. It can be stated that, in case of the theoretical model, the maximum social benefit is at around 15 % penetration rate and at around 40% all benefit is disappeared.

It is shown that at penetration rates over 40%, the traffic system start oscillating, which has some bad consequences. Congestion can start occurring on the routes, which had no problems before. That also harms travellers, which previously were not involved to the problems.

Economical influence
The fact that from an economical perspective it is doubtful whether the maximum point of social benefit will be achieved, could be seen as a disadvantage of the system.

Improvement of information quality
In case of an improvement of the information for the DRGS both the users and non-users profit from that. So from the total perspective it is valuable to achieve more accurate information.

Influence of users compliance
When the effect that not all users do follow the advice of the DRGS is taken into account, the moment that the situation is worse than without any DRGS's is delayed to around 85% which makes the system profitable to a longer extend.

Effects on network scale
One of the outcomes in the network study is the reduction of the travelled distance. By increasing the number of DRGS's the total distance travelled is being reduced by using DRGS's, it is however questionable when this can be fully attributed to the dynamic influence of the DRGS. The influence of the static part, assigning travellers to a shorter route, is difficult to distinguish here.
On a network scale the profits seem to be much lower compared to the 2-link system, for the non-users the profit compared to a system without DRGS's is only a few percent. However due to the fact that there are a lot of route captive travellers, the profitability is extended to a much higher penetration rate.
Another point of interest is that, due to the shift of traffic over alternative routes, travellers that had no problems before the influence of the DRGS can encounter delays. This is of course not preferable for these travellers themselves although it might be beneficial for all travellers together.

- There is a social optimal point, which provides a travel time reduction of 10%, at around a15% penetration rate.
- At a penetration rate of 40% there is no advantage of using DRGS in traffic management (in case of the 2-link system and all users are complying.
- It is unlikely that the optimal social point can be achieved, because of economical causes.
- It is valuable to invest on improving the traffic information as both users and non-users profit from that.
- When the users reaction is taken into account it leads to a stretch of the profitability from 40% penetration rate to around 85%.
- Due to the fact that there are a lot of route captives in a network the profitability, for both users and non-users of the DRGS, is much less compared to the 2-link system.

- Due to those captives the system is profitable at higher penetration rates (nearly 100%)
- The total traveled distance in the network is reduced by using DRGS, it is however doubtful whether that can be fully contributed to the DRGS.
- Travelers on different routes can encounter different effects of the DRGS.

As stated in the beginning of this section RWS is the representative of the public interest. It can be seen that DRGS's, as they operate right now, guide somehow to a situation that is best for all users individually. However on the contrary to that RWS might want to guide to a situation that is best for the system as a whole. The question is whether that is possible with a system as DRGS's. Paragraph 6.4 will present some remarks on that subject.

6.3 Recommendations

RWS should be willing to stimulate the purchase of DRGS's as the total social profit is increasing at low penetration rates, especially because there is an economical gap between the profit for the users and the costs for purchasing a DRGS. A way to bridge that gap between the maximum benefits of the DRGS-users and the preferable social benefit is the use of subsidies. The national government could subsidize the use of DRGS in order to reach the social optimum. Therefore it is interesting to investigate on what the value of that gap is, as the total profit from 10%-15% is not increasing significantly.

On the other hand, at the moment the benefits of the DRGS turn into a disadvantage, measures have to be taken, to prevent the travellers against these negative consequences. Although doubtful whether that point would practically be reached. (Because of the influence of compliance and network characteristics) By then the stimulation of buying DRGS's should be stopped en probably some other measures have to be taken. In order to support such decisions one should find a way to measure the influence of DRGS's in real life and verify its profitability.

When the maximum point of social welfare is achieved (at around 15%) the situation will get worse compared to that situation. It is likely that from that maximum on, one prefers to maintain that situation or even improve furthermore. Not allowing more DRGS's, or improving the performance of DRGS could provide that request. How that might be achieved will be discussed in the next section.

Improving the quality of information is most profitable at higher penetration rates. One of the possibilities that can be investigated further more, is the influence of the "national data warehouse". This project has possibilities the increases the accuracy and thus the quality of the information.

More detailed investigations on the oscillation effects and improvements on that are preferable, such that its negative consequences can be reduced. For instance by using split fractions in the advices when a certain penetration rate is exceeded. Such however should then be incorporated in the software of the DRGS.

Some other remarks, that are little more off topic, are nevertheless important to keep in mind:

- It should be taken into account that dynamic route guidance systems can intervene with other DVM tools (like ramp metering, or peak lanes) especially as private companies operate the DRGS's. A good fine-tuning between the influence of DRGS's and other DVM tools is required.
- It should be taken into account that the network characteristics can be of major importance for the outcomes. The influence of possible alternative routes and specific locations of bottlenecks are likely to influence the results significantly.
- The sizes of traffic networks that are investigated are also of major importance. In this study, short regional trips are considered. On for instance a national scale, when long national trips are more important, the influence of time in predicting the best route is much higher, and so might be the consequences.

Recommendations

- Stimulate the purchase of the DGRS's until the social optimal situation
- Prevent the system from a higher penetration rate as the social optimal situation
- Investigate on measuring that social optimum
- Improve the quality of input information, as that is profitable for all stakeholders involved
- Investigate on solving the oscillations effects that occur at higher penetration rates
- Be aware of the coherence with other DTM measurements
- Be aware of network characteristics in interpreting these results
- Be aware of the influence of different trip patterns in interpreting the results

6.4 Glimpse on the future

From this study it becomes clear that providing traffic information via DRGS's is beneficial for all travellers. There is however an optimal situation, where the profit for all travellers is maximized and it is questionable what should be done when that point is achieved. It is wise to investigate on what will happen afterwards, as the profits will decrease at higher penetration rates and as it is doubtful whether the system will stabilize itself on that optimal penetration rate.
It is likely that manufactures of DRGS's will improve their equipment over the next years. As a consequence of that, the advices given will be more accurate. It is shown that more accurate information leads to a more profitable system, which again is beneficial for all users. One of the ongoing projects within RWS, that can play a huge role in that, is the National Data Warehouse, which aims for a better provision of traffic data.
However there will always be an optimal situation and if the penetration rate exceeds that, the benefit will drop. Subsequently the question is than, whether there can be a system that has no optimal point but is constantly improving the benefits at an increasing penetration rate, or at least reaches a steady state. Like scattered in *Figure 6-2* when there is no drop of performance anymore.
To do so the information provided should be 100% accurate and consistent. Therefore however the traffic situation needs to be predicted, as per definition 100% accurate and consistent information tells you the situation you are going to encounter. The problem with that is, besides that it is hard to predict the future, the predicted situation will be changed by traffic that is re-routed, at the current moment.

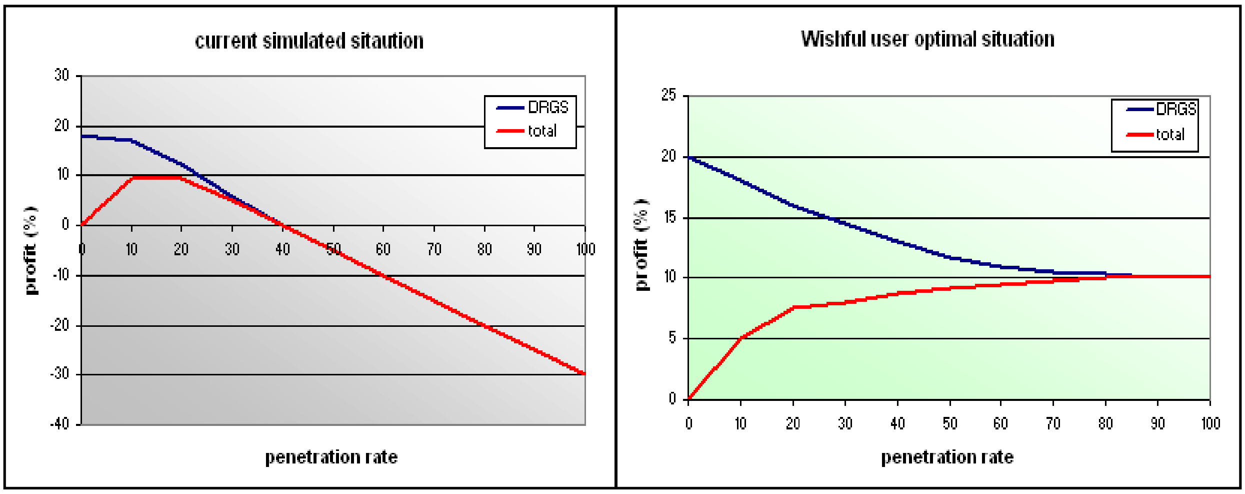


Figure 6-2 preferable performance shift

A possible solution to that could be a further development of the DRGS's. When eventually the DRGS will be developed more, it is likely there will be a technical possibility that al individual systems can somehow communicate with a central computer. So for all users it is known where they are and where they want to go. Thus their preferred route can be computed, which makes it theoretically far easier to somehow predict the future traffic situation.

From that point on it is also theoretical small step towards guiding these individual travellers to a situation that is not only beneficial for themselves, but for the whole society, the system optimum. (See Figure 6-3) However it is a technical challenge to be able to compute a traffic situation in advance, based on the mentioned information of the travellers.

Another doubtful influence could again be the reaction of the users themselves. If everybody would follow the advice of the DRGS's that guides to a system optimum, it will be achieved. However it is likely that if people now there are hindered a bit in order to let others profit from that, their willingness to cooperate might be not so big. So also in that case some stimulating measures might be needed.

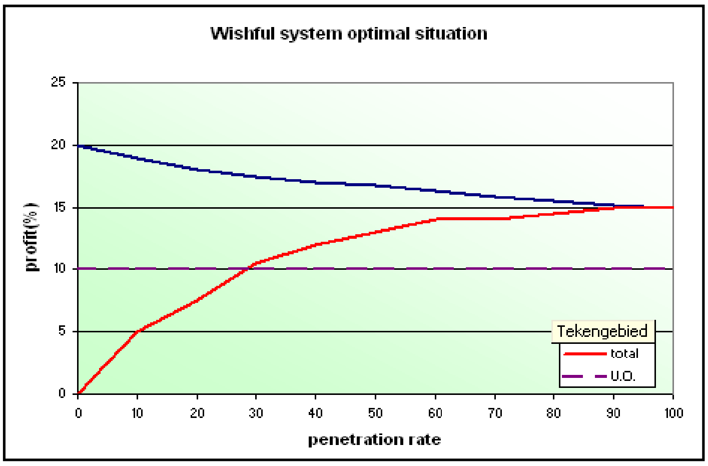


Figure 6-3 preferable shift to system optimum

Bibliography

1) P. H. L. Bovy, M. C. J. Bliemer. 2002. *Transport Mondeling CT4801*.p19,20
2) Ministerie van Verkeer en Waterstaat, Ministerie van Volkshuisvesting Ruimtelijke Ordeningen en Milieu. 2004. Nota mobiliteit, naar een betrouwbare en voorspelbare bereikbaarheid.
3) Joustra, W. 2007. stedelijke verkeerscirculatie met behulp van Navigatiesystemen.
4) Rijkswaterstaat, Adviesdienst Verkeer en Vervoer. 2005. Monitoring In-Car systemen, RDS-TMC in Nederland.
5) W.Y. Ochieng, K Sauer. 2001. Urban road transport navigation: performance of the global positioning system after selective availability.
6) TNO. 2007. Onafhankelijk onderzoek toont aan dat navigatiesystemen een positieve invloed hebben op verkeersveiligheid belangrijkste resultaten.
7) Tomtom. *Tomtom HD Traffic* 2007 [cited. Available from http://www.tomtom.com.
8) Yafeng Yin, Hai Yang. 2002. Simultaneous determination of the equilibrium market penetration and compliance rate of advanced traveler information systems.
9) Wikipedia. *Diminishing returns* 2007 [cited. Available from http://en.wikipedia.org/wiki/Diminishing_returns.
10) J.C. Smith, K. Russam. 1989. Some possible effects of autoguide on traffic in London.
11) S.P. Hoogendoorn, P.H.L. Bovy, S. Hoogendoorn-Lanser. Voorspellen van de waarde en marktpenetratie van individuele reisinformatie onder invloed van collectieve verkeersinformatie.
12) Hall, Randolph W. 1996. Route choice and advanced traveler information systems on a capacitated and dynamic network.
13) V&W, Ministerie van. 2004. Reisinformatie en weggebruiker.
14) 2006. *Effecten verkeersmanagement*.
15) Broeders, H. Katteler W. 2002. Weggebruikers en on-line verkeersinformatie in de auto.
16) S.P. Hoogendoorn, J.W.C. van Lint. 2008. Reistijdvoorspellingen en betrouwbaarheid. *NM-magazine*, 32-36.
17) Lint, J. W. C. Van. 2006. Evaluatie en Analyse van Reisinformatie.
18) P.W. Bonsal, T. Parry. Using an interactive route-choice simulator to investigate drivers compliance with route guidance advice.
19) Vervoer, Adviesdienst Verkeer en. 2002. Mobiliteitsbeleving nader toegelicht.
20) Dia, Hussein. 2002. An agent-based approach to modeling driver route choice behavior under the influence of real-time information.331-349.

21) Adler, J.L. 1999. Investigating the learning effects of route guidance and traffic advisories on route choice behavior.
22) R. Jayakrishnan, Hani S. Mahmassani, Ta-Yin Hu. 1994. An evaluation tool for advanced traffic information and management systems in urban networks.129-149.
23) Wikipedia. 2008. discrete event simulation.
24) S.P. Hoogendoorn, H. Botma, M.M. Minderhoud. 2005. Traffic flow theory and simulation, CT4821.p83-90
25) J.L.Adler, M.G.McNally. 1994. In-laboratory experiments to investigate driver behaviour under advanced traveler information system.
26) F.M. Dekking, C. Kraaikamp, H.P. Lopuhaä, L.E.Meester. 2004. *Kanstat, Probability and Statistics for the 21st century*.
27) MoniGraph version 2.0.2.
28) CPB. 2007. Centraal economisch plan 2007.
29) Kraaijeveld, R., Onderzoek naar de identificatie van kwetsbare wegvakken, oktober 2008

Bijlage A Program structure and program code

A.1 Event database

The event database consist of a database which stores the events based on the moment they need to happen combined with the vehicle involved. Like the example in table

Table -1

event	time	car number
1	0	2
2	10	5
3	11	7

To keep this database ordered there are 3 processes that happen while the model is running.

- Every time a event is going to happen it is removed from the database
- Every time a new event is scheduled to happen it is inserted at the right position in the database

Getting a new event en removing it from the database

currentcar becomes the new active vehicle (1) and *currentime* determines the actual time(2). When these two variables have been assigned the current event can be removed from the database. (3)

Program code 1: getting the next event

```
currentcar = event(1,1);                          (1)
currenttime = event (1,2);                        (2)
event(1,:) =[];                                   (3)
```

Scheduling a new event

First the current size of the database is determined. (1,2) The event to insert is set (3). The last considered event is set to be last. (6-8) So eventually the process will first compare the new event to the last and then the second last and so on.

To do so a loop is been implemented that repeats itself until the required location has been found. (12) It does so by comparing the event time of the new event to the time of the event in the database. If the time of the new event is smaller then the event that is on the place in the database it put the new event at that place. It can do so because meanwhile (while (17) is applicable) all events with a larger starting time are moved one place down in the database. (18-21)

Finally a rule is inserted that deals with the problems that can occur when the new event is scheduled to be inserted at the top of the database. (22-29)

Program code 2: inserting a new event

```
sizeevents = size(event);
aantalevents = sizeevents(1,1);

event_to_insert =[newcarnumber,newtime];
time_1 =newtime;
aantal_groter =0;
last= [];
last(1,1) = event(aantalevents,1);
last(1,2) = event(aantalevents,2);
place = aantalevents+1;
laatste = aantalevents;
klaar = false;


while klaar == false
    if time_1 > last (1,2)
        event(place,1) = to_insert_event(1,1);
        event(place,2) = to_insert_event(1,2);
        klaar = true;
    else
        event(place,1) = last(1,1);
        event(place,2) = last(1,2);
        laatste = laatste-1;
        place = place-1;
        if laatste == 0
            event(1,1) = to_insert_event(1,1);
            event(1,2) = to_insert_event(1,2);
            klaar= true;
        else
            last(1,1) = event(laatste,1);
            last(1,2) = event(laatste,2);
        end

    end
end
```

A.2 Navigation system assignment

For the assignment of the navigation systems a process is used that can cope with the fact that over different runs with different penetration rates the same vehicles can keep a navigation system. The script below assigns a system to a new group of users when there is a difference in penetration rate between the current run and the last run. One should be careful when using this because it is only applicable when the penetration rates are increasing. When a smaller rate is used the assigning of DNS's is not valid anymore

The first lines the increase of penetration rates is determined compared to the previous run. The increment is set to be the new group of DNS users that has to be assigned. (1,2)
Thereafter the program checks whether the current car (newcar) had a DNS in the previous run (which is stored in the *vehicle* database) (3-4)
The final part determines, according to the normal distribution (r), for the remaining unequipped vehicles a percentage of navigation systems that will be equipped as well (5-11).

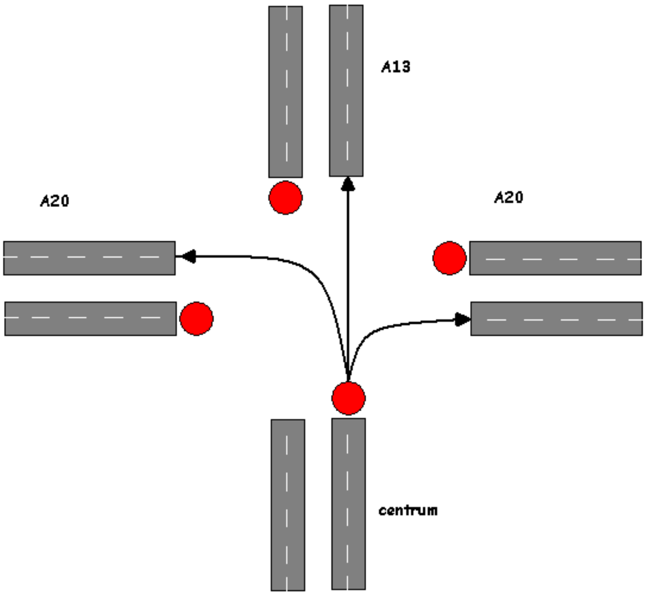
Program code 3: DNS assignment

```
r=(100-percentage_vorig)*rand(1);               (1)
toename_penetratie = pengraad-percentage_vorig; (2)
if vehicle(newcar).nav_sys == true              (3)
      car(newcar).nav_sys = true;               (4)
else                                            (5)
      if r < toename_penetratie                 (6)
      car(newcarnumber).nav_sys = true;         (7)
      number_nav_sys = number_nav_sys + 1;      (8)
      else                                      (9)
      car(newcarnumber).nav_sys = false;        (10)
      end                                       (11)
end                                             (12)
```

A.3 Node Layout

When the traffic situation becomes more complex compared to the basic 2-link system, where cars can only drive only one way, the configuration of especially the nodes requires some extra attention. When for instance 4 bi-directional links come together (like the Kleinpolderplein in the Rotterdam network) problems will occur when only using one node. If one direction is blocked then all directions will be hindered as shown in the node movement. Therefore the node layout has been improved such that traffic that has no interaction in reality will not conflict in the model as well.
Figure 6-4 shows that the general node Kleinpolderplein has been exploded to 4 sub-nodes for al 4 directions. The sub-nodes are situated at the end of the arriving links. That is because route choice is performed at the nodes and should thus be executed before the traffic is spilt up. From the sub-nodes traffic is moved directly to the next links and if one of them is blocked the traffic will spillback over the sub-node, without influencing the other 3 arriving directions.

Figure 6-4: Node layout out Kleinploderplein



For movement along the nodes when the next link is occupied this also becomes a bit more difficult. Picture 2 shows this process as presented in chapter 4.

Figure 6-5 Movement along the node in case of an occupied link

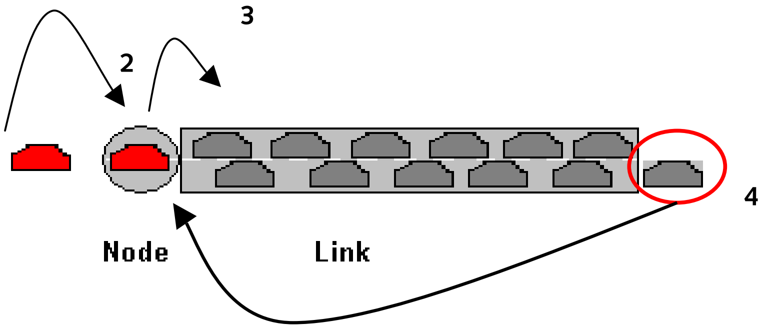
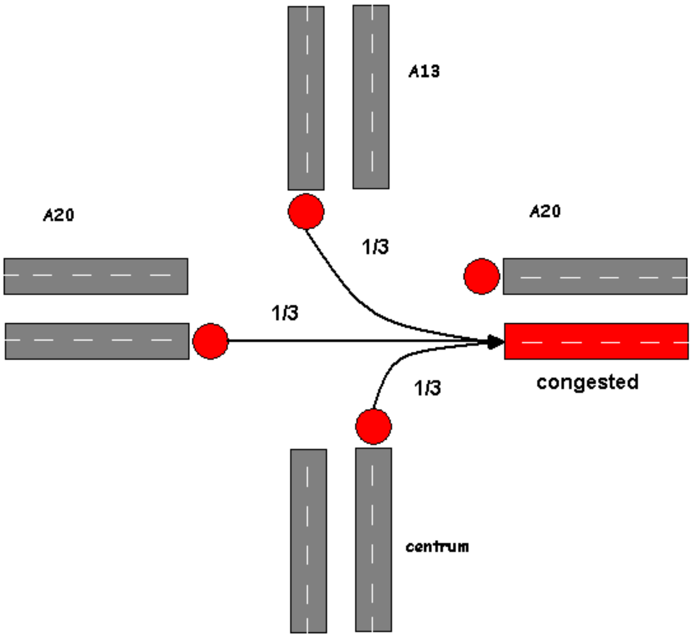


Figure 6-5 shows that when a vehicle leaves an occupied link it should be checked for all preceding sub-nodes whether or not there are vehicles waiting to enter the link. Therefore a distribution has to be implemented that verifies from which node the next vehicle can enter the link. It is chosen to have an equal chance for al three arriving nodes to be selected regardless of the amount of traffic waiting. (See *Figure 6-6*)

Figure 6-6: vehicle distribution in case of congested downstream link



Scripting

A vehicle on a node can become active in two ways either because it is directly moved from the "*endlink*", or because it was standing on the node and waiting to be moved to the next link. Where the vehicle comes from is checked in the statements as presented in *Program code 4* (1) and when it comes from an "*endlink*" also the choice for the next link is performed. (5)

Program code 4: arriving at node

```
if car_via_previous_link == true                    (1)
    voertuig = currentcar;                          (2)
    currentnode = car(voertuig).next_node;          (3)
    car(voertuig).current_node= currentnode;        (4)
    linkchoice;                                     (5)
    next_link = car(voertuig).next_link;            (6)
    car_via_previous_link = false;                  (7)
elseif car_via_next_link == true;                   (8)
    voertuig= car_from_node;                        (9)
    currentnode = car(voertuig).current_node;       (10)
    next_link = car(voertuig).next_link;            (11)
    car_via_next_link = false;                      (12)
end                                                 (13)
```

Afterwards the scripting (*Program code 5*) for the actual movement on the node is performed, when the current node happens to be the destination, the vehicle is moved to the arrival process by giving it the status “arri”. (2) Furthermore it is checked whether new cars can enter the node by the *endlink outflow* procedure. (13) The *endlink* process is described more in detail in.

Program code 5 Moving along Node

```
if currentnode == vehicle_destination                      (1)
car(voertuig).next_type_location = 'arri';                 (2)
car(voertuig).current_location = currentnode;              (3)
newcarnumber = voertuig;                                   (4)
entrance_time= currenttime+0.001;                          (5)
newtime = entrance_time;                                   (6)
insertevent                                                (7)
Node(node_numerical).inflow = true ;                       (8)
Node(node_numerical).car_waiting_at_node = false;          (9)
car(voertuig).waiting_at_node = false;                     (10)
Node(node_num).cars_past=Node(node_num).cars_past+1;       (11)
number_outflow = previous_link;                            (12)
endlink_outflow;                                           (13)
```

If the current node is not the destination then the process of *Program code 6* is used. It is distinguished whether there is space on the next link to move the vehicle or not (1) and according to that the vehicle is then moved (2-15) or stored (16-20) at the node.

Program code 6 moving along node II

```
else
    if link(next_link).space == true                       (1)
    car(voertuig).next_type_location = 'link';             (2)
    car(voertuig).current_location = currentnode;          (3)
    newcarnumber = voertuig;                               (4)
    entrance_time= currenttime+0.002;                      (5)
    newtime = entrance_time;                               (6)
    insertevent                                            (7)
    Node(node_numerical).inflow = true ;                   (8)
    Node(node_numerical).car_waiting_at_node=false;        (9)
    car(voertuig).waiting_at_node = false;                 (10)
    Node(node_numerical).cars_past =
      Node(node_numerical).cars_past +1;                   (11)
         if entr_node == 0                                 (12)
         number_outflow = previous_link;                   (13)
         endlink_outflow;                                  (14)
         end                                               (15)
    elseif link(next_link).space == false                  (16)
    car(voertuig).waiting_at_node = true;                  (17)
    Node(node_numerical).car_at_node = voertuig;           (18)
    Node(node_numerical).car_waiting_at_node=true;         (19)
    End                                                    (20)
End                                                        (21)
```

A.4 Movement along the links

When entering the link procedure, the active link will be determined based on the vehicle properties. The needed inflow and travel times (BPR) and navigation travel times will be computed. Finally the outflow is controlled by comparing possible interval time based on the capacity to the computed interval time in case of congested circumstances (50% of the space on the link is used)
Here the travel time is corrected in case the vehicles will follow up on each other to fast, compared to the capacity.

Program code 7 Link travel time

```
L = car(currentcar).next_link;
t = round (currenttime);
if t <=1
    t=1;
end
[link(L).q_in] = Link_inflow (link(L).in, inflowtimer);
[link(L).current_BPR_tt]=BPRtraveltime(L,link(L).cars_on_link,
link(L).eff_cap, link(L).ff_tt, alfa, beta, entrance_links,
link(L).q_in);
link(Linknr).possible_traveltime = link(Linknr).ff_tt+
((link(Linknr).cars_on_link/link(Linknr).eff_cap)*3600);
if link(Linknr).cars_on_link >= (0.50* link(Linknr).totalspace)
    link(Linknr).current_tt = link(Linknr).possible_traveltime;
else
    link(Linknr).current_tt = link(Linknr).current_BPR_tt;
end
```

Afterwards all parameters for the link and vehicle are updated

Program code 8 Updating link and car properties

```
link(L).cars_on_link = link(L).cars_on_link +1;
link(L).total_cars_on_link = link(L).cars_on_link +
link(L).cars_on_endlink;
[space]  = Check_space (link(L).cars_on_link,
link(L).cars_on_endlink, link(L).totalspace);
link(L).space = space;
link(L).max_tt = max(link(L).max_tt, tt);
link(L).inflow = link(L).inflow +1;
link(L).in(t) = link(L).inflow;
link(L).last_tt = tt;
link(L).last_past_at = currenttime;
car(N).linkentrancetime = currenttime;
car(N).traveltime(L) = tt;
car(N).expected_endlinkarrival(L) = tt+currenttime;
car(N).last_expected_endlinkarrival =tt+currenttime;
car(N).currentlink = L;
car(N).next_endlink = L;
car(N).link_past(Linknr)=true;
car(N).link_entrance(Linknr) = N;
car(N).next_type_location = 'endl';

newcarnumber =currentcar;
newtime = currenttime + tt;
insertevent
```

A.5 Endlink Process

The endlink process mainly consist out of 2 process first process is to putt the vehicle in the endlink storage array the second process is to move it from the array to the following node.

First all parameters, like the number of vehicle on al link and some control indicators for the vehicles are computed, afterwards the vehicle is put in the database of all vehicles waiting on the endlink.

```
t=round(currenttime);
i = car(currentcar).next_endlink;
link(i).cars_on_link = link(i).cars_on_link -1;
link(i).cars_on_endlink = link(i).cars_on_endlink +1;
[space]  = Check_space (link(i).cars_on_link,
link(i).cars_on_endlink, link(i).totalspace);
link(i).space = space;
car(currentcar).current_endlink = i;
car(currentcar).last_link = i;
car(currentcar).endlinkentrancetime = currenttime;

car(currentcar).endlink_past(i) = true;
car(currentcar).endlink_entrance(i) = currenttime;
link(i).endlink_inflow = link(i).endlink_inflow +1;
link(i).total_cars_on_link = link(i).cars_on_link +
link(i).cars_on_endlink;

s=size(link(i).endlinkDB);
lengthDB= s(1,2);
link(i).endlinkDB(lengthDB+1)=currentcar;
number_outflow = i;

endlink outflow
```

Moving the vehicle from the endlink array

This process called “endlink outflow” describes the movement of the vehicles from the storage array to the next node
Whereby

- It is first checked whether there is a vehicle in the storage array
- If there is storage the first vehicle is selected.
- If there is space on the node the vehicle is moved to the node
- If there is vehicle can be moved to the node all data for the link and the vehicle itself are updated
- If the vehicle is moved to the next node it is checked if a vehicle of the previous node can enter the link as there becomes new space available

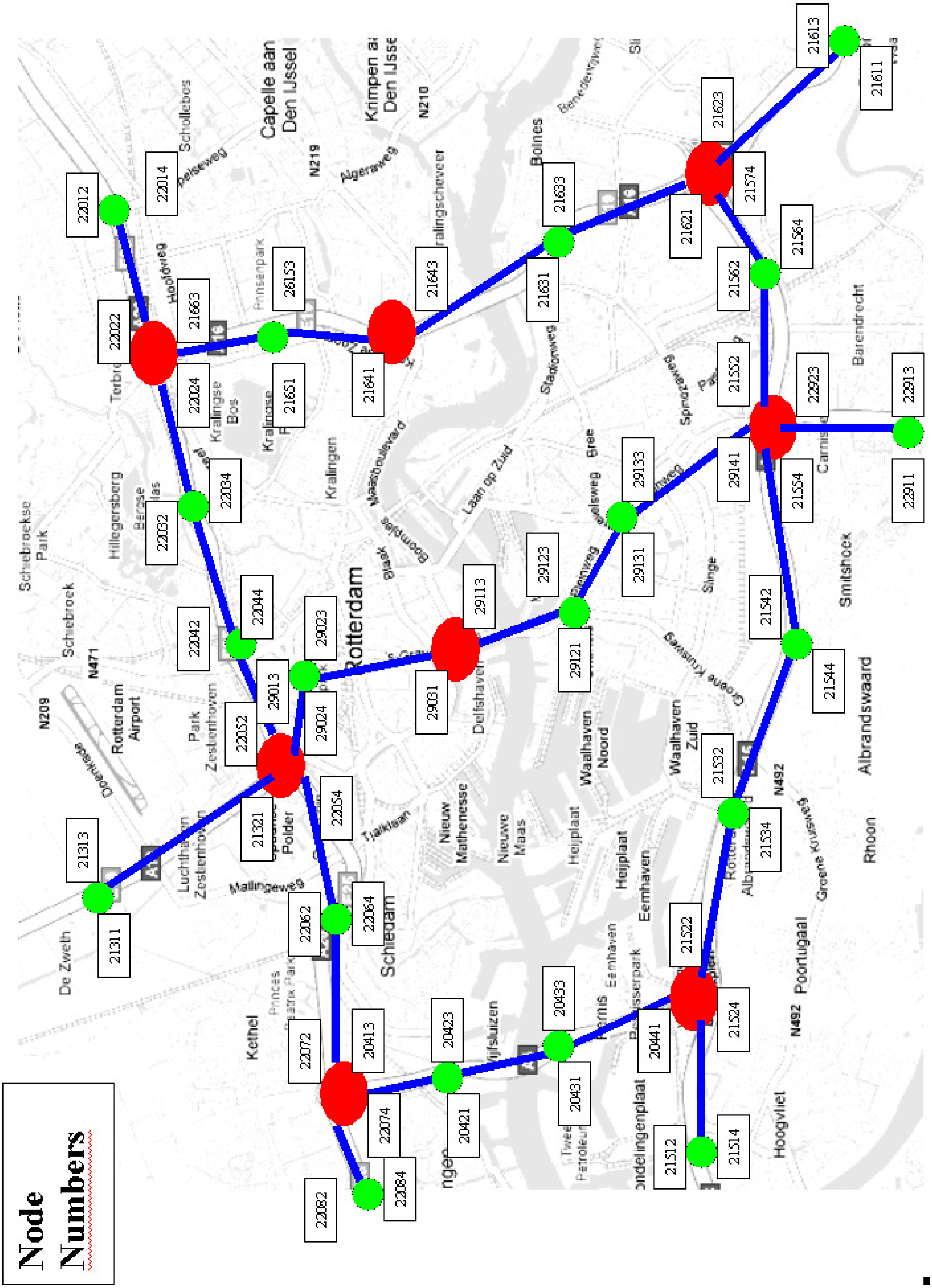
```
Link = number_outflow;
omvang = size(link(Link).endlinkDB);
lengthDB = omvang(1,2);
t = round(currenttime);
if omvang > 0
    car_from_end_link = link(Link).endlinkDB(1) ;
    [nextnode]= Check_next_node(Link);
    [next_node_numerical] = Check_node (nextnode);
    [exit_node] = Check_exit_node (nextnode, exitnodes);
    if Node(next_node_numerical).inflow == true
        endlink_traveltime = 0.001;
        newcarnumber = car_from_end_link;
        newtime = currenttime + endlink_traveltime;
        insertevent;
        sortevent;
        car(car_from_end_link).next_type_location = 'node';
            if next_node_numerical == 1200
            Node(next_node_numerical).inflow = true;
            else
            Node(next_node_numerical).inflow = false;
            end
        link(Link).endlinkDB(1) = [];
        maat= size(link(Link).endlinkDB);
        gemeten_reistijd = currenttime-
        car(car_from_end_link).linkentrancetime;
        link(Link).gemeten_endlinkreistijd =
        currenttime-car(car_from_end_link).endlinkentrancetime;   (12)
        car(car_from_end_link).traveltime(Link)= currenttime -
        car(car_from_end_link).linkentrancetime;
        link(Link).measured_tt(t) = gemeten_reistijd;
        link(Link).cars_on_endlink=link(Link).cars_on_endlink-1; (12)
        [space]  = Check_space (link(Link).cars_on_link,
        link(Link).cars_on_endlink, link(Link).totalspace);
        link(Link).space = space;
        link(Link).total_cars_on_link = link(Link).cars_on_link+
        link(Link).cars_on_endlink;
        link(Link).endlink_outflow=link(Link).endlink_outflow+1;
        measured_tt = [];
        measured_tt = link(Link).measured_tt;
        [link(Link).measurement] = measured_traveltime(t ,
        slagdelay_nav, measured_tt, link(Link).ff_tt);
        link(Link).outflow = link(Link).outflow +1;
        link(Link).out(t) = link(Link).outflow;
        [link(Link).q_out] = Link_inflow (link(Link).out,
        inflowtimer);

        [previous] = Check_previous_node(Link);
        [vorige] = Check_node (previous);
            if Node(vorige).car_waiting_at_node == true
            car_from_node = Node(vorige).car_at_node;
            car_via_next_link = true;
            passnode
            end
       end
end
```

Bijlage B Details on Rotterdam network

Road	Link	From	Abrev	node	To	Abrev	node	Length	Parts	Lanes	Speed
A04		Kethelplein			Knooppunt Benelux			7.7	3		
	10411	Kethelplein	KET	Multiple	(16)Vlaardingen Oost	VLA	20421	2.5		4	100
	10412	(16)Vlaardingen Oost	VLA	20423	Kethelplein	KET	20413	2.5		4	100
	10421	(16)Vlaardingen Oost	VLA	20421	Einde tunnel	BTN	20431	2.3		4	100
	10422	Einde tunnel	BTN	20433	(16)Vlaardingen Oost	VLA	20423	2.3		4	100
	10431	Einde tunnel	BTN	20431	Knooppunt Benelux	BEN	20441	2.9		4	100
	10432	Knooppunt Benelux	BEN		Einde tunnel	BTN	20433	2.9		4	100
A13		(11)Berkel			Kleinpolderplein			2.6	1		
	11311	(11)Berkel	DEL	21311	Kleinpolderplein	KPP	21321	2.6		3	80
	11312	Kleinpolderplein		Multiple	(11)Berkel	DEL	21313	2.6		3	80
A15		(17)Hoogvliet			Knooppunt Benelux			2.5	1		
	11511	(17)Hoogvliet	EUR	21514	Knooppunt Benelux	BEN	21524	2.5		3	100
	11512	Knooppunt Benelux	BEN	Multiple	(17)Hoogvliet	EUR	21512	2.5		3	100
A15		Knooppunt Benelux			Vaanplein			8.1	3		
	11521	Knooppunt Benelux	BEN	Multiple	(18/19)Charlois/Rhoon	CHA	21534	2.1		3	100
	11522	(18/19)Charlois/Rhoon	CHA	21532	Knooppunt Benelux	BEN	21522	2.1		3	100
	11531	(18/19)Charlois/Rhoon	CHA	21534	tankstation A15	TAN	21544	3		3	100
	11532	tankstation A15	TAN	21542	(18/19)Charlois/Rhoon	CHA	21532	3		3	100
	11541	tankstation A15	TAN	21544	Vaanplein	VPL	21554	3		3	100
	11542	Vaanplein	VPL	Multiple	tankstation A15	TAN	21542	3		3	100
A15		Vaanplein			Ridderster			4	2		
	11551	Vaanplein	VPL	Multiple	(20)Barendracht	BAR	21564	2		4	100
	11552	(20)Barendracht	BAR	21562	Vaanplein	VPL	21552	2		4	100
	11561	(20)Barendrecht	BAR	21564	Ridderster	RID	21574	2		4	100
	11562	Ridderster	RID	Multiple	(20)Barendrecht	BAR	21562	2		4	100
A16		Ridderkerk			Ridderster			2.6	1		
	11611	Ridderkerk	DOR	21613	Ridderster	RID	21623	2.6		6	100
	11612	Ridderster	RID	Multiple	Ridderkerk	DOR	21611	2.6		6	100
A16		Ridderster			(25)Kralingseplein			5.1	2		
	11621	Ridderster	RID	Multiple	(24)Feyenoord	FEY	21633	2.7		4	100
	11622	(24)Feyenoord	FEY	21631	Ridderster	RID	21621	2.7		4	100
	11631	(24)Feyenoord	FEY	21633	(25)Kralingseplein	KPL	21643	2.4		4	100
	11632	(25)Kralingseplein	KPL	21641	(24)Feyenoord	FEY	21631	2.4		4	100
A16		(25)Kralingseplein			Terbrechtseplein			4.1	2		
	11641	(25)Kralingseplein	KPL	21643	(26)Kralingen	KRA	21653	1.2		5	100
	11642	(26)Kralingen	KRA	21651	(25)Kralingseplein	KPL	21641	1.2		5	100
	11651	(26)Kralingen	KRA	21653	Terbrechtseplein	TBP	21663	2.9		5	100
	11652	Terbrechtseplein	TBP	Multiple	(26)Kralingen	KRA	21651	2.9		5	100
A20		(16)Alexanderpolder			Terbrechtseplein			2.3	1		
	12011	(16)Alexanderpolder	GOU	22012	Terbrechtseplein	TBP	22022	2.3		3	100
	12012	Terbrechtseplein	TPB	Multiple	(16)Alexanderpolder	GOU	22014	2.3		3	100
A20		Terbrechtseplein			Kleinpolderplein			6.7	3		
	12021	Terbrechtseplein	TBP	Multiple	(15)Crooswijk	CRO	22032	3.1		3	100
	12022	(15)Crooswijk	CRO	22034	Terbrechtseplein	TBP	22024	3.1		3	100
	12031	(15)Crooswijk	CRO	22032	(14)Centrum	CTR	22042	1.8		3	80
	12032	(14)Centrum	CTR	22044	(15)Crooswijk	CRO	22034	1.8		3	80
	12041	(14)Centrum	CTR	22042	Kleinpolderplein	KPP	22052	1.8		3	80
	12042	Kleinpolderplein	KPP	Multiple	(14)Centrum	CTR	22044	1.8		3	80

Road	Link	From	Abrev	node	To	Abrev	node	Length	Parts	Lanes	Speed
A20		Kleinpolderplein			Kethelplein			5.4	2		
	12051	Kleinpolderplein	KPP	Multiple	(11)Schiedam	SCH	22062	2.7		3	100
	12052	(11)Schiedam	SCH	22064	Kleinpolderplein	KPP	22054	2.7		3	100
	12061	(11)Schiedam	SCH	22062	Kethelplein	KET	22072	2.7		3	100
	12062	Kethelplein	KET	Multiple	(11)Schiedam	SCH	22064	2.7		3	100
A20		Kethelplein			(8)Vlaardingen			2.5	1		
	12071	Kethelplein	KET	Multiple	(8)Vlaardingen	HVH	22082	2.5		2	100
	12072	(8)Vlaardingen	HVH	22084	Kethelplein	KET	22074	2.5		3	100
A29		(20)Karnisselande			Vaanplein			1.8	1		
	12911	(20)Karnisselande	BOZ	22913	Vaanplein	VPL	22923	1.8		4	100
	12912	Vaanplein	VPL	Multiple	(20)Karnisselande	BOZ	22911	1.8		4	100
A90		Kleinpolderplein			Drooglever Fortuynplein			4	2		
	19011	Kleinpolderplein	KPP	Multiple	Statenweg	BLY	29024	1.5		2	50
	19012	Statenweg	BLY	29023	Kleinpolderplein	KPP	29013	1.5		2	50
	19021	Statenweg	BLY	29024	Drooglever Fortuynplein	DFP	29031	2.5		2	50
	19022	Drooglever Fortuynplein	DFP	29033	Statenweg	BLY	29023	2.5		2	50
A91		Drooglever Fortuynplein			Vaanplein			6.4	3		
	19111	Drooglever Fortuynplein	DFP	29031	Maastunnelplein	MTP	29111	1.9		2	50
	19112	Maastunnelplein	MTP	29123	Drooglever Fortuynplein	DFP	29113	1.9		2	50
	19121	Maastunnelplein	MTP	29121	Zuiderpark	ZUI	29131	1.7		2	50
	19122	Zuiderpark	ZUI	29133	Maastunnelplein	MTP	29123	1.7		2	50
	19131	Zuiderpark	ZUI	29131	Vaanplein	VPL	29141	2.7		2	50
	19131	Vaanplein	VPL	Multiple	Zuiderpark	ZUI	29133	2.7		2	50


Node Numbers
22012
22014
22022
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21641
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21633
21631
21621
21623
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21613
21611
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21564
21552
22923
22913
22911
21554
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29131
29123
29121
29113
29031
22024
21651
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22032
22044
22042
29023
29013
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20413
22074
22084
22082
20423
20421
20433
20431
20441
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21512
21514
21532
21534
21542
21544

Bijlage C Detailed graphical results

Figure C 1 Total time loss: full illustration of figure 5.1

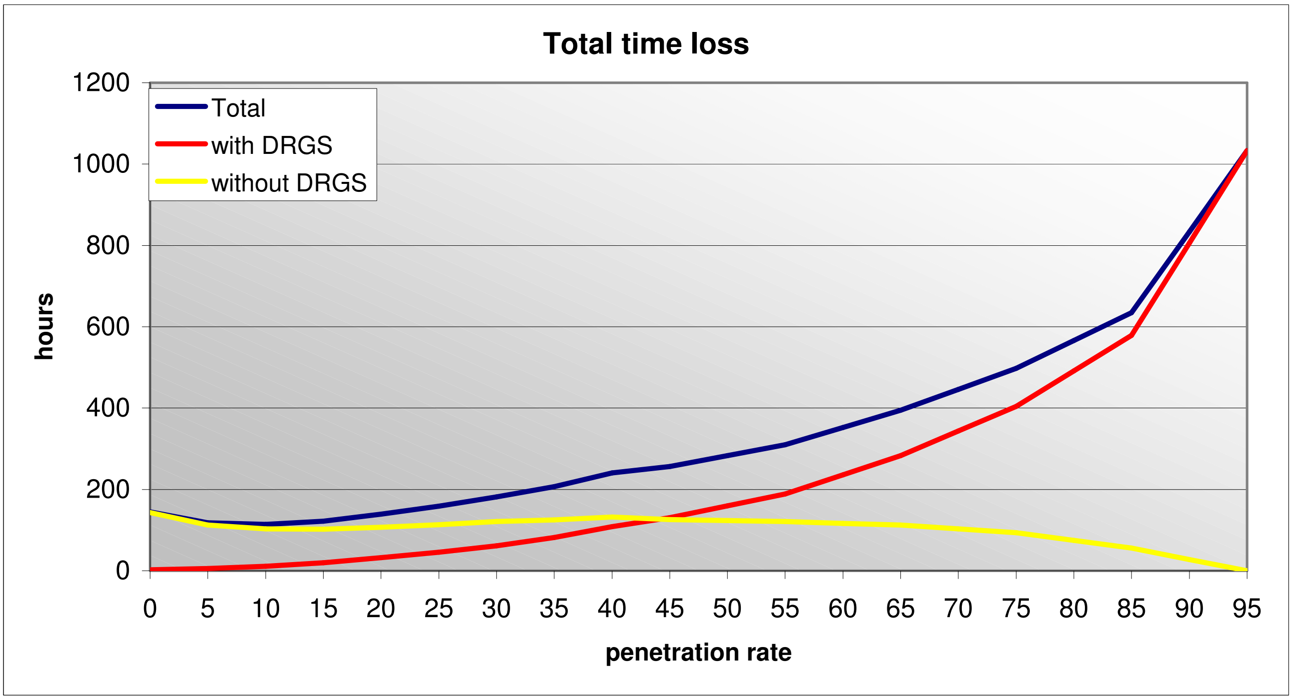

Figure C 2 Average time loss: full illustration of figure 5.2

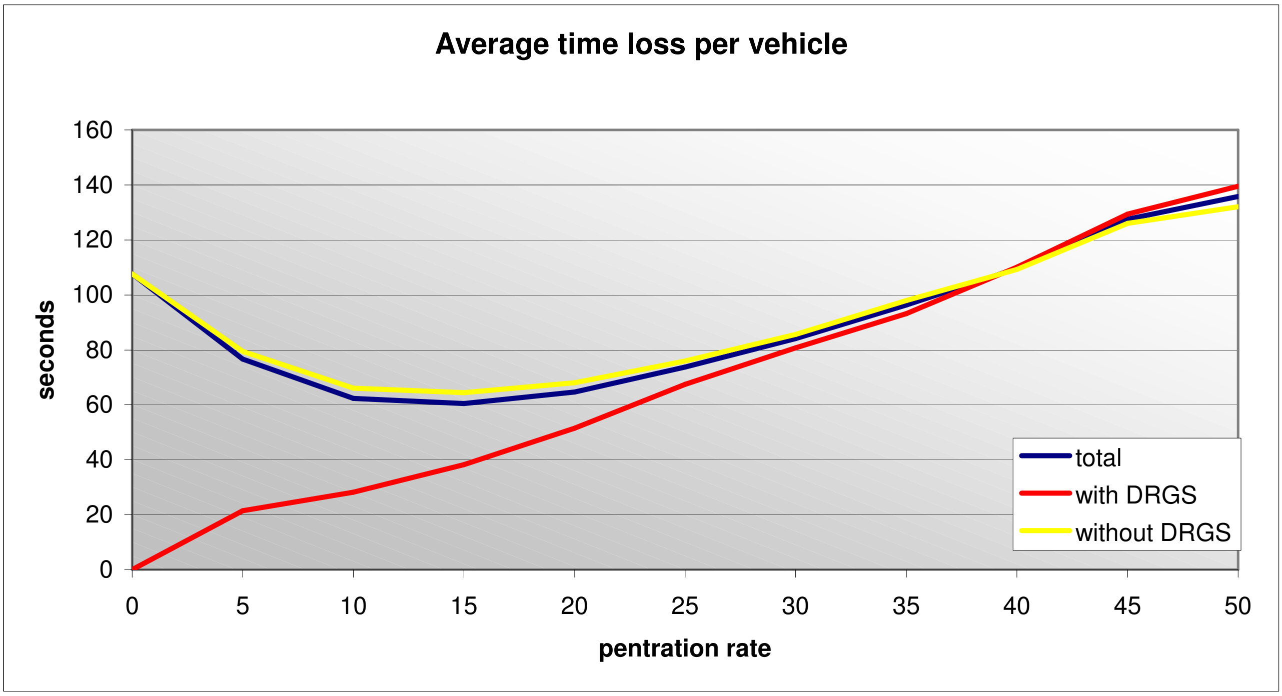

Figure C 3 Average travel time profit compared to situation without DRGS. Full illustration of figure 5.3

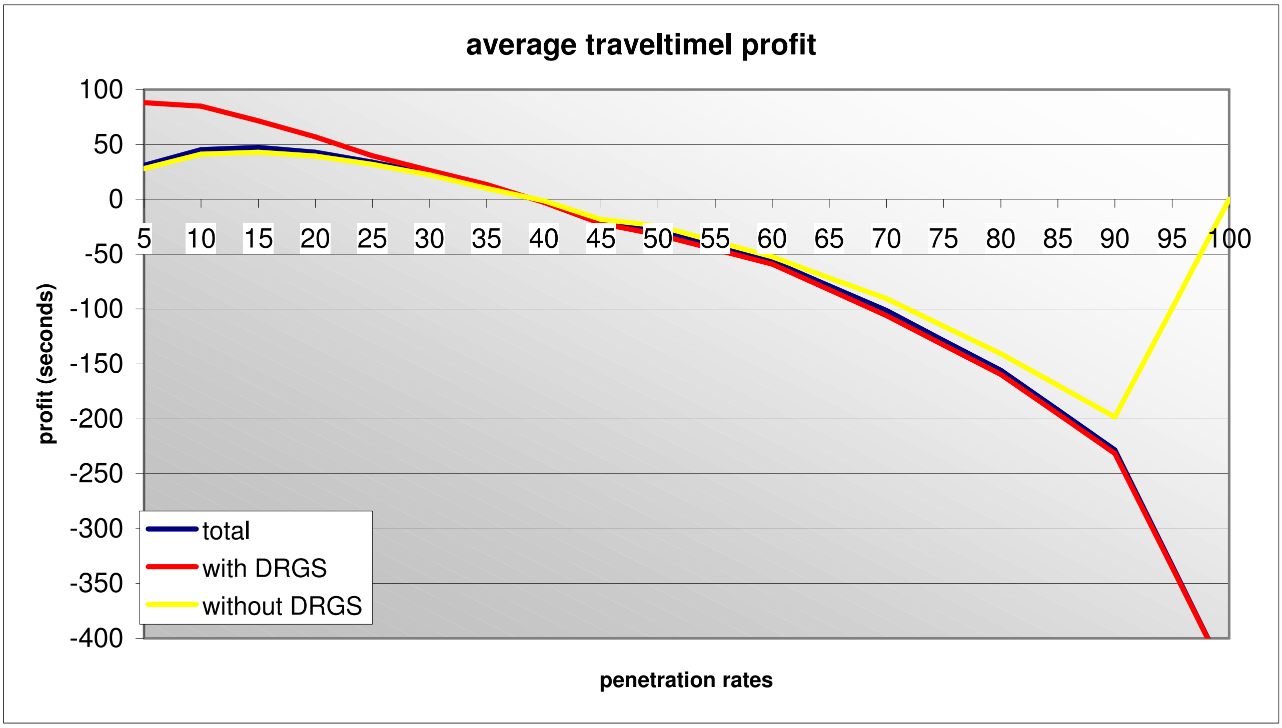

Figure C 4 Relative travel time profit. Full illustration of figure 5.4

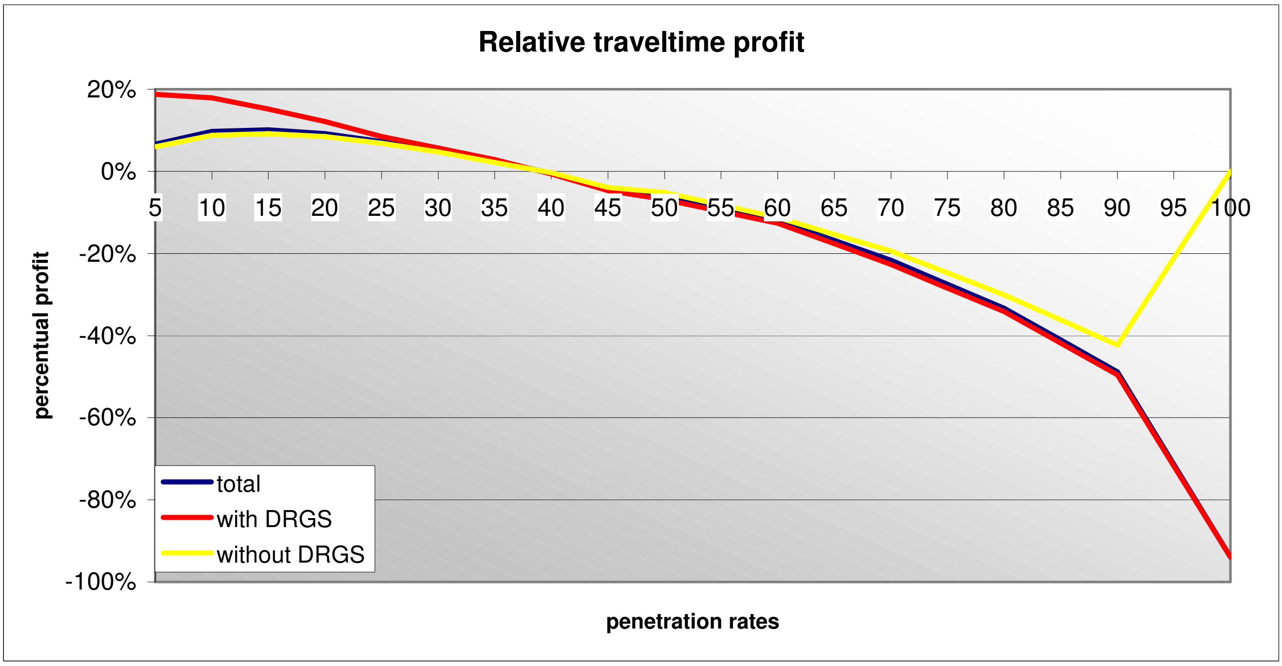

Figure C 5 Profit of the DRGS user compared to the non-users. Full illustration of figure 5.6

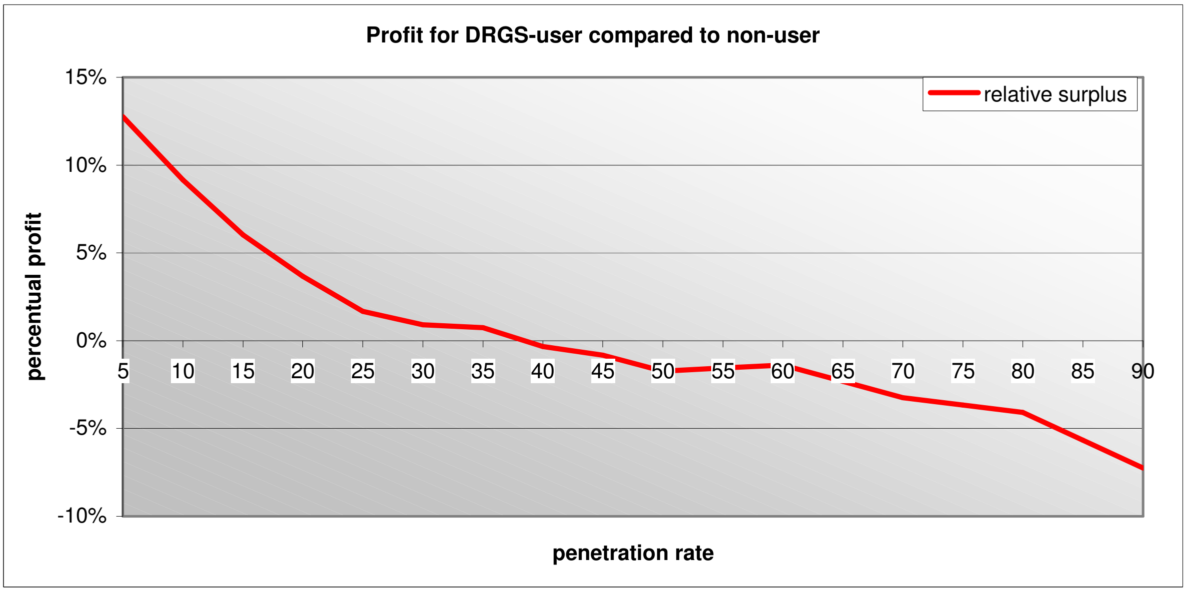

Figure C 6 Total time loss in Rotterdam network case. Full illustration of figure 5.24

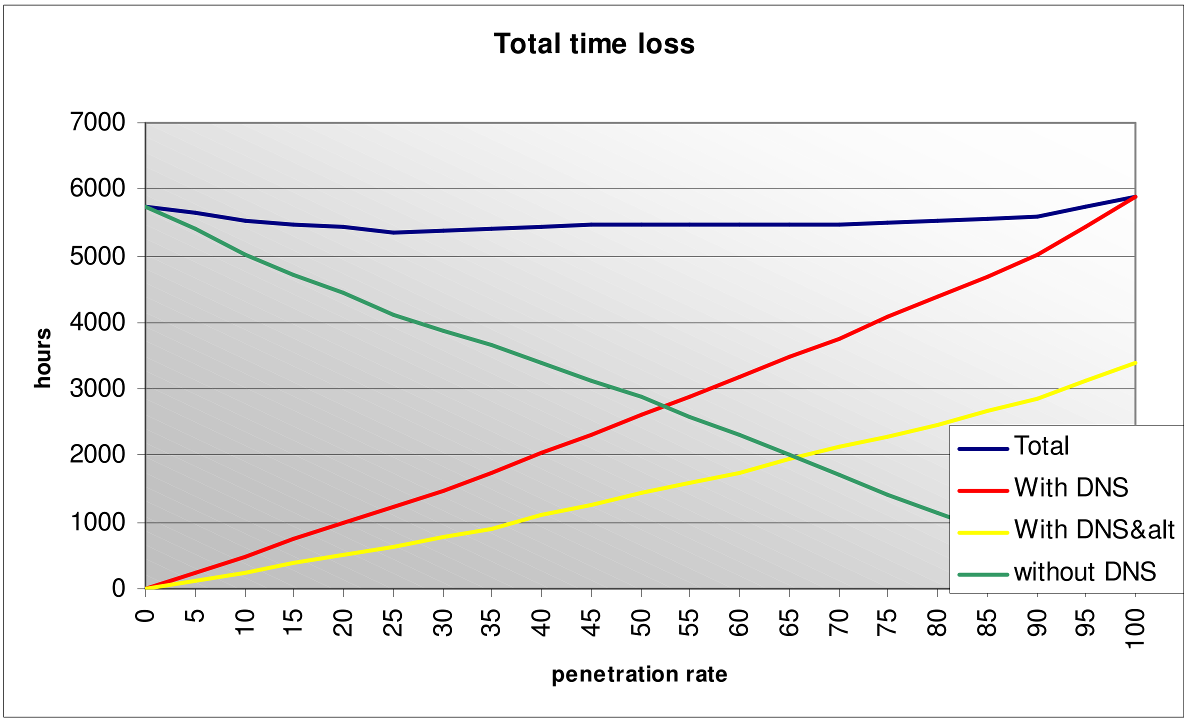

Figure C 7 Average time loss per vehicle. Full illustration of figure 5.25

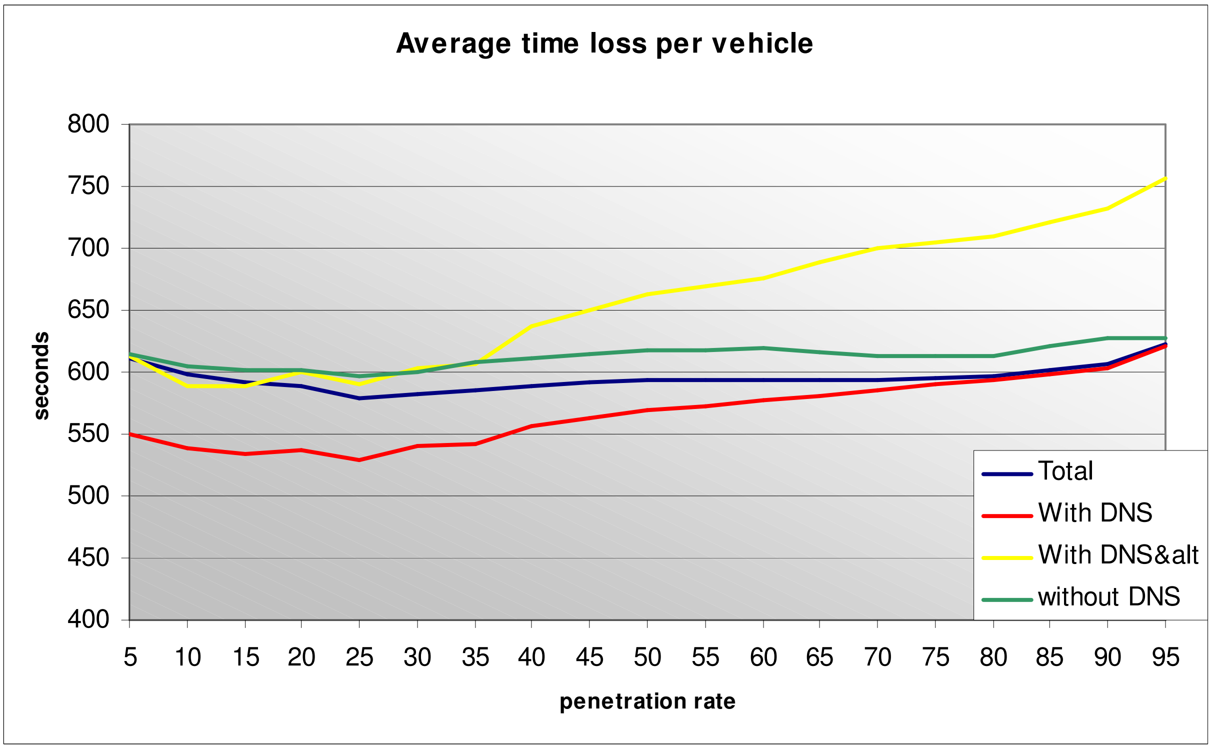

Figure C 8 Average travel time profit per vehicle. Full illustration of figure 5.26

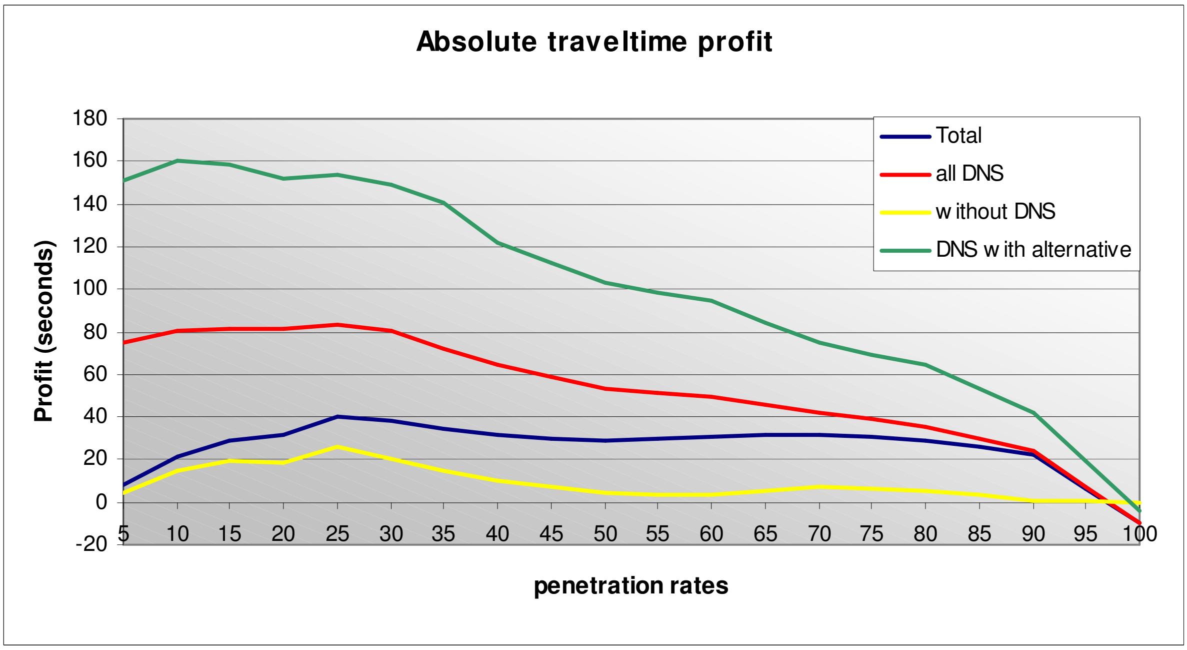

Figure C 9 Relative travel time profit in network case. Full illustration of figure 5.27