The influence of adverse weather conditions on the probability of congestion on Dutch highways

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Preface

This thesis is the final deliverable during my time as a student of the master study Systems Engineering, Policy Analysis and Management at Delft University of Technology. It is the product of six months of study at the TNO Smart Mobility research group. I do not know how time flew by so fast during my stay at TNO and my time as a student. I would like to express my gratitude towards the people who have contributed to the result of this graduation thesis.

First and foremost I would like to thank the members of the examination committee. Simeon Calvert, my supervisor at TNO, was always available to help me out with problems related to the capacity analysis and provided valuable advice regarding other parts of the research. The informal student-supervisor relationship created an enjoyable atmosphere. I want to thank Eric Molin, my first supervisor from the university, for his enthusiasm during our meetings, the quick and valuable responses to my questions and for letting me make my own decisions. I am also grateful for the precise and stimulating feedback from Bert van Wee and Pieter Bots and from my daily supervisors, which proved to be a helpful contribution to this graduation thesis.

I am grateful for the internship opportunity that TNO gave me and the financial support for the stated adaptation experiment. I would also like to say a word of thanks to my colleagues at TNO, who provided a fun and relaxed atmosphere. It has always been a pleasure to go to work. Especially the lunch break on Friday has been the highlight of each week during my stay!

I want to thank my father, mother and sister for their continuous support and for having faith in me. You have given me sufficient space to focus on performing well. Thanks to you I was able to overcome each and every challenge and pass swiftly through my study. My family and friends are also appreciated for their efforts to take my mind off the research during the evenings and in the weekends. Thank you to Karunika Kardak for taking the time to read through the extensive report and offering corrections. Special thanks go to Toni Budimir; he is the best. He was always available to help me with challenges related to Matlab. Most appreciated was the continuous interest in the progress of the thesis and the development of the post-graduation plans.

Wouter van Stralen
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Summary

Congestion effects at the Dutch highways account for serious economic damage. Between May 2010 and April 2011 there were 68 million vehicle loss hours as a result of congestion (TNO, 2011). The external factor weather is widely acknowledged as a contributor to the occurrence of congestion in two different ways. Firstly, weather conditions can influence the traffic supply through a temporal reduction of capacity. Secondly, weather conditions can influence the traffic demand by changing travel behaviour. The influence of the weather on both the traffic demand and traffic supply has been studied by many researchers. Surprisingly though, a study towards the combined effect of changes in highway capacity and highway traffic demand as a result of the weather has not been carried out yet to the knowledge of the author. Studying the combined effect of highway traffic demand and highway capacity on congestion as a result of adverse weather conditions seems interesting, because both aspects have an influence on the probability of breakdown at a highway. This leads to the main question of the proposed research:

What is the influence of adverse weather conditions on the probability of congestion on Dutch highways?

To be able to answer the main research question it was investigated how the traffic demand and highway capacity could be linked to each other. The link between highway capacity and highway traffic demand is based on the influence that both factors have on the probability of breakdown. A stated adaptation experiment has been conducted and the change in highway traffic demand as a result of adverse weather is estimated with a Panel Mixed Logit model. To examine the influence of precipitation on highway capacity it was chosen to estimate capacity distribution functions for dry weather, light rain and heavy rain based on the Product Limit Method. In addition, a script has been written in Matlab that makes it possible to calculate the corresponding breakdown probability when the traffic demand and median capacity are entered. With the development of this generic model based on a cumulative normal distribution, breakdown probabilities can be calculated for any given traffic demand and median capacity. The main results of the study can be found in Table 1 and is elaborated upon in the remainder of the summary.

Table 1 - Main results regarding the influence of precipitation on probability of congestion

	Dry	Light rain	Heavy rain
Travel behaviour			
Average highway traffic demand change (%)	-	+2.3%	-2.3%
Highway capacity			
Average highway capacity change (%)	-	-5.7%	-8.9%
Standard deviation	-	1.9%	2.6%
Breakdown probability			
Average highway breakdown probability (%)	50%	86.7%	77.4%
Standard deviation	-	4.6%	11.4%

The influence of adverse weather conditions on travel behaviour

For the analysis of travel behaviour a distinction was made between utilitarian trips (business trips, commuter trips and educational trips) and recreational trips (visiting family or friends, grocery shopping, shopping, a day-out, going to sports etc) during the morning peak. First the results for utilitarian trips are elaborated upon, after which the results concerning the recreational trips are presented.

From the attributes that were included into the analysis (current weather, weather forecast and weather alarm) it can be concluded that the weather forecast does not have an influence on the travel behaviour for utilitarian trips. The current weather and a weather alarm on the other hand can have a significant effect on the adaptation of travel behaviour. Trip generation could be affected by some weather conditions. Rainfall, however, does not have a significant effect on trip generation. Heavy snowfall, on the other hand, results in an increase in the probability of not making the trip. Mode choice changes for utilitarian travellers do not occur a lot as a result of the weather. There is a very small change in the cyclists group towards the usage of the car, but this effect can be considered marginal. Route choice changes for car users resulting from weather conditions are also limited. Travellers who normally use the highway will not change their route and avoid the highway in case of severe weather conditions. With regards to non-highway travellers changing the route is also not very common. Departure time changes only occur if there is a weather alarm. Overall, it can be concluded that the effect of weather conditions on departure time change is limited. The biggest decision that utilitarian travellers make is whether to stay at home or to make their normal trip.

The influence of the weather conditions on recreational trips is slightly different from the utilitarian trips. In the case of a recreational trip purpose the weather forecast plays a small role in the choice to avoid the morning peak. It leads to a positive approach to avoiding the morning peak when the travellers know that the weather is going to improve. Both the current weather and the weather alarm influence the adaptation of travel behaviour more effectively for recreational trips than as compared to utilitarian trips. Trip generation of recreational trips is significantly influenced by adverse weather conditions. Very heavy rainfall leads to relatively high probabilities of not making a trip. Heavy snow combined with a snow or icy roads alarm leads to probabilities of 67.4% to 80.4% to decide not to make the trip, which is a remarkably high probability. Mode choice changes for recreational travellers as a result of the weather occur more than for utilitarian travellers. In the rain scenario there is a significant modal shift from cyclists towards the car. Route choice changes for recreational trips are mostly comparable to utilitarian trips. There is, however, a relatively high route choice change (up to 22.3%) for the non-highway users group in the case of very heavy rain. The departure time is changed more often in comparison to utilitarian trips. Overall it can be said that the alternative to avoid the morning peak period is preferred by recreational trip travellers. A possible explanation for this is (to some extent) the more flexible nature of the recreational purposes compared to utilitarian purposes.

As a result of the behavioural adaptation of travellers, the highway traffic demand rises by 2.3% in light rainfall due to a small route shift of non-highway travellers and a marginal modal shift of cyclists. The other scenarios result in less highway traffic demand. Highway traffic demand decreases by 2.3% in the heavy rainfall scenario. Some travellers might link heavy rainfall to an increase in probability of congestion and therefore avoid the highway. The traffic demand decreases by 7.7% when compared to dry weather as a result of very heavy rainfall. This large decrease could be explained by the extreme rain intensity that was presented to the respondents in the stated adaptation experiment. It can be concluded that snowfall leads to enormous decreases in highway traffic demand. Light snowfall leads to a decrease of 22.2%, while heavy snowfall leads to a decrease of 29.4% in comparison to the dry weather traffic demand. Travellers might know from historic events that snowfall leads to more congestion on Dutch highways, which could be a reason not to use the highways. The addition of a weather alarm results in the demand being reduced by 19.4% in case of very heavy rain and a rain alarm. Heavy snow and a snow alarm leads to a reduction of 48.8% and heavy snow in combination with an icy roads alarm results in a decrease of 52.4% in highway traffic demand when compared to dry weather. Some travellers thus tend to accept the advice of the KNMI to avoid travelling in extreme weather situations.

The influence of precipitation on highway capacity

For the capacity analysis a reference case of dry weather was used to investigate the effect of precipitation. Alongwith a reference case, the scenarios of light rain (rain intensity < 1mm/h) and heavy rain (rain intensity ≥ 1mm/h) were analysed. Due to limited data regarding snowfall and limited observations of congestion during snowfall, it was decided to exclude snowfall from the capacity analysis.

Light rainfall results in an average capacity reduction of 5.7% compared to dry weather. There is a significant difference in the capacity reduction if the results from different bottleneck locations are analysed, with the capacity reductions ranging from 3.9% to 8.9%. It is interesting to note that heavy rainfall, on an average, leads to a higher capacity reduction than light rainfall for freeflow capacity, which is in accordance with the expectations. There is a significant difference, but the average difference in reduction is not extremely high between light and heavy rain (5.7% vs. 8.1%) when considering the fact that light rain only includes observations with rain intensities less than 1mm/hour and heavy rain includes all observations higher than 1mm/hour. The difference in capacity between dry conditions and light rain is relatively large compared to the difference in capacity between light rain and heavy rain. This could indicate that the effect of rain on capacity is similar to the effect as described by Ries (1981), who concluded that the slightest amount of rain would result in an 8% reduction in capacity and every increase of 1mm/hour leads to an extra reduction of 0.2% in capacity.

Observations of the capacity reductions for the same scenario at the same location lead to the conclusion that the capacity reduction at one bottleneck location is very robust and does not change a lot over the years. Taking into account the small difference between observations at the same location, it can be concluded that the huge difference between observations at different locations (between -3.7% and 11.1%) is related to the different characteristics at the different locations. This could be the result of differences in precipitation intensities during a year at the different locations, but a more plausible conclusion is that the different highway characteristics lead to the effect of heavy rainfall on highway capacity being different at those locations. The road surface at the different locations might be an important factor in the reduction of highway capacity. It could be the case that the capacity reduction is smaller on highway sections with porous asphalt. This is in accordance with the study of Cools et al. (2007) on the effect of rain on different locations, which concluded the existence of heterogeneity in the effect of rain on different traffic count locations and the homogeneity of the rain effects on the upstream and downstream side of a certain location. Comparing the results obtained in the analysis with findings from other studies leads to the conclusion that most other researchers have found capacity reductions which are within the same range as that of this study, leading to an increase in confidence concerning the results of this study.

The main conclusion that can be drawn from the capacity analysis is that conclusions regarding the effect of precipitation on highway capacity should not be based on the average reduction in capacity, since there is a high variety in capacity reductions for both the light rain and the heavy rain scenario.

The influence of precipitation on breakdown probability on Dutch highways

The combined effect of demand and capacity change as a result of the weather leads to the average breakdown probability to increase from 50% in the dry scenario to 86.7% due to light rain. This is the result of the decreased capacity and an increasing traffic demand in this scenario. In the heavy rain scenario the average breakdown probability is increased from 50% to 77.4%. The average probability of breakdown is lower than in the light rain scenario, while the average capacity reduction in the heavy rain scenario is larger than in the light rain scenario due to the decreased traffic demand in the heavy rain scenario. The range of breakdown probabilities for the different locations is between 81.7% and 94.6% in the light rain scenario, which can be explained by the location specific capacity reductions. In the heavy rain scenario there is a bigger range in the breakdown probability (between 57.0% and 88.8%) resulting from the relatively high capacity reduction at the highways A20L and A27L that are included in the heavy rain scenario.

The first conclusion that can be drawn is that rain on an average leads to a significant increase in probability at bottleneck locations. A breakdown probability of 50% in dry weather leads to an average breakdown probability of 86.7% in light rain and 77.4% inheavy rain conditions. Since the magnitude of the capacity reductions differs at different bottleneck locations, the breakdown probabilities should be analysed location-wise. Another interesting conclusion is that a small change in demand can have a significant effect due to the steep curve of the probability distribution functions. The relatively small influence of rain on highway traffic demand in the morning peak thus significantly influences the breakdown probability at the highways. An increase in demand of only 2.3% could for example lead to an increase in breakdown probability of 11 percentage points at a specific bottleneck location. An analysis solely based on the capacity reduction without incorporating the demand change would lead to incorrect results. In addition, it can be concluded that the breakdown probabilities vary for the different locations as a result of the different capacity reductions at these locations. Consequently, it can be inferred that both traffic demand and location specific highway capacity should always be incorporated in order to arrive at accurate predictions regarding breakdown probabilities as a result of adverse weather conditions.

Implications of the results

For TNO these results are, in the first place, an addition to their knowledge of the effect of weather conditions on travel behaviour and breakdown probability of highways. Additionally, these results can be used to incorporate stochasticity into the traffic models that are used by TNO. The influence of the weather is one of the stochastic factors that could be incorporated into TNO's traffic models. One should include distribution functions into traffic models to create stochasticity. This research can contribute by serving as input for estimation of these distribution functions and could provide an opportunity towards the increase of accuracy of the traffic models at TNO.

Rijkswaterstaat could analyse the underlying factors for the different capacity reducing effects at different locations as a result of rainfall. When different road surfaces lead to other capacity reductions, Rijkswaterstaat should take into consideration changing the road surface at the bottleneck locations to the surface that reduces capacity the least in adverse weather conditions.

The Ministry of Infrastructure and the Environment could benefit if the results of the study of Rijkswaterstaat lead to more cost-efficient reduction of congestion than constructing new highways. In this way, the probability of the Ministry reaching the goals of reduction of congestion will increase. The results regarding the various increases in breakdown probability at different locations as a result of precipitation can also be taken into account in the decision-making to assign the budgets to specific highway improvement projects.

Companies in the navigation market (like TomTom and Garmin) can use the insights from this study. Data regarding the effect of extreme weather situations is scarce, but is needed in order to create accurate traffic predictions. These companies could use these insights as a first step towards smarter routing of travellers in order to decrease the probability of congestion.

For the Royal Netherlands Meteorological Institute (KNMI) the results regarding the weather alarms can be useful. The KNMI initiates a weather alarm when a weather situation could lead to a heavy nuisance and disruption of the community. The weather alarm has led to some debate over the past years. From the stated adaptation experiment it can be concluded that despite the debate, the weather alarm still has a significant effect on travellers (up to 16.9 percentage points eduction of trips). This should create more confidence in the effectiveness of the weather alarms.

The implications of this study for the public transport sector are relatively limited. The effect of adverse weather on the amount of public transport trips thus seems to be marginal based on this study. The results are, however, only based on a small group of 35 utilitarian public transport travellers and the recreational public transport group was not included into the analysis. For accurate insights into the effect of adverse weather on public transport travel behaviour it would be advisable to conduct a study that focuses more on the public transport sector.

In the end, the travellers using the highway could become the biggest beneficiaries of the efforts of other parties. The likely result of those efforts is a better circulation of traffic and less congestion at static bottleneck locations, leading to travel times and travel time uncertainty related to congestion to decrease. The congestion effects due to precipitation could be reduced if utilitarian drivers would avoid the morning peak more or work more at home. According to the experiment at most 6.6% of the utilitarian highway users would avoid the morning peak and 35.8% would not make a trip in the extreme situation of heavy snowfall and an icy roads alarm. More flexibility in working hours or the possibility to work at home could result in more utilitarian travellers to avoid travelling during the morning peak in adverse weather conditions. It could be valuable to test if more flexibility provided by employers would lead to higher behavioural adaptation of employees and thereby can reduce congestion during the morning peak in adverse weather conditions.

Recommendations for further research

The results regarding the effect of rain on highway breakdown probability can eventually be used to incorporate stochasticity into the traffic models that are used by TNO. It should first be investigated how stochasticity can be best incorporated into the traffic models. When the best approach towards including stochasticity into the model is known, the results from this study can contribute to this by serving as input for estimation of the capacity distribution functions.

It would be an addition to analyse the effect of snow on highway capacity, which could not be carried out in this research. The first hurdle towards capacity estimations with snow was that there is no bottleneck location specific data regarding the occurrence of snow available at TNO. Additionally, there were very limited days with snow within the examined years (2007, 2008 and 2009). An analysis of the effect of snow on highway capacity could, however, provide valuable additions to the results of this study. In order to arrive at sufficient breakdown observations on days with snowfall, it is advised to combine the traffic data from different years at the same bottleneck location. The snow analysis would be more accurate if reliable location specific snowfall information could be obtained. Lastly, it might be valuable to analyse whether or not the filtering algorithm can cope with breakdown observations at snow conditions.

From the conclusions it follows that the capacity reductions and breakdown probabilities at different bottleneck locations are location specific. The increase in breakdown probability as a result of rainfall at one specific location does not have to be an accurate estimate for bottleneck locations that are not included in this study. It is therefore not recommended to apply the average results in this study to other Dutch highway bottleneck locations. Further research into the capacity reducing effect of rainfall at other bottleneck locations is therefore advised.

The results obtained regarding the highway traffic demand changes in this research have three limitations. Firstly, the results are based on stated behaviour instead of revealed behaviour. The disadvantages might be that the stated behaviour differs from actual behaviour and that hypothetical weather situations were differently interpreted by respondents. Secondly, the results of the travel behaviour analysis are average changes in highway traffic demand. With the high importance of small changes in travel demand, it should be considered to investigate the effect of rain on the highway traffic demand location specific. Thirdly, there was no data available of the number of travellers in the different travel groups (car highway, car non-highway, public transport and bicycle). In this study the importance of the groups was based on the number of respondents in the groups. Data regarding the division of the groups in the population could have increased the accuracy of the traffic demand predictions. The three limitations can be overcome through travel data that will become available in the near future. TNO is developing a smartphone application that can track the trips made by travellers via GPS. Such an application has already been used by TNO in a project in Assen. There are however plans for an application to be used by 500.000 Dutch travellers. In the future, revealed data from 500.000 travellers can provide information regarding location specific demand changes as a result of the weather. In addition, the standard mode of each traveller could be investigated by analysing the GPS data to be able to weigh the travel groups based on the share of the travel groups in the population. This data from the smartphone tracking application project of TNO can be an addition to the results obtained in this study.

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1. Introduction

This chapter introduces the subject of the thesis project, starting with background information in section 1.1. The problem exploration is provided in section 1.2, which leads to the research gap in section 1.3. In section 1.4 the project is defined and delineated. Then the research questions are formulated in section 1.5. Finally, section 1.6 provides the outline of the thesis document.

1.1 Background

Traffic models are very important tools nowadays which can be used for estimation, prediction and control related tasks at highways. For most traffic models it is vital that uncertainty is limited and thereby resemble the traffic flows in the real world as accurate as possible. Outcomes of the models can influence important decisions that are made regarding traffic. There are however many causes that lead to uncertainty regarding traffic flows. An overview of causes that can influence traffic flows is provided by several authors (Lay, 2009; Hoogendoorn, 2007). They show that causes can be divided into design factors (i.e. surface quality, lane widths and horizontal alingements) and external factors (i.e. traffic composition, traffic flow variations and the weather). For traffic modellers and policy makers in the Netherlands the external factors are assumed to be more interesting than the design factors, because it is expected that very limited new highways will be built in the Netherlands in the future. The external factors are also more likely to fluctuate over time compared to the design factors, hence are more likely to affect traffic flows.

The focus in this study is on the external factor weather, which is widely acknowledged to have an important effect on the traffic flow variations. Weather conditions can influence traffic flow in two different ways. Firstly, weather conditions can influence the traffic supply through a temporal reduction of capacity. Secondly, weather conditions can influence the traffic demand by changing travel behaviour. The influence of the weather on both the traffic demand and traffic supply has been studied by many researchers. Surprisingly though, only few researchers have studied traffic demand and traffic supply at the same time. Maze et al. (2006) are one of the few researchers that have studied the effect of both traffic demand and traffic supply, but a study towards the combined effect of the weather on traffic demand and supply has not been carried out yet. Studying the combined effect of traffic demand and supply on congestion seems interesting, because both aspects determine the possibility of a occurrence of congestion.

1.2 Problem exploration: Effect of weather on traffic supply and demand

The effect of the weather on solely the traffic supply has been widely studied. Chin et al. (2004) show that there are many weather events that can cause a temporal reduction of the capacity of highways. The most common and most studied events are rain and snow, but fog (Liang et al., 1998; Shepard, 1996), sun glare (Auffray, 2007) and wind storms (Knapp & Smithson, 2000) are also studied sometimes. One of the most well-known studies to the effect of weather on traffic flow is presented in the Highway Capacity Manual (Transportation Research Board, 2000). Although the book is cited many times in the literature, the study presented in the book is not the most extensive study in the field. The section of the I-84 highway in the United States that is studied is in a rural area, which means that there are limited congestion effects. Despite this, the manual suggests to include capacity reductions between 0% and 15% as a result of precipitation. A more recent study by Okamoto et al. (2004) also categorized precipitation intensities on the Tokyo-Nagoya highway in

Japan. This categorization is more extensive than all prior authors used in their studies. The results of the study were that the capacity of the freeway was reduced by 0%, 5%, 11%, 14%, 25%, and 33% for the rain intensity categories. Recently a European study was carried out by Cools et al. (2007) in Belgium. The most interesting results obtained by Cools were the heterogeneity of effects of the weather conditions on different traffic count locations and the homogeneity of the weather effects on the upstream and downstream side of a certain location. Cools thus proved that it is not possible to use results from a different study as capacity reductions are case specific. Due to heterogeneity of effects of weather conditions on capacity at different locations, which can be caused for example by population density or different highway design factors, it is not possible to apply results from foreign studies to the Dutch highway situation.

The effect of weather on traffic demand has received much less attention than the effect on traffic supply according to Böcker et al. (2012), because it is harder to determine the traffic demand than the travel supply. In their literature review, Böcker et al. show that many studies have found different effects of precipitation, temperature and wind on traffic demand. Call (2011), amongst others, reported considerable reductions in trip-making with snowfall. As a consequence of rainfall car traffic reductions are also reported, for example by Hassan and Barker (1999) in Scotland. Where most studies show negative percepitation effects on trip generation, a Dutch study from Sabir (2011) shows a positive relationship between precipitation and car and public transport usage. This is the result of the large amount of cyclists in the Netherlands, from which some switch to motorized transport modes in response to precipitation. Also the trip purpose of the traveller seems to have an influence on the adaptation to weather; Call (2011) has found much lower impact of weather on professional traffic compared to ordinary personal traffic. Most of the studies compared trip generation to the actual weather (which is in most cases retrieved from national meteorological sources), whereas travelers are also likely to refer to expectations of future weather while making a choice. A travel decision for a trip to work is likely to involve the forecast of the weather later that day for the trip back home. Kilpeläinen and Summala (2007) detected an important role of rain forecasts for travel changes in Finland. From the reviewed studies, Kilpeläinen and Summala (2007) are the only researchers that took subjective weather ratings into account due to triangulation with absolute weather data, where subjective weather data has a higher explanatory value on travel behaviour than objective weather data. A detailed study to the impact of expectations and weather forecasts to travel behaviour has not been conducted yet to the knowledge of the author. On top of that the different demographic situation in the Netherlands with the large amount of cyclists, which results in a positive relationship between precipitation and car and public transport usage, leads to the conclusion that results from foreign studies can not be applied to the Netherlands.

1.3 Research gap

Studies that were carried out to analyse the effect of weather conditions on highway capacity have several shortcomings which makes it difficult to apply the findings to the Dutch highways. Firstly, precipitation intensities are not quantitatively categorized in numerous studies, like Kyte et al. (2000) and Akin et al. (2011), where in other studies intensities are differently categorized. The usage of different precipitation categories makes it very difficult to compare the outcomes of different studies. On top of that some studies, like Brilon and Ponzlet (1996), used weather information of weather stations that were remotely located from the highways, which could reduce the accuracy of the predictions. Next to that, Cools et al. (2007) showed that there is heterogeneity in the effects of the weather conditions on different traffic count locations. Finally, multiple researchers (e.g. Elefteriadou et al. 1995; Minderhoud et al. 1997; Persaud et al. 1998; Lorenz and Elefteriadou 2001) have shown that the maximum capacity of a highway varies even when the external factors are constant. Breakdown does not necessarily have to occur at maximum flow and breakdown could occur at flows lower or higher than those traditionally accepted as capacity (Lorenz & Elefteriadou, 2001). Providing a constant value or a regression line for the relation between the weather data and capacity reduction therefore ignores the stochastic nature of capacity. Using a stochastic approach including a probability of capacity reduction given certain traffic volumes would be more suitable. Combined with the fact that currently no research has been conducted in the Netherlands, this leads to the conclusion that there is a lack of knowledge regarding the effect of weather on the capacity of Dutch highways.

From the studies that were conducted towards the effect of weather on travel behaviour, most of the studies compared trip generation to the current actual weather, whereas travelers are also likely to refer to expectations of future weather while making a choice. A travel decision for a trip to work is likely to involve the forecast of the weather later that day for the trip back home. Kilpeläinen and Summala (2007) detected an important role of rain forecasts for travel changes in Finland. From the reviewed studies, Kilpeläinen and Summala (2007) are the only researchers that took subjective weather ratings into account due to triangulation with absolute weather data, where subjective weather data has a higher explanatory value on travel behaviour than objective weather data. A detailed study to the impact of expectations and weather forecasts to travel behaviour has not been conducted yet.

1.4 Problem statement: definition and delineation of the project

Based on the shortcomings of current research the problem statement can be concluded, which is:
There is a lack of knowledge regarding the effect of weather conditions on Dutch highway capacity and of weather conditions and predictions on highway travel behaviour in the Netherlands.

The effect of weather conditions on highway capacity has been studied by many researchers. These studies however are focused on other countries than the Netherlands. The effect of weather conditions on travel behaviour in the Netherlands is to some extent studied by Sabir (2011). This study did not take the weather effect on route choice into account, which is an important factor for analysing highway travel behaviour. Lastly the influence of weather predictions on highway travel behaviour has had very little attention. Kilpeläinen and Summala (2007) have incorporated rain forecasts in Finland into their study, but the importance of weather forecast for travel behaviour has not been studied yet. Where the effect of weather conditions on highway capacity and highway travel behaviour lacks research regarding the Netherlands, the effect of weather predictions on travel behaviour has a worldwide knowledge gap.

From the problem statement it follows that only traffic flows on Dutch highways are analysed. This results from the fact that for a Dutch traffic model a study to the effect of weather is only relevant for Dutch highways. The delineation to the highways results from the traffic data that are only available for the highways and the importance of congestion on highways for the total network compared to the city network. To get accurate predictions of the traffic demand change and have sufficient observations with congestion, it is chosen to limit this study to the morning peak period (between 6:00 and 10:00 am). The study towards the influence of the weather on capacity is delineated to the influence of actual precipitation on the capacity. At first the influence of rain is studied. When time restrictions allow a wider range of factors to be studied, snowfall could be added to the study. For the travel behaviour more factors can be taken into account, like the weather at the time of the trip (including precipitation, temperature), the weather forecasts and possible traffic alarms.

1.5 Involved actors and relevance of the study

In this section the relevance of the study is elaborated upon based on the expected impact of the study on the involved actors. The expected impact of the study on TNO, highways car travellers, the Ministry of Infrastructure and the Environment, Rijkswaterstaat, companies in the navigation market, the Royal Netherlands Meteorological Institute (KNMI) and public transport operators are presented.

TNO wants to gain more insight in the effect of adverse weather conditions on congestion to get to more accurate traffic predictions. Accuracy of traffic models is an important issue in The Netherlands, as can be concluded from the questions that the members of the parliament Kuiken, Fokke (PVDA), De Rouwe and Geurts (CDA) asked in November 2012 regarding the accuracy of the traffic models that the Ministry of Infrastructure and the Environment uses (Schultz van Haegen, 2012a; Schultz van Haegen 2012b). The results of this study could be an opportunity towards the increase of accuracy of the traffic models at TNO.

Highway car travellers are important actors in this study, since the highway car travellers are experiencing the effects of congestion. According to highway car travellers a decrease of congestion will be the most important improvement at the highways, followed by the quality of the highways (Rijkswaterstaat, 2013a). Insights into the effect of adverse weather on the congestion probability could be a first step towards reducing congestion, hence could be very beneficial for highway car travellers.

The Ministry of Infrastructure and the Environment is connected to the congestion issue by the budget that it assigns to highways each year. The Ministry is the policy maker regarding the highways and the policy focuses on construction of new highways, improving current highways and smarter usage of the current highways (Rijksoverheid, 2013a). The road authority Rijkswaterstaat is a body of the Ministry. Rijkswaterstaat is commissioned by the Ministry to maintain the Dutch highways and further develop the highways. Development of the highway network is for example done by construction of new highways or new lanes (Rijkswaterstaat, 2013b). The mission of Rijkswaterstaat is to have a safe and fluent traffic flow on the highway network.

Other parties that are connected to congestion on the highways are companies in the navigation market (like TomTom and Garmin). For these companies, providing accurate travel information to the customer is very important. Data regarding the effect of extreme weather situations is scarce, but is needed in order to create accurate traffic predictions. This study could gain insights into the effect of adverse weather situations on the probability of breakdown at Dutch highway, which can be the basis for strategies to mitigate the breakdown probability as a result of weather conditions.

The weather alarm is an important instrument in trying to reduce congestion effects in adverse weather conditions. The KNMI, a body of the Ministry of Infrastructure and the Environment (Rijksoverheid, 2013b), initiates the weather alarm when a weather situation could lead to a heavy nuisance and disruption of the community. Between 1999 and 2009, the weather alarm was initiated 47 times. Seven alarms were initiated too late and 10 alarms turned out to be incorrect (KNMI, 2009). This resulted in questions from the parliament towards the minister in December 2009 (Huizinga-Heringa, 2010). The criteria were then revised and the most important changes made were that the alarm would be regional instead of for the whole country and the alarm would only be initiated when there is at least 90% probability of the occurrence of adverse weather. The weather alarm seemed to work well on December 7th 2012, when chaos on the highways could be avoided by the weather alarm (NU.nl, 2012). On January 15th 2013 however, a weather alarm for snowfall was not initiated and this led to more than 1000 kilometres of congestion on the Dutch highways during the morning peak. According to the KNMI the criteria for initiating a snowfall alarm had not been met. The validity of the weather alarm was widely questioned by the media, which resulted in the KNMI to decide to evaluate the criteria for initiating an alarm (RTL, 2013; NU.nl, 2013; AD.nl, 2013). The weather alarm thus has led to debate in the past years, which could have harmed the effect of the weather alarm. The effect of a weather alarm on the travel behaviour after the debate is tested in this study.

Finally, the public transport operators might benefit from the insights that will be provided about the modal shift as a result of adverse weather conditions and weather information. Since extreme weather conditions do not occur often, the stated adaptation experiment can lead to valuable extra information regarding predictions of the amount of travellers using public transport during these conditions. This information could for example be taken into account by the Dutch Railways when decisions are made regarding whether or not to adapt the train table during adverse weather conditions.

The scientific relevance of this study results from the creation of knowledge regarding the effect of weather and weather forecasts on highway capacity and highway travel behaviour in the Netherlands. Next to that an attempt is made to link impact on travel behaviour to impact on capacity, which has not been done yet to the best of our knowledge. The social relevance of the subject results from the fact that congestion effects at the Dutch highways account for serious economic damage. Between May 2010 and April 2011 there were 68 million vehicle loss hours as a result of congestion in The Netherlands (TNO, 2011). The weather is widely acknowledged to contribute to the occurrence of congestion. First of all, the outcomes of the study could be implemented in traffic models of TNO to be able to make more accurate traffic predictions. This may in the end lead to more accurate advice to users of the travel advice application which TNO is currently working on. On top of that insights obtained from this study could lead to insights regarding the best strategy to mitigate congestion in adverse weather conditions. In addition, the effect of usage of weather information to avoid congestion on highways can be tested in this study. Finally the results regarding adaptation of travel behaviour could be taken into account by public transport operators to be better prepared to changes in travel demand during adverse weather conditions.

1.6 Research questions

In order to incorporate the effect of the weather in the traffic models of TNO and to be able to address the effect of traffic policies regarding the weather, it is proposed to conduct research to the combined effect of capacity and traffic demand changes as a result of the weather on congestion on the Dutch highways. This leads to the following main question of the proposed research:

What is the influence of adverse weather conditions on the probability of congestion on Dutch highways?

In order to answer the main research question, the following sub-questions and sub-sub-questions are addressed:

- How can the highway traffic demand and capacity change as a result of adverse weather be combined into a probability of congestion?
- What is the effect of current and forecasted weather on travel behaviour?
    - Which current and forecasted weather attributes are important for making travel choices?
    - What is the influence of current and forecasted weather attributes on trip generation, mode choice, route choice and departure time choice for utilitarian and recreational trips?
    - What is the effect of current and forecasted weather on highway traffic demand?
- What is the effect of precipitation on highway capacity?
    - What are requirements for a bottleneck location to be suitable for capacity analysis?
    - Which capacity estimation approach is most suitable for analysing the effect of precipitation on highway capacity?
    - Which distribution function fits best with the empirical results of the capacity estimation?

1.7 Thesis outline

The structure of the report is as follows: First the concepts of traffic demand and capacity are elaborated upon in chapter 2. This chapter also presents a literature review regarding the effect of weather conditions on both traffic demand and capacity. Along with that a conceptual model is made to link the concept of traffic demand to capacity. In chapter 3 the methodology of the stated adaptation experiment is introduced, which is used to answer the sub-questions regarding travel behaviour. The results from the stated adaptation experiment are presented in chapter 4. The effect of precipitation on capacity is then estimated with capacity distribution functions for different scenarios in chapter 5. After that, the results from the traffic demand change and capacity reductions are combined in order to come to a probability of breakdown at Dutch highways as a result of weather conditions. Chapter 7 concludes by answering the main and sub research questions, elaborates on the implications of the results for different actors and provides recommendations for further research. Lastly in chapter 8, a reflection on the choices made and the process of this thesis is presented.

2. Conceptualising the relation between traffic demand and supply

In this chapter the main factors that are used in the thesis are defined. Firstly, there is elaboration on highway traffic supply, which is defined as the capacity of a highway. Next to the highway traffic supply also the highway traffic demand is defined in this chapter. The effect of the weather is addressed for both highway traffic supply and demand based on a literature review. Lastly, the concepts of highway traffic demand and supply are linked to each other via the effects that both factors have on the probability of breakdown at a highway and a conceptual model are presented to provide more insights into the influence of the weather on the probability of breakdown at highways.

2.1 Traffic supply

In section 2.1.1 highway traffic supply is be defined and the need for a stochastic approach towards highway capacity is addressed. Next to that the underlying factors that determine highway capacity are presented. Section 2.1.2 then elaborates on the effect of adverse weather conditions on these factors and on highway capacity.

2.1.1 Highway traffic supply

Highway traffic supply can be defined by the variable capacity (q_c). As in the Highway Capacity Manual 2000, traditionally highway capacity is viewed as a deterministic phenomenon, using the notion that a traffic breakdown occurs if demand exceeds an identified capacity value. This approach is suitable to get an initial idea about capacity on a strategic level. In the planning phase highway designers can be assumed to be able to make a well-founded decision for a highway with for example two or three lanes. In operational and tactical traffic models this deterministic approach is however less suitable due to the requirement for accuracy in these models.

Multiple researchers (Elefteriadou et al. 1995; Minderhoud et al. 1997; Persaud et al. 1998; Lorenz and Elefteriadou 2001, Brilon et al., 2005) have shown that the maximum capacity of a highway varies. Even in ideal conditions capacity cannot be regarded a constant value because unobservable variations in driver and vehicle characteristics are present in the traffic flow (Minderhoud et al., 1997). When the traffic volume approaches the capacity these heterogeneities in the traffic stream can lead to small perturbations, which will be amplified through a shockwave as a result of the vehicles following each other at high speeds with relatively short headways. Examples of heterogeneities are speed differences between vehicles in one lane, speed differences between lanes or flow differences between lanes. These heterogeneities relate to specific kinds of unpredicted events resulting from driving behaviour of individual drivers (Smulders, 1990). This unpredictable behaviour is regarded to have properties of randomness, which leads to the conclusion that breakdown does not necessarily have to occur at maximum flow and breakdown could occur at flows lower or higher than those traditionally accepted as capacity (Lorenz & Elefteriadou, 2001). Providing a constant value or a regression line for the relation between the weather data and capacity reduction thus ignores the stochastic nature of capacity. In operational and tactical traffic models it is necessary to include the stochastic approach to come to the right level of accuracy of traffic predictions. A definition of capacity that takes the probabilistic nature of capacity into account defines capacity as *"the rate of flow along a uniform freeway segment corresponding to the expected probability of breakdown deemed acceptable under prevailing traffic and roadway conditions in a specific direction*" (Lorenz & Elefteriadou, 2001).

Capacity can be influenced by many different factors. An overview of causes that can influence highway capacity provided by Lay (2009) and Hoogendoorn (2007) leads to the following non-exhaustive list with factors that influence highway capacity:

- Road specific factors (road type, lane width, curvature, grades, surface quality and lighting).
- Weather conditions (rain, snow, fog, sun glare, wind storms).
- Vehicle composition (cars vs. trucks) and driver composition (familiarity and travel purpose).
- Road works and incidents.

In this study however only the effects of weather conditions are taken into account.

Capacity is a result of the underlying macroscopic traffic flow characteristics, which in traffic flow theory are referred to as fundamental diagrams. These fundamental diagrams (Figure 1) are based on the three variables velocity, intensity and density, which are shortly elaborated upon in this section.

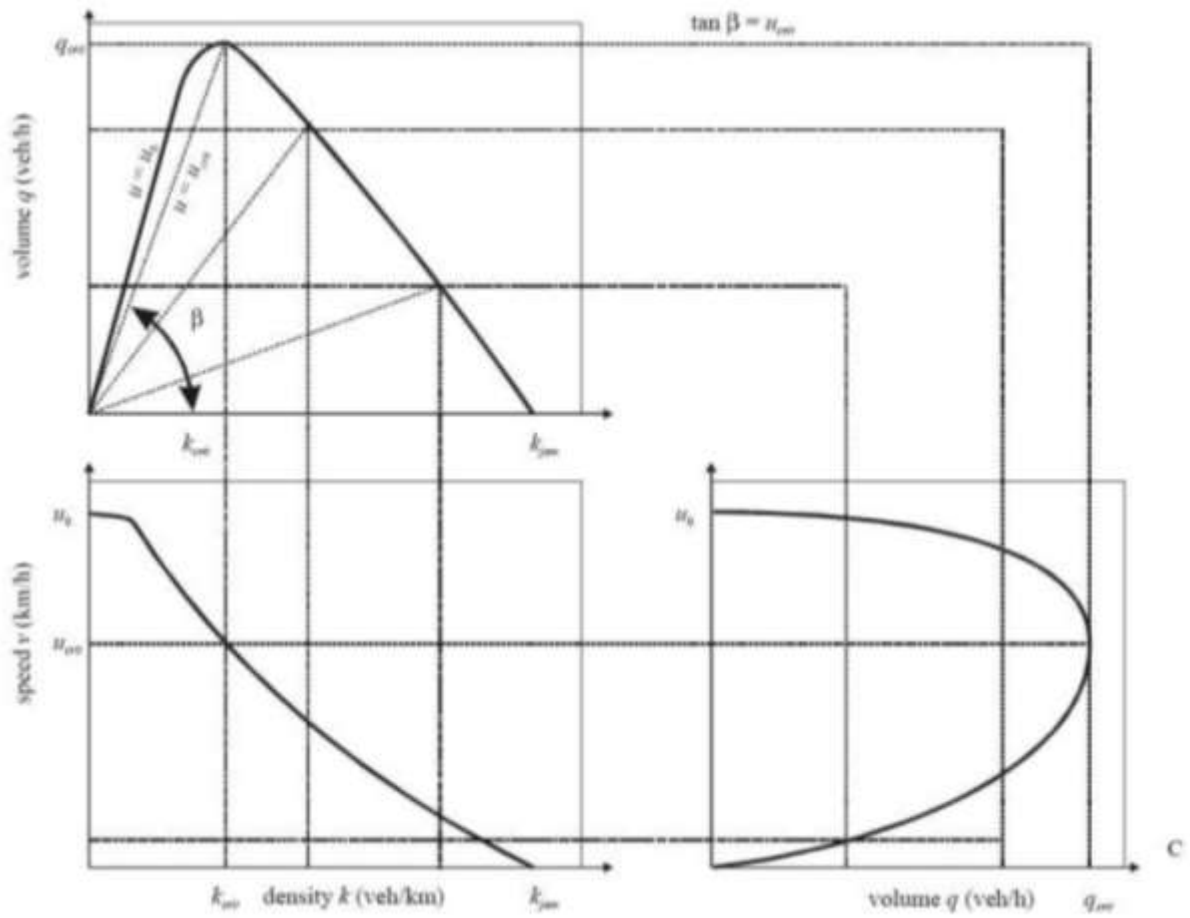

Figure 1 - Fundamental diagrams (Hoogendoorn, 2007)

The velocity is the distance travelled per unit of time. There are two types of mean velocity, which are the space mean velocity and the local mean velocity. The space mean velocity describes de mean velocity of all vehicles that are present on a road section at a certain moment in time. The local mean velocity describes the mean velocity of all vehicles that pass a certain cross-section during a certain period. Traffic data that is used in this study provides information regarding the local mean speed, which can be obtained from the loop detectors in the motorways. Time-distance diagrams can be used to visualize the local mean speed. The following formula is used to calculate the local mean velocity, with *n* being the number of vehicles passing a cross-section during a certain period. In the formula v_i is the observed velocity of car i and u_L is the local mean velocity:

$$u_L = \frac{1}{n}\sum_{i=1}^{n} v_i$$

Intensity is defined as the number of vehicles passing a cross-section of a road per time unit. The intensity can be calculated for a total cross-section of a road, but also for individual lanes. Any time unit can be used, but hour is mostly used. The intensity is a local characteristic defined at a cross-section, according to the following expression by q, with n being the number of vehicles passing a cross section and t being the time unit:

$$q = \frac{n}{t}$$

Density is defined as the number of vehicles present on a road at a given moment. Density can refer to a total road, a roadway or a lane. When the density is low, this means that the vehicles move with a relatively large distance headway. The expression to calculate the density k, with m being the number of vehicles on a roadway section at that instant and X being the unit of length, is:

$$k = \frac{m}{X}$$

According to the fundamental flow diagram the capacity of a highway is reached at the point of critical intensity. When the intensity is higher than this critical value this results in a breakdown. The capacity (or critical intensity) of a highway is determined by the critical speed and critical density of a traffic flow via the relations between the velocity, density and intensity (Figure 1). These are the speed and density respectively, above which the flow becomes congested. The critical intensity that can be achieved (i.e. the capacity) is thus a result of the optimal combination of speed and density on a certain road section (Figure 2).

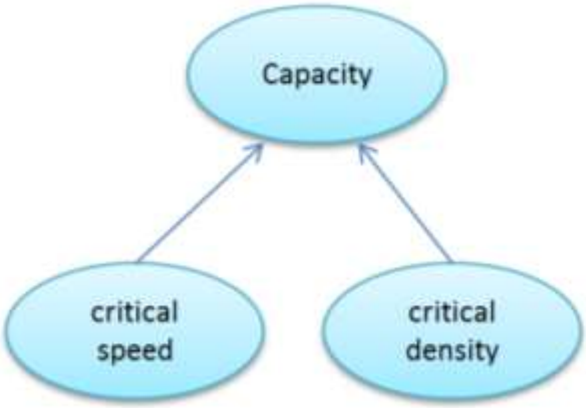

Figure 2 - Influence of the critical speed and critical density on capacity

This approach is based on the assumption of the capacity being a deterministic phenomenon. If the probabilistic nature of capacity is taken into account and the definition of Lorenz and Elefteriadou (2001) is used, the essence of the relations is equivalent. Assuming a certain intensity at which there is an acceptable probability of breakdown, this intensity is the result of the critical speed and critical density. The critical speed and critical density corresponding to this capacity value are however negatively affected as a result of precipitation (see 2.1.2), meaning that the intensity at which there is an acceptable probability of breakdown also increases. In other words the capacity of a certain road section decreases as a result of adverse weather condition.

2.1.2 Influence of weather on highway capacity

Studies have shown that both critical density and critical speed are negatively affected by precipitation and therefore highway capacity is negatively affected by precipitation. The critical density at a certain road section is a result of the headways between the cars on the road. Several researchers reported precipitation leading to larger headways between cars (Hogema, 1996; Habtemichael, 2012; Alhassan & Ben-Edigbe, 2012). Habtemicheal et al. (2012) showed with regression analysis that the efficiency of a motorway deteriorated due to the risk acceptability of drivers being affected and the increased speed variability among them. Hogema (1996) found that headways that were smaller than one second occurred less often in rainy conditions compared to dry conditions. In the analysis of the fast lane headways of one second or less were observed 50% less in rainy conditions. There was a smaller effect of rain on the larger headways of three and five seconds analysed. Alhassan and Ben-Edigbe (2012) found increases in mean headways of 16% between no-rain to light rain conditions. Between no-rain and medium rain the increase is 20%, while between no-rain and heavy rain conditions the mean headway is increased with 26%.

The negative impact of precipitation on the critical speed is also reported by many scholars (among others Kyte et al., 2000; Ibrahim & Hall, 1994; Akin et al., 2011). Kyte et al. (2000) found that a wet surface as a result of rainfall reduces the speeds on average with 4.5 km/h, which is a 50% lower speed reduction in comparison to the suggested speed reductions in the Highway Capacity Manual. Ibrahim and Hall (1994) studied the effect of precipitation in Canada. Multiple regression analysis provided conclusions that light rain caused 3-5% reductions in speed and heavy rain results in speed reductions of 14-15%. In this study there were no intensity ranges specified within the categories light and heavy rain. On top of that Ibrahim and Hall used a very small dataset including only six clear days and two rainy days, which makes the outcomes less robust. Akin et al. (2011) investigated amongst others the influence of rainfall on the average speed and on the capacity of the first and second Bosporus bridge routes in Istanbul, which are clearly urban highways. The results were that average speed dropped by 8-12% and capacity reduced by 7-8%. Snowfall resulted in even bigger drops of the average speed at the Bosporus bridge. The decreasing speed and density as a result of precipitation explains a decreasing capacity of the highway section (Figure 2).

There are also numerous studies with conclusions regarding the effect of precipitation on capacity. Okamoto et al. (2004) categorized intensities in a study towards the Tokyo-Nagoya highway in Japan. This urban highway with congestion effects made it possible for the researchers to use the direct approach to estimate the capacity reduction. The rain intensities were divided and categorized in intensity groups of 0.0, 0.1 to 0.6, 0.7 to 1.2, 1.3 to 2.4, 2.5 to 4.8, and 4.9 to 9.6 mm/hour. This categorization is more extensive than all prior authors used in their studies. The results of the study were that the capacity of the freeway was reduced by 0%, 5%, 11%, 14%, 25%, and 33% respectively for the rain intensity categories.

The studies from Agarwal et al. (2005) and Maze et al. (2006) in the United States are, together with Okamoto et al. (2004), the most extensive studies. Agarwal et al. (2005) and Maze et al. (2006) examined the effect of rain on the capacity reduction at an urban highway in the United States and intensity categories were classified. Maze et al. (2006) found capacity reductions of 2%

for 0-0.01 inch/hour, 7% for 0.01-0.25 inch/hour and 14% for >0.25 inch/hour rainfall. Agarwal et al. (2005) found capacity reductions of 1-3% for 0-0.01 inch/hour, 5-10% for 0.01-0.25 inch/hour and 10-17% for >0.25 inch/hour rainfall.

From the literature it follows that the range of the effects in the different studies is rather high, with capacity reductions varying from 0-15% according to the Highway Capacity Manual (2000) and capacity reductions from 0-33% according to Okamoto et al. (2004). It can be seen that there is a big difference in the capacity reduction effect of rain according to these studies. This calls, in combination with the need for a stochastic approach to capacity, for an empirical study in the Netherlands in order to be able to take the capacity reductions into account.

2.2 Traffic demand

In section 2.2.1 highway traffic demand is defined and the factors influencing highway traffic demand in the morning peak are presented. Section 2.2.2 then elaborates on the effect of adverse weather conditions on these factors and on highway traffic demand.

2.2.1 Highway traffic demand during the morning peak

Traffic demand can be described as the number of vehicles that want to make a trip from A to B at a certain period of time. In this study the highway traffic demand is the number of cars that use the highway during the morning peak. The morning peak is delineated to the period between 6 and 10 am, which is a broad interpretation of the morning peak. Most of the congestion during the morning peak occurs between 7 and 9 am, but such an interpretation would fail to include all congestion effects during the morning peak. The stated adaptation experiment is used to come to an estimate regarding the relative amount of vehicles on the highways during the morning peak as a result of the weather conditions compared to a normal situation. The aim of the analysis is to reveal what the effect is of certain weather conditions and weather forecasts on trips with different purposes. Counting vehicles on a certain road section would not provide information regarding the trip purpose of the vehicles on that road section. Next to that it is not feasible to count vehicles for every weather situation and forecast, since some aspects have to do with extreme situations and thus only occur a few times in a year. In 2011 for example no weather alarm was carried out by the Royal Netherlands Meteorological Institute (KNMI), implying that opportunities for road section counts of these very specific and rare weather situation and forecast combinations will be very limited. While a stated adaptation experiment could be less accurate than vehicle counts on a road section, the trip purpose can be taken into account in the experiment and the effect of specific and rare weather situation and forecast combinations can be analysed with this method. In order to come to an estimate of the highway morning peak traffic, one has to know which travel choices influence the amount of traffic on the highway. On the first level there are three factors that all influence the morning peak highway car traffic, namely car trip generation, route choice and time of day choice (Figure 3).

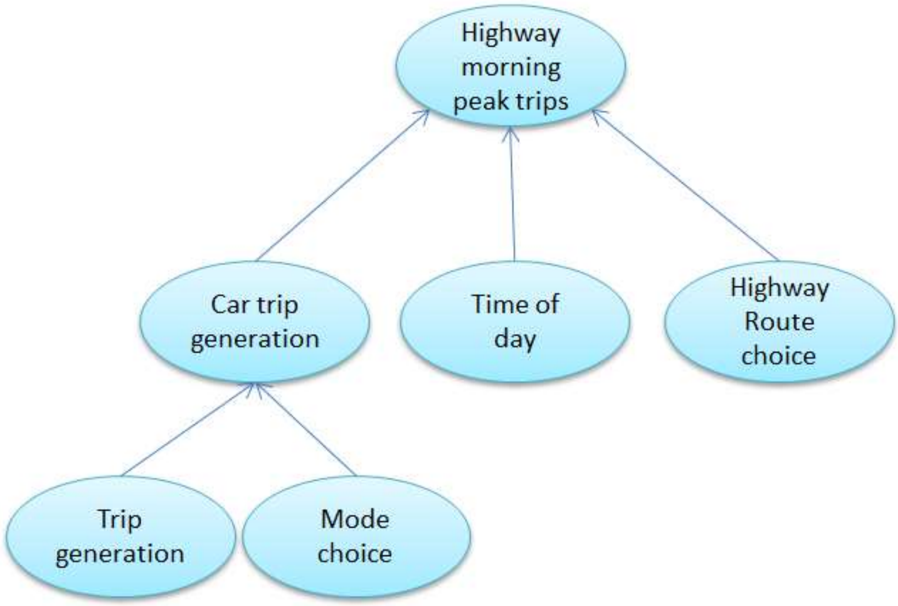

Figure 3 - Factors influencing morning peak highway traffic demand

The three premises of making a car trip, during the morning peak, while using the highway all have to be satisfied in order to contribute to the amount of highway traffic during the morning peak. Car trips that do not make use of the highway or use the highway outside the morning peak period are therefore left out of the scope. Car users that normally do not use the highway, but change their behaviour as a result of weather conditions are of course included in the scope. Car trip generation is dependent on the factors trip generation and mode choice. Users of other modes, like public transport and bicycles, can however also be relevant in this study when they shift from their standard mode to the car as a result of weather conditions. A more detailed explanation of the stated adaptation experiment can be found in chapter 0.

2.2.2 Influence of the weather on highway traffic demand during the morning peak

The factors presented in Figure 3 are all affected by the weather conditions according to studies from several researchers. In this section, a sample of the studies that found significant relations between weather conditions and these factors are presented.

The generation of car trips is significantly affected by weather conditions. Based on Keay and Simmonds (2005) there are statistically significant decreases of traffic volume in Melbourne ranging from 1.35 to 3.43% as a result of rain, with the decrease being bigger during weekends. Hassan and Barker (1999) reported car traffic reductions of more than 4% in the Lothian region in Scotland as a result of rainfall. This study also shows that snow has a bigger effect on the traffic activity, with a 10 to 15% traffic reduction in the Lothian region as a result of snow. Other snow related studies are mostly from the Northern American region. Call (2011) amongst others reported a significant effect of snowfall on car traffic in New York State. Maze et al. (2006) reported that snow had effects ranging from 20% to 80% traffic reduction on the I-35 in Iowa, depending on the visibility and wind speed combined with the snowfall. Where most researchers find negative precipitation effects on car trip generation, Sabir (2011) on the other hand found a positive effect of precipitation on car trip generation. This is the result of the large amount of cyclists in the Netherlands, from which some switch to motorized transport modes in response to precipitation.

The weather conditions also have an effect on the amount of trips generated by travellers. Aaheim and Hauge (2005) found significant shortening of the travelled distance as a result of precipitation, indicating that people choose closer destination or cancel trips to further destinations in response to precipitation. Cools et al. (2010) found that respectively 6.2% and 24.6% of the work/school trips are cancelled due to rain and snow. The effect on shopping trips was a lot bigger, with snow resulting in 58.1% of the trips being cancelled and 51.6% of the trips being cancelled due to rain. Leisure trips were also often cancelled due to rain (43.9%) and snow (64.4%).

Regarding the influence of weather conditions on mode choice, Cools et al. (2010) found for 15.2% and 24.2% of the work/school trips a modal shift for rain and snow respectively. With shopping trips the rain resulted in a modal shift for 14.4% of the trips and snow for 21.8% of the trips and leisure trips for 16.1% and 25.6% of the trips. As already mentioned with car trip generation, research from Sabir (2011) shows a modal shift from active open-air to motorized transport modes in response to precipitation. In the study of De Palma and Rochat (1999) 21.8% of the respondents indicated the weather to be important for the mode choice, whereas 32.9% indicated this to be very important. From these studies it can be concluded that mode choice can be significantly affected by weather conditions.

The choice of routes as a result of the weather is less often studied nonetheless a certain effect of the weather on the route choice has been confirmed by several researchers. Cools et al. (2010) found stated route changes of 15% and 43.6% as a result of rain and snow respectively for work/school trips. For the shopping trips rain results in 18.3% route changes and snow leads to changing routes in 41.2% of the cases. Leisure trips are affected by rain in 23.6% and for snow in 44.9% of the cases. According to this study a possible reason for route changes is the attempt to avoid traffic jams by changing the paths of the trips. Following from the study of De Palma and Rochat (1999) 22.8% of respondents indicated the weather to be important for the route choice, whereas 26.8% indicated this to be very important.

Another response to weather conditions is adapting the departure time. A possible reason for this is to avoid anticipated traffic jams as a result of the weather conditions. Cools et al. (2010) reported departure time changes for work/school trips in 29.7% of the trips for rain and in 52.2% of the trips due to snow. Shopping trips are more affected with 58.2% and 70.6% respectively. Finally departure times of leisure trips are also strongly affected with 45.7% for rain and 64.9% for snow. An interesting notion by Khattak and De Palma (1997) is that the departure time behaviour often differs across individuals with and without flexible work times. From the respondents in the study of De Palma and Rochat (1999) 29.8% indicated the weather to be important for the departure time choice, whereas 42.9% indicated this to be very important.

2.3 Influence of adverse weather conditions on the probability of a breakdown

In the previous paragraphs the effect on precipitation on highway capacity and the effect of adverse weather conditions on highway morning peak demand have been analysed based on findings in the literature regarding these topics. In this section a conceptual model is presented that links both highway capacity and highway morning peak demand to each other. To link these factors, one needs insight into the approach towards highway capacity that is used. As explained in paragraph 2.1, a stochastic approach to capacity is used based on the definition of capacity, which is *“the rate of flow along a uniform freeway segment corresponding to the expected probability of breakdown deemed* *acceptable under prevailing traffic and roadway conditions in a specific direction*” (Lorenz & Elefteriadou, 2001). Applying the concept of stochasticity to the highway traffic demand leads to a probability density function which is shown in Figure 4.

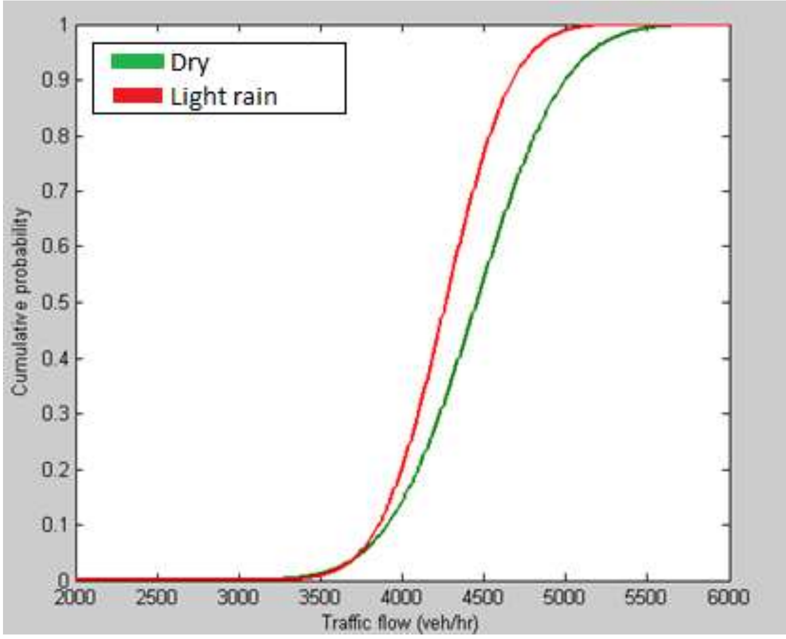

Figure 4 - Breakdown probability at highway A4R in 2007 in dry and heavy rain conditions

Figure 4 shows the capacity distribution function at highway A4R in 2007 in dry weather conditions (green) and in light rain weather conditions (red). Probability density functions are estimated for scenarios with and without precipitation to come to a capacity reduction by comparing the different functions. The result of precipitation on capacity is that the capacity distribution function with precipitation will be to the left compared to the capacity distribution function of dry weather, which means that the probability of a breakdown increases when the flow rate stays the same. At this part the highway traffic demand also influences the probability of breakdown. Based on the findings regarding travel behaviour in paragraph 2.2, it can be assumed that a certain part of travellers will adapt their behaviour as a result of the weather conditions. Whether this leads to an increase or decrease in highway traffic demand is yet to be known. Nevertheless it can be concluded that the travel demand, whether increasing or decreasing, affects the flow rate at the highway. The difference in flow rate at the highway as a result of weather conditions affects the probability of a breakdown. The link between highway capacity and highway traffic demand is thus based on the influence that both factors have on the probability of breakdown. A conceptual model has been constructed to provide more insights into the influence of the weather on the probability of breakdown at highways, which is presented in Figure 5.

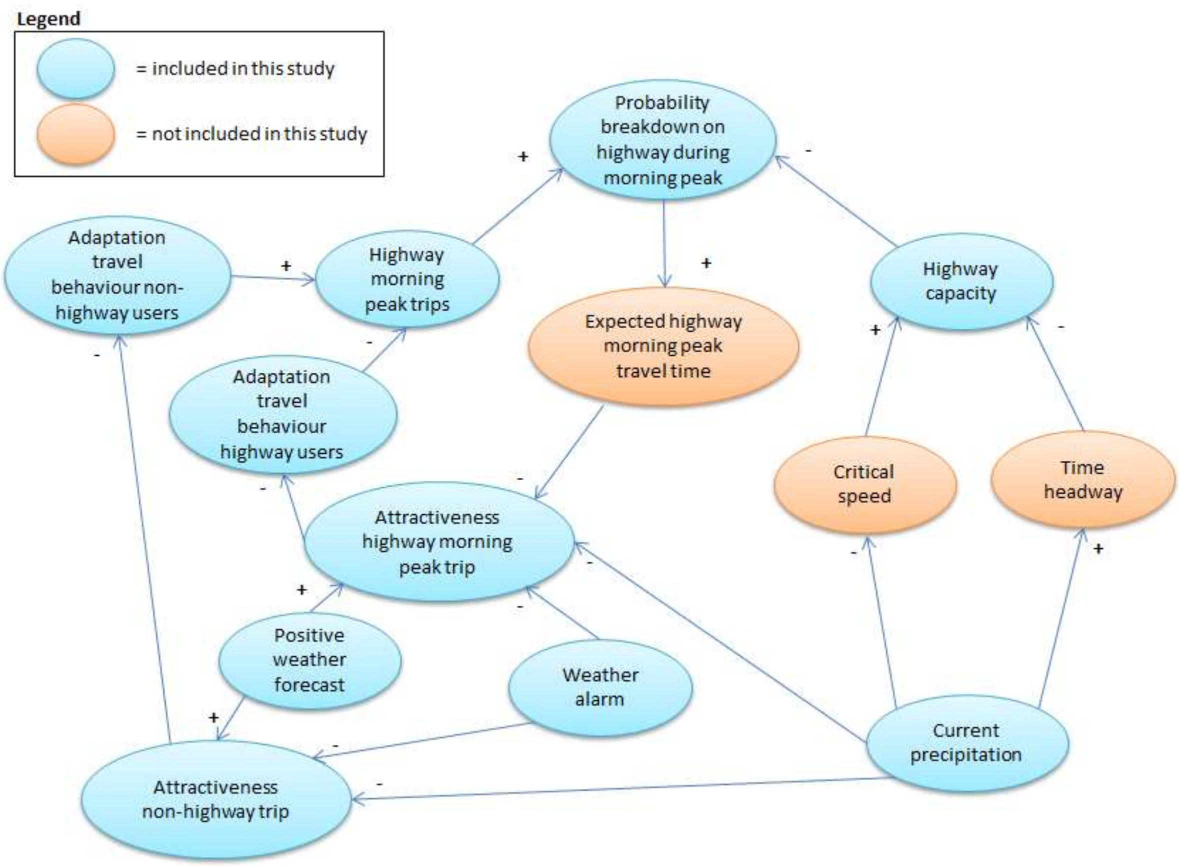

Figure 5- Conceptual model of the influence of weather on breakdown probability

At the right hand side of the conceptual model, the probability of breakdown is influenced by the highway capacity. From paragraph 2.1.2 it follows that the capacity is negatively influenced by precipitation via the factors critical speed and the time headway between vehicles, which decrease and increase respectively as a result of precipitation. Critical speed and time headway are included in the conceptual model, because these are the underlying factors affecting highway capacity. In this study the effect of precipitation on the critical speed or the time headway is not analysed and the choice is made to measure directly the effect of precipitation on highway capacity. From other studies it follows that precipitation has a negative effect on highway capacity. In this study the magnitude of the negative effect for the Dutch highways is explored. The decrease in highway capacity results in an increase of the probability of breakdown. A factor that could further reduce highway capacity is the presence of a wet surface, as investigated by Akin et al. (2011) and Mahmassani et al. (2009). As data on this is not available at TNO, this is not included into the research.

The left hand side of the model includes the effect of traffic demand on the breakdown probability. The breakdown probability has a positive effect on the expected travel time. When congestion often occurs at a route, travellers will have to take this into account in their expected travel time. This negatively influences the attractiveness of a highway morning peak trip. The expected travel time as a result of the probability of breakdown is not explicitly taken into account in this study. The assumption is that travellers will implicitly take into account what the effect of the weather would be on the travel time, based on the effect that previous weather situations had on travel time.

The main factors for the traffic demand are the attractiveness of making a highway morning peak trip and the attractiveness of making a non-highway trip. Non-highway users included in this study are car users that normally avoid the highway, public transport users and cyclists. Based on the relative attractiveness of these factors, travellers will make a decision on adaptation of their normal behaviour. The relative attractiveness is implicitly taken into account in the study based on the influence of the current precipitation, a weather alarm and the weather forecast on behavioural adaptation. The hypothesis is that the effect of these weather factors will have the same sign for both highway users and non-highway users. One can imagine that heavy rainfall makes both highway trips as non-highway trips less attractive, but the hypothesis is that some travellers (cyclists) are more affected than other users (car users). The magnitude of the effect on travel behaviour can thus be different for different travel groups, which is analysed in this research. Adaptation of behaviour can be a decision to use another mode of transport, to change the departure time, to change the route or not to make the planned trip.

This research explicitly takes into account the adaptation in behaviour of both highway users and non-highway users. Adaptation in behaviour of highway users leads to a decrease in highway morning peak trips, ceteris paribus. Adaptation of non-highway user could positively influence the highway morning peak trips, depending on the choices that these travellers make. When a cyclist for example decides to travel by car and wants to avoid the morning peak period, this does not influence the highway morning peak trips. Only when non-highway users decide to use the highway during the morning peak there is a positive effect of behavioural adaptation to highway morning peak trips. More on the effect of behavioural adaptation is explained in paragraph 3.1.3.

2.1 Conclusions

In this paragraph the answer to the sub research question regarding the link between highway traffic demand and highway capacity is provided.

How can the highway traffic demand and capacity change as a result of adverse weather be combined into a probability of congestion?

To be able to answer the main research question, the highway traffic demand and highway capacity should be linked to each other. Insight is needed into the stochastic approach towards highway capacity to link these factors. With the stochastic approach towards capacity, a certain traffic volume leads to a probability of breakdown. The higher the traffic volume is, the higher the breakdown probability becomes ceteris paribus. The link between highway capacity and highway traffic demand is based on the influence that both factors have on the probability of breakdown. Probability density functions can be estimated for scenarios with and without precipitation to arrive at a capacity reduction by comparing the different functions. The result of precipitation on capacity is that the probability of a breakdown increases if the intensity stays the same. At this part the highway traffic demand also influences the probability of breakdown. The travel demand, whether increasing or decreasing, affects the flow rate at the highway. The difference in flow rate at the highway as a result of weather conditions affects the probability of a breakdown. The steep curve of the capacity distribution function suggests that small changes in travel behaviour could have a significant effect on the breakdown probability. With both highway traffic demand and highway capacity being affected by adverse weather conditions, and the significant effect highway traffic demand changes can have, both traffic demand and highway capacity should always be incorporated in the analysis to come to accurate predictions regarding breakdown probabilities.

The goal of this research is to investigate the effect of current precipitation, the weather forecast and a weather alarm to the probability of breakdown of a highway during the morning peak period, while taking into account both the traffic demand and the capacity. In chapter 0 and 0 the stated adaptation experiment provides insights into the highway traffic demand during certain weather conditions as a result of behavioural adaptation of travellers. Chapter 5 delves into the effect of precipitation on highway capacity. Afterwards both findings are used to come to the effect of weather conditions on the breakdown probability on Dutch highways in chapter 6.

3. Methodology to analyse the influence of weather conditions on travel behaviour

In this chapter the methodology to analyse the influence of weather conditions on the adaptation of behaviour of travellers is presented. In paragraph 3.1 the used method and approach of analysing travellers' behaviour is presented. The attributes and attribute levels included in the experiment are given in paragraph 3.2. Then the construction of the stated adaptation experiment is elaborated upon in paragraph 3.3. After that, paragraph 3.4 provides an explanation regarding the data preparation phase and the data analysis.

3.1 Modelling travellers' choices

This paragraph first explains utility maximisation theory and the discrete choice model that is used in the analysis of travelling behaviour. After that, the framework to analyse the effect of weather conditions on highway traffic demand is presented.

3.1.1 Choice modelling based on utility maximisation

In this study a discrete choice model is estimated that uses the concept of random utility. In this section the theory of the random utility concept, the multinomial logit model and the panel mixed logit model are briefly explained.

Individual's preferences for choosing certain modes, routes and departure times can be expressed in utility. In Random Utility Models (RUMs) a decision maker faces a choice among several alternatives. The decision maker obtains a certain amount of utility from each alternative. The assumption that underlies these models is that the decision maker behaves rationally and chooses the alternative with the highest relative utility, hence the decision maker tries to maximize his benefit. The researcher observes the choice made by the decision maker and knows attributes of the alternatives of the decision maker, combined with attributes of the decision maker. A function, often called representative utility, is then specified relating the observed factors to the decision maker's utility. The assumption is that the decision maker chooses the alternative that has the highest utility for the decision maker. There are four causes of uncertainty that influence the utility, namely attributes that are not observed in the experiment, unobserved characteristics of individuals, measurement errors and proxy variables (Manski, 1977). In order to reflect the uncertainty, the utility of alternative *j* for decision maker *n* has to be decomposed as:

$$U_{nj} = V_{nj} + \varepsilon_{nj}$$

Where V_{nj} is the observed deterministic part and this component is defined as:

$$V_{nj} = \beta_j * X_{nj}$$

Here β_j resembles the coefficient of the attribute and X_{nj} is the attribute value. For each attribute a structural component is estimated. ε captures the factors affecting utility which are not included in V. ε is presumed to be independently and identically distributed (IID) across alternatives with a type 1 extreme-value distribution. Following from the IID assumption, the property of independence of irrelevant alternatives (IIA) also holds. This means that ratio between probabilities of choosing alternatives are independent of the availability of other alternatives. The probability that decision maker *n* will choose an alternative *i* over alternative *j* can be calculated as follows:

$$
\begin{aligned}
P_{ni} &= \text{Prob}(U_{ni} > U_{nj}\ \forall j \neq i\ ) \\
&= \text{Prob}(V_{ni} + \varepsilon_{ni} > V_{nj} + \varepsilon_{nj}\ \forall j \neq i\ ) \\
&= \text{Prob}(V_{ni} - V_{nj} > \varepsilon_{nj} - \varepsilon_{ni}\ \forall j \neq i\ )
\end{aligned}
$$

This means that the choice probability of alternative *i* is the probability that the difference in deterministic part between alternative *i* and alternative *j* is bigger than the difference in the error components. McFadden (1974) proposed the multinomial logit (MNL) model, which is based on the IID assumption of the error term. With this MNL model, which possesses the IIA property, the choice probability of an alternative can be calculated with the formula:

$$P_{ni} = \frac{\exp(V_{ni})}{\sum_{i=1}^{J} \exp(V_{nj})}$$

As a result of its simple mathematical structure and ease of estimation, the MNL model is (one of) the most used discrete choice models. An unlikely assumption of the MNL model is that all observed choices are independent of each other. This is unlikely since multiple choices are observed from the same respondent, which are to a certain extent correlated as a result of the preferences of the respondent. To take this into account a Mixed Logit model for panel data can be estimated. In a panel Mixed Logit model an error component is drawn from a Gumbel distribution (as in MNL). In addition the structural components can be drawn from other distributions. The difference of panel mixed logit versus normal mixed logit is that one error is drawn per respondent, instead of one error per choice situation. In panel Mixed Logit, to account for repeated choices by one decision maker, the coefficients that enter utility are treated as varying over people but being constant over choice situations for each person. The utility from alternative j in choice situation t by person n is:

$$U_{njt} = \beta_{n} * X_{njt} + \varepsilon_{njt}$$

with ε_{njt} being an IID extreme value over time, people, and alternatives. Conditional on β the probability that person n makes a specific sequence of choices is the product of logit formulas:

$$\mathrm{L}_{n\mathrm{i}}(\beta) = \prod_{t=1}^{T} [\frac{\exp(\beta'_{n} V_{ni_t t})}{\sum_{i=1}^{J} \exp(\beta'_{n} x_{njt})}]$$

The unconditional probability is the integral of this product over all values of β, because the error components (ε_{njt}) are independent over time:

$$P_{n\mathrm{i}} = \int \mathrm{L}_{n\mathrm{i}}(\beta) f(\beta) d\beta.$$

The choice probability of an alternative in this panel mixed logit form cannot be calculated exactly, because the integral does not have a closed form. The integral is approximated through simulation, where a draw of β is taken from its distribution. The logit formula is then calculated for each period and the product of these logits is taken. With a process of averaging the results of many draws, the integral can be approximated (Train, 2003). A more detailed explanation regarding the presented models can be found in Louviere et al. (2000) and Train (2003).

3.1.2 Motivation for estimation of different models

In this study a basic MNL model, a segmented MNL model and a segmented Panel Mixed Logit model where estimated. In this section the choices for these models are elaborated upon and the additions of the segmented MNL model and the Panel Mixed Logit model compared to the basic MNL model are presented.

The first model that was estimated is a basic MNL model. This model serves as a base model, but it has several drawbacks. A first drawback of using MNL models is that they are based on the assumption that tastes for attributes are homogeneous in the sample, meaning that one beta reflects the average taste for the attribute. One approach to account for heterogeneity in the sample is to estimate a mixed logit model. This model gives insight into the preferences of different people within the sample. Where information is obtained regarding the difference in preferences by using mixed logit, it does however not provide any information regarding the groups of respondents that have different preferences. A latent class model does provide information about the respondents with different preferences. An attempt has been made to estimate a latent class model with the software package NLogit. The software package was unable to create a latent class model with a normal approach due to already high number of attributes due to need to estimate alternative specific parameters. After several futile attempts, it was decided not to estimate a latent class model. In order to be partly able to account for heterogeneity in the sample, the decision was made to sort the respondents into different groups and thus estimate an MNL model with different groups in the software package Biogeme (Bierlaire, 2003). This way the model accounts for heterogeneity between the groups, but does not account for heterogeneity within the groups. It was chosen to sort the respondents into four groups, based on their standard mode of transport for utilitarian and recreational trips. Interaction effects where estimated for each of the groups. The four groups that were used are car users that use the highway, car users that do not use the highway, public transport users and cyclists. The assumption is that these groups of users all have different preferences towards the use of the transport modes and routes. There is a reason for having a preferred mode of transport. The weather can influence their travel behaviour, but it can be assumed that other factors than the weather, like the distance to work, also influence the decision of the traveller. For example, respondents that normally use the highway will be more likely to prefer using the highway instead of using the bike for making a utilitarian trip. Including interaction effects based on these groups is the only segmentation made in this research, because it was expected that accounting for differences based on the standard mode enhances the model the most compared to other factors (like age, gender, etc.).

A second drawback of using an MNL model is the assumption that all observed choices are independent of each other. This is an unlikely assumption since ten choices are observed from the same respondent, which are to a certain extent correlated. To take this effect into account a Panel Mixed Logit model was estimated. A normal distribution for each of the alternative specific constants was added to the model. The panel effect is taken into account by drawing a single error for all choices from one respondent, which produces corrected t-values that are more valid for significance tests. The final model that included only significant coefficients was estimated by applying 500 Halton draws.

3.1.3 Modelling the effect of weather conditions on highway traffic demand

To model the effect of weather conditions on highway traffic demand, a stated adaptation experiment is conducted. One firstly has to create a complete picture of the highway traffic demand for comparison of normal behaviour with behaviour in certain weather circumstances. The approach is different in comparison to standard stated choice models. In a standard stated choice experiment the respondent is asked to choose between several choice sets of which the attributes levels will vary. In this experiment it is examined whether the respondent adapts his behaviour given one weather situation. The experiment can thus be viewed as a stated adaptation experiment as a result of given weather situations. The framework presented in Figure 6 gives an overview of the parts that are included in the survey in order to come to the complete picture of highway traffic demand.

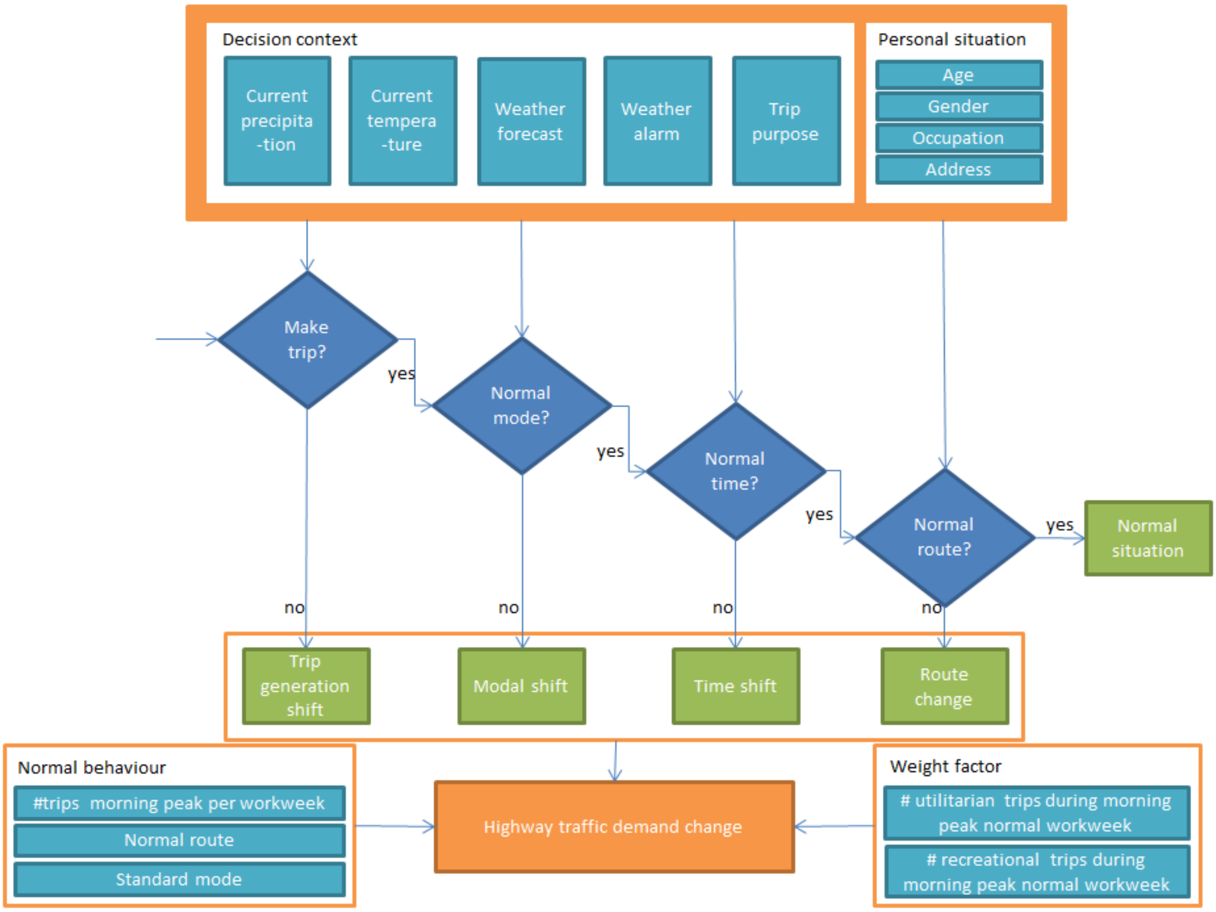

Figure 6 - Highway traffic demand framework

As explained in section 2.2.1 the factors trip generation, mode choice, time of day and highway route choice together determine whether a highway trip is made during the morning peak or not. The decision whether or not to make a highway trip can be influenced by the decision context and by personal characteristics of the respondent. The decision context consists of the attributes that are structurally varied in other to get insights into the effect of the attributes current precipitation, current temperature, weather forecast and weather alarm on highway traffic demand, as well as the effect of these attributes on trips with different trip purposes. In this study two different categories of trip purposes are distinguished. The first category consists of business trips, commuter trips and educational trips. This category is named utilitarian trips. The second category consists of trips for visiting family or friends, grocery shopping, shopping, a day-out, going to sports et cetera. This category is defined as the recreational category.

Three types of respondents enter the traffic demand framework:

- Car travellers who normally use the highway in the morning peak.
- Car travellers who normally avoid the highway in the morning peak, but on certain occasions travel by car on the highway during the morning peak.
- Cyclists or public transport users that on certain occasions travel by car on the highway in the morning peak.

All these types of respondents can influence the highway usage in certain weather conditions. The car travellers that normally use the highway in the morning peak can change their behaviour and avoid the car, avoid the highway or avoid the morning peak. This leads to a decrease of highway traffic demand ceteris paribus. Car travellers who normally avoid the highway in the morning peak are not included in the calculation of the normal highway situation. Respondents in this group can however change their behaviour and decide to make use of the highway during the morning peak in certain weather circumstances. The same applies to the cyclists and public transport users. A potential reason could be that the driving on the highway is regarded to be safer in, for example, snowy conditions. This would lead to an increase of highway traffic demand if all other factors remain the same. Depending on the type of respondent, a shift in trip generation, mode, departure time and route could thus influence the highway traffic demand. Respondents were filtered if they did not have a driver's license or have not travelled on the highway in the morning peak during the last month. The survey was carried out in Dutch, since the population that is studied are people that regularly use the Dutch highways in the morning peak. The respondents were selected from a panel of the company Respondentendatabase (Respondentendatabase, 2013). As a result of the limited budget combined with the payment type per question per respondent, the number of questions and the number of respondents (see 3.3.2) had to be limited. The complete survey can be found in Appendix 1 – Scientific article.

The survey consists of different parts which all relate to one or multiple fragments of the framework in Figure 6. In the first part of the survey the normal behaviour of the respondents is mapped to serve as a reference point. The following questions were asked in order to come to an understanding of some demographics and the normal behaviour of the respondents:

- The personal situation of the respondent
  Questions were asked about the age, gender, occupation and postal code of the respondent. The postal code was asked to be able to analyse the difference between respondents from areas with a relatively low amount of highway traffic congestion and respondents from areas with a relatively high amount of highway traffic congestion. Other factors are used to verify that the sample sufficiently reflects the population.
- Normal behaviour of the respondents for utilitarian related trips in the morning peak
  Questions regarding the number of utilitarian (commuting, business or education) trips that are made in a normal workweek (Monday-Friday) in the morning peak, the mode that is most often used during a normal workweek, the distance from home to work, the amount of days that the standard mode is not used, the possibility to avoid the morning peak due to flexible starting hours or working at home.
- Normal behaviour of the respondents for recreational trips in the morning peak

Questions regarding the number of recreational (visits, grocery shopping, shopping, making a tour, sports, etc.) trips that are made in a normal workweek (Monday-Friday) in the morning peak, the mode that is most often used during a normal workweek, the amount of days that the standard mode is not used and the possibility to avoid the morning peak.

The second part of the survey, the stated adaptation experiment, serves to draw conclusions regarding possible changing behaviour of respondents as a result of weather conditions and predictions. If the respondent makes business and leisure trips in the morning peak during a normal workweek, the respondent is asked what he would do if he had planned a business trip in the morning peak and is confronted with a given weather situation. For the same given weather situation a second question is asked what he would do if he had planned a leisure trip in the morning peak. A respondent that only makes business or leisure trips is asked what he would do if he had planned a trip with the corresponding purpose. These respondents thus only have to fill out half of the questions, since the other trip purpose does not apply to them. The following answers could be chosen by the respondents:

- Travel by car on the highway in the morning peak
- Travel by car, but avoiding the morning peak (before 06:00 or after 10:00)
- Travel by car, but avoiding the highway
- Travel by bicycle
- Travel by public transport
- Decide not to make the trip

Both the first and the second part of the survey provide useful information for the framework to come to an estimate of the amount of vehicles on the highway for different weather situations.

3.2 Attributes and attribute levels

The first part of a stated adaptation experiment involves the identification of the weather attributes relevant for the travel choice. In this section the attributes that are included in the experiment are presented. After that, the choices for the attribute levels of the attributes are elaborated upon.

The attributes that are taken into account in this research are precipitation, temperature, weather forecast and weather alarm. Precipitation is expected to be the most important attribute in the experiment. Call (2011) and Maze et al. (2006), amongst others, reported considerable reductions in trip-making with snowfall. As a consequence of rainfall car traffic reductions are also reported for example by Hassan and Barker (1999) in Scotland. Where most studies show negative precipitation effects on trip generation, a Dutch study from Sabir (2011) shows a positive relationship between precipitation and car and public transport usage as a result of the high share of cyclists in the Netherlands. In this experiment both the effect of rainfall and snowfall are examined.

Temperature is taken into account because several European studies (Cools et al., 2010; Sabir, 2011) have found significant positive effects of temperature on cycling and negative effects on car and public transport usage. In other words, travellers are more likely to cycle when temperature is higher; hence temperature could affect the highway morning peak traffic via a model shift. The weather forecast is included in the experiment as a result of the hypothesis that the weather forecast for the return trip influences the travel choices of the traveller. Very little research has been conducted towards the effect of the weather forecast on trip choices. Kilpeläinen and Summala (2007) detected an important role of rain forecasts for travel changes in Finland. As an example from personal experience a forecast of very heavy rain in the afternoon makes me decide not to travel by bicycle in the morning. Lastly the effect of weather alarms is tested in this experiment. The KNMI initiates out a weather alarm when a weather situation could lead to a heavy nuisance and disruption of the community. In essence the weather alarm is a forecast in cases of extreme weather. In the next sections the choices for the attribute levels of the attributes are elaborated upon.

3.2.1 Current precipitation

The precipitation attribute reflects the current precipitation at the decision moment, thus in the morning at the moment that the decision about a trip in the highway morning peak will be taken. This attribute consists of five levels, which are dry, light rainfall, very heavy rainfall, light snowfall and heavy snowfall. Pictures are included to the precipitation levels in order to make the terms light and heavy more concrete. This is done in order to mitigate the effect that these precipitation conditions are differently interpreted among different respondents. Another use of the pictures is that the intensities of the precipitation at the moment of the pictures are known. Due to this, quantification of the precipitation is possible in a later phase of the study. The precipitation intensities were not mentioned in the survey. The assumption is made that respondents would be able to distinguish the different categories and link this to comparable rainfall and snowfall intensities in the past. Light rainfall is represented by the picture in Figure 7 corresponds with a rain intensity between 0 and 2mm/hour. Figure 8 is used for very heavy rainfall and depicts a rain shower of 2mm/minute. Light snowfall is illustrated with Figure 8 which resembles a snow intensity of 1-2cm/hour. Lastly heavy snowfall in Figure 10 corresponds to 5cm snow per hour.

Figure 7 - light rainfall

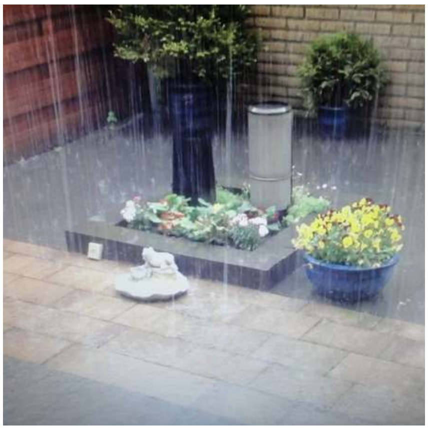

Figure 8 – very heavy rainfall (Spek, 2012)

Figure 8 - light snowfall (Wiersema, 2013)

Figure 10 - heavy snowfall (NRC, 2013)

Garden or backyard pictures fit best with the choice situation where travellers at home have to make a decision about a planned trip in the morning peak period. Pictures of the road could on the other hand give the travellers more insight into the situation on the road. At first the choice for garden or backyard pictures was made. Because of the limited amount of pictures that include specific precipitation intensity, it was not possible to find usable garden pictures for snowfall. Therefore for both light and heavy snowfall road pictures are used.

3.2.2 Temperature

The temperature attribute reflects the current temperature at the decision moment, thus in the morning at the moment that the decision about a trip in the highway morning peak will be taken. This attribute consists of three levels, namely -5, 10 and 25 degrees Celsius. These attribute levels are chosen based on weather data from the previous five years by KNMI. The weather data show that the current range of the values covers almost all the temperatures during the morning peak hours. There are only a handful days where the temperature during the morning peak was out of the range of the current attribute levels. Combined with the fact that the focus of this study is not on extreme temperatures, it is chosen for the abovementioned three attribute levels of -5, 10 and 25 degrees Celsius. The temperature is related to the precipitation form. Precipitation is assumed to be snow with a temperature of -5 degrees Celsius. With 10 and 25 degrees Celsius the precipitation that is included in this experiment is rain. This results in correlation between the attributes temperature and current precipitation. Correlation leads to a less efficient experiment and the need for more observations in order to come to statistically significant results. The choice was made to include the temperature in the experiment and depending on the outcomes of the estimated model the choice can be made to either retain or remove the attribute from the experiment.

3.2.3 Weather forecast

In order to come to realistic attribute levels for the weather forecast, I have watched weather forecasts of the news broadcasting (RTL Nieuws at 19:30 and NOS Journaal at 20:00). What is interesting to see is that most weather forecasts for the next day are relatively generic for the whole country. The forecasts did not provide very specific information regarding the weather during the coming day. Providing the respondents with information about the weather for the return trip is difficult, since respondents can have different return trip patterns. Some commuters will work only half a day and will return early in the afternoon, while other commuters will return much later. Regarding recreational activities, some people go shopping and return within several hours where other people could visit family and return in the evening. An approach could be taken to provide a weather forecast that applies to the exact time of the return trip, without mentioning this time. An example is: at the moment of your return trip the weather is the same as at this moment. This is however a delicate statement, because the respondent probably do not know the exact return trip time. The fact that the weather forecast is usually very generic creates a solution for this difficulty. It is chosen to create a weather forecast for the rest of the day by having the following attribute levels: during the day the weather conditions can improve, get worse or stay the same as the current weather conditions. Possible interaction effects of precipitation and the weather forecast are not included in the analysis.

3.2.4 Weather alarm

The KNMI initiates a weather alarm when a weather situation could lead to a heavy nuisance and disruption of the community. A weather alarm with code red will be carried out at most twelve hours in advance and if the probability of occurrence of the event is at least 90%. It is only used if the area that is confronted with the weather at least has a length of 50 kilometres (KNMI, 2011). There are several different alarms applicable to the weather events in this experiment, which are code red for very heavy rainfall (at least 75mm in 24 hours), code red for snow (at least 3cm per hour or 10cm per 6 hours) and code red for icy roads. These weather alarms are not carried out very often. Code red for very heavy rainfall was carried out three times between 2007 and 2012. Code red for snow was put in practice four times and code red for icy roads two times between 2007 and 2012. The fourth level that is included in the experiment is the event of no weather alarm.

3.3 Construction of the stated adaptation experiment

The stated adaptation experiment is the second part of the survey and follows the part in which normal travel behaviour is identified. In the stated adaptation part the respondents are presented with hypothetical weather situations. Several choices have to be made regarding construction of the choice sets of the stated adaptation experiment, like the type of experimental design that is used, the amount of choice sets that are presented to the respondent and the number of respondents that are required in order to get significant results from the data. The software package Ngene (ChoiceMetrics, 2013) is used to construct the weather situations for the stated adaptation experiment.

3.3.1 Types of experimental design

There are several types of experimental designs which can be applied in order to generate the choice sets for a stated adaptation experiment. The types of designs can be categorized as orthogonal or efficient. In this section both categories of designs are shortly presented.

A design is orthogonal if all the attribute levels for each column in the design are uncorrelated (Bliemer and Rose, 2006). This enables estimation of the parameters to be unbiased. There are two different designs, of which a compromise can be made, within the orthogonal design category, namely a full factorial design and a fractional factorial design. Full factorial designs are designs that include all possible combinations of attribute levels in the choice situations. Applied to this study this would lead to 180 choice situations (5*4*3*3), which is a very large number of choice situations. The second orthogonal design is the fractional factorial design. A fractional factorial design only uses a (small) set of choice situations from the full fractional design. This results in more reasonable numbers of choice sets, while still fulfilling the orthogonality requirement. When conducting a stated adaptation experiment, orthogonality however does not necessarily lead to the most efficient design.

Designs from the other category, efficient designs, are experimental designs that enable parameter estimation with as low as possible standard errors (Bliemer and Rose, 2006). The aim of efficient designs is to improve the reliability of estimated parameters, to decrease the sample size for getting reliable parameters and ruling out dominant alternatives as much as possible (Bliemer et al., 2007). A dominant alternative outperforms the other alternative for every attribute and such an alternative does not provide a trade-off between the attributes of the alternatives. The result is that no information can be obtained from the choice set with the dominant alternative. Making utilities of the different alternatives more similar helps in preventing dominant alternatives. This requires information regarding the utilities of the different attributes and levels, which can be added via prior values. When these prior values are added in the design of the choice situations, this can make the design more efficient. There are several approaches to find estimated values for the prior parameters, like a literature research, focus groups or expert judgement (Sandor & Wedel, 2001). It is difficult to get accurate quantified parameter values based on these approaches. The most convenient and accurate approach is to execute a pilot study from which the parameter estimates are used as prior values for the design of the choice situations for the main experiment.

3.3.1.1 Choice on efficient design based on wish for realistic choice sets

Realism of the choice sets is a very important aspect in stated adaptation experiment. The importance is a result of the fact that respondents will be asked what they will do in the presented situation. Realism of situations can be lost if the presented situations are not considered to be credible (Rose & Hensher, 2005). In order to provide respondents realistic and logical weather situations, several restrictions had to be added to the choice generation in Ngene, which are:

- If the temperature is -5 degrees, then the precipitation form cannot be rain
- If the temperature is 10 or 25 degrees, then the precipitation form cannot be snow
- If the current weather is light snowfall and there is a weather alarm for snow, then the forecasted weather has to be worse.
- If the current weather is light rainfall and there is a weather alarm for rain, then the forecasted weather has to be worse.
- If the current weather is very heavy rainfall and the weather is forecasted to stay the same or get worse, then there has to be a weather alarm for rain.
- If the current weather is heavy snowfall and the weather is forecasted to stay the same or get worse, then there has to be a weather alarm for snow.
- If the current weather is dry and the weather is forecasted to stay the same or get better, then a rain or snow alarm is not possible.

Due to these restrictions it is impossible to produce an orthogonal experimental design. This has led to the choice to use an efficient experimental design in order to come to the choice situations for the experiment.

3.3.1.2 Pilot study

An efficient design requires information regarding the utilities of the different attributes and levels, which can be added via prior values. It is chosen to obtain the prior values of the parameters in this study by conducting a pilot study.

For the pilot study 18 choice situations were generated with Ngene (ChoiceMetrics, 2013), blocked into three blocks of six choice situations. Each of the blocks was filled in by ten respondents, resulting in 30 respondents creating 180 choice observations. First the respondents were asked what their main transportation mode was during the morning peak period between 6:00 and 10:00 am (car using the highway, car not using the highway, public transport or bicycle). The choice task of the experiment was whether respondents would adapt their behaviour given that they had planned to make a trip and are confronted with the presented weather and weather forecast situation. Adaptation of behaviour for car users means avoiding the morning peak, using another route (highway or not highway), using a different mode (public transport or bicycle) or deciding not to go. For public transport and bicycle users adaptation of behaviour would be to use another mode or deciding not to go. Based on these 180 observations an MNL model was estimated with Biogeme in order to come to the prior estimates. The prior values for the parameters were then used to generate an efficient design in Ngene.

3.3.2 Generating choice situations

The prior values obtained from the pilot study were used in order to generate the choice situations of the survey. In Ngene one can specify what kind of model will be estimated after the data collection so that when generating the choice sets this can be taken into account. Possibilities are for example multinomial logit models, mixed logit models and panel mixed logit models.

An attempt has been made to generate choice situations for all these models. It was however not possible for Ngene to come to a design of choice sets based on a mixed logit and panel mixed logit model. A possible explanation for this is the complexity that was added to the design due to the restrictions (see 3.3.1.1) that had to be satisfied. Therefore choice situations were generated based on a multinomial logit model, which is a simpler model than the model that is expected to be used in the data analysis phase (see Appendix 3 – Design syntax). Efficient designs for multinomial logit models do however also perform relatively efficient for mixed logit models (Bliemer & Rose, 2010).

The number of choice situations shown to the respondent is an important factor in the generation of the choice situations. There has to be a balance between on the one hand the desire to provide the respondents with many choice situations to get lots of information and on the other hand the avoiding fatigue and boredom of the respondents, which could lead to inconsistency in filling out the choice experiment. For this study it is chosen to generate 20 different choice situations, blocked in two surveys with both 10 different choice situations. Having 10 choice situations for each respondent is presumed to be feasible, because the respondents are selected from an existing panel of respondents and thus are used to filling in surveys.

There are multiple efficiency measures that can be used in order to gain insights into the efficiency of the generated choice sets. The efficiency measure that is applied in the generation of the choice sets is the S-error. The S-error shows the sample size that is required to come to significant coefficients, based on the magnitude and sign of the prior values. Optimizing for the S-error means that the software searches for the optimal combination of choice sets that requires the least amount of respondents to get significant coefficients. The choice for optimization of the S-error instead of the D-error is based on the limited budget available for recruiting respondents. Some of the coefficients however required an unrealistically high sample size (ranging from 3000 to 85000 respondents) in order to become significant. Based on these results the coefficients regarding light rain, very heavy rain, light snowfall and the rain alarm would only become significant with a very large sample, which is very implausible. Solely based on the figures these coefficients should have been left out of the experiment, but with confidence in the results becoming significant in the experiment at a lower sample size a different approach was chosen. These four coefficients were fixed to zero and the sample size was optimised for all but these coefficients.

This optimisation resulted in the need for 165 respondents in order to get the rest of the coefficients significant and 110 respondents are needed to get one coefficient less significant. One has to take into account that this sample size applies to 20 choice situations to be filled in by each respondent. Due to the blocking twice as much respondents, thus 330, are needed. The presented amount of respondents can only be considered to be rough estimates, since they are based on the assumption that the priors are the real values. As result of budget constraints the choice is made to have a sample of at least 300 respondents.

3.4 Preparation of the data analysis

This section describes the preparation of the data for the analysis. In section 3.4.1 the collection of the data via an online survey and the filtering of respondents are presented. In section 3.4.2 the characteristics of the sample are shortly described in order to draw conclusions regarding the confidence in representativeness of the sample. After that, section 3.4.3 elaborates on important modelling choices that are made in the project.

3.4.1 Data collection and preparation

The first part of the survey is used to map the normal behaviour of respondent and the second part consists of the stated adaptation experiment to draw conclusions regarding possible changing behaviour of respondents as a result of different weather conditions and predictions. All the questions have to be combined in order to come to a complete survey. It is chosen to use the online program Survalyzer (Survalyzer, 2013) to fill in the questions and come to an online survey.

With this program an internet link can be generated which leads the respondent to the survey. In collaboration with RespondentenDatabase.nl panel members were asked to fill out the survey. In total 1550 panel members were invited to fill out the survey. Before entering the survey the respondents needed to answer two filtering questions. The first question asked whether the respondent had a driving license and the second question whether or not the respondent used the highway during the morning peak in the last month. Respondents that did not have a driver's licence or had not been on the highway in the morning peak during the last month were excluded from the survey. In total 177 respondents filled in the survey with the first block and 165 surveys were filled in of the second block, resulting in a total of 342 respondents and a response rate of 22%, which is considered relatively low for a paid survey. A possible explanation is that a part of the invited respondents consider itself not to be within the target group. The relatively low response rate could lead to a bias in the sample as a result of self-selection. Sample statistics (3.4.2) however increases confidence in the representativeness for the population of the respondents in the sample. Regarding the survey of the first block three respondents did not complete the survey. Four respondents said that they normally do not make any trips during the morning peak and those respondents were also excluded, leading to 170 useful surveys of the first block. For the survey of the second block three surveys were incomplete and nine respondents did not make any trips during the morning peak in a normal week. In the end 153 useful surveys of the second block were collected. This resulted in 323 surveys that were completely filled out.

Onto closer inspection of the data it was found out that a small group of sixteen respondents always travelled via the highway, while this group stated that their standard behaviour was to travel by car and avoid the highway. Even in a normal weather situation with dry weather conditions and no weather alarm, these respondents chose to adapt their standard behaviour. It seems reasonable to assume that these respondents have incorrectly filled in the question regarding the standard behaviour. In order to avoid changing the obtained data and thereby manipulating the result, it has been decided to exclude these sixteen respondents from the analysis.

Another group of respondents, the public transport users, is also excluded from the recreational trips analysis. The reason for the exclusion is that there are only ten respondents that normally use public transport for recreational trips. As a rule of thumb thirty respondents are needed in order to be able to obtain significant results. As a result, it was decided to exclude these ten public transport users from the recreational trip analyses. The exclusions eventually lead to a sample of 132 respondents (1320 observations) for the recreational trip analysis and 271 respondents (2710 observations) for the utilitarian trip analysis.

3.4.2 Sample statistics

In this section the characteristics of the sample are briefly explained in order to draw conclusions regarding the confidence in representativeness of the sample. Out of the total sample of 299 respondents, there were 144 male respondents (48.2%) and 155 female respondents (51.8%). From the sample, 104 respondents make both utilitarian and recreational trips in the morning peak during a normal workweek. 167 respondents only make utilitarian trips and 28 respondents only make recreational trips during a normal workweek. The total amount of trips that the respondents make in the morning peak during a normal workweek is 1183 trips, with 973 (82.2%) trips being utilitarian trips and 210 (17.7%) trips have a recreational purpose. Research from Ruimtelijk Planbureau (2006) shows that the utilitarian purpose accounts for 79% of the total highway morning peak trips and that the other 21% are recreational trips. Assuming that the same division of trip purposes still holds several years later, the sample is fairly representative based on this factor.

The normal transport mode of the sample was in 77.2% of the cases the car, while public transport was normally used by 7.4% and the bicycle by 15.4% of the respondents. According to figures from Statistics Netherlands (CBS, 2010) the car has a share of 61.8%, public transport 6.6% and the bicycle accounts for 31.5% of the trips during a day. These are however not figures of the highway morning peak. Nevertheless this could indicate that car users are overrepresented and cyclists are underrepresented. However in combination with the other sample statistics there is still a fairly high confidence in the sample being representative for the population.

Lastly, interesting information is obtained from the average distance of the utilitarian trip. The highway user group has the highest average distance of 35.9 kilometres, followed by public transport users (31.5 km). The highway avoiding car user group lives a lot closer to its utilitarian destination (12.2 km) and cyclists have an average distance of 6.25 kilometres. The distance could play a role in the response of the groups to certain weather events, which is further investigated in chapter 4.

3.4.3 Modelling choices

The models that were estimated are considered not to be standard stated choice models. In a standard stated choice experiment the respondent are asked to choose between several choice sets of which the attributes levels will vary. In this experiment it is examined whether the respondent adapts his behaviour given one weather situation. Instead of having a trade-off between choice sets with different attribute levels, the trade-off in this experiment is between the different travel options:

- Travel by car on the highway in the morning peak
- Travel by car, but avoiding the morning peak (before 06:00 or after 10:00)
- Travel by car, but avoiding the highway
- Travel by bicycle
- Travel by public transport
- Decide not to make the trip

The experiment can thus be viewed as a stated adaptation experiment as a result of given weather situations. The chosen design of the experiment has implications for the model estimations. Utility functions based on the included attributes have to be estimated for all six alternatives presented above. On top of that, the modelling approach also results in the need for the parameters to be estimated alternative specific. This can be illustrated by an example that rain could negatively influence the bicycle alternative, while it could less negatively or even positively influence car alternatives.

While estimating the MNL models it became clear that the attribute temperature was too highly correlated with the current weather and weather forecast. The p-values and robust p-values of the parameters were very different, which is often a sign of misspecification of the model (Bierlaire, 2011). In combination with the parameter values that were highly implausible, it was chosen to exclude temperature from the estimation process.

Without the temperature parameters, the software package Biogeme still had some difficulties with estimating the model. With all other parameters included, some of the p-values and robust p-values still differed a bit. The assumption is made that the large amount of parameters to be estimated caused this. A solution to the small misspecification was to adopt an iterative approach of fixating the non-significant parameters to zero. Due to the correlation between attributes fixating non-significant parameters does have a small influence on other parameters. The effect of fixed parameters is then (partially) added to other parameters, which could lead to losing the pure effect of these parameters. The choice between a well specified model and a wrongly specified model with the pure effect of the parameters was however straightforward, because model misspecification can lead to highly implausible parameter values.

Another important modelling choice is to apply effects coding to the attribute levels in order to be able to incorporate a test for non-linearity in utility between the attribute levels and for coding of interval and ratio attribute levels. This however means that for n-1 coefficients have to be estimated for n attribute levels. The number of estimated coefficients is thereby increased significantly. Another advantage of effects coding is that the strength of the estimated coefficients can be directly compared in terms of the impact of the attributes on overall utility if all attributes are effects coded (Molin, van Stralen, & van Wee, 2012). There are four current weather indicator variables, two weather forecast and three weather alarm indicator variables. The effects coding applied to the attribute levels can be seen in Table 2.

Table 2 - Effects coding attribute levels

Current precipitation

	Light rainfall	Very heavy rainfall	Light snowfall	Heavy snowfall
light rainfall	1	0	0	0
very heavy rainfall	0	1	0	0
light snowfall	0	0	1	0
heavy snowfall	0	0	0	1
dry	-1	-1	-1	-1

Weather forecast

	Worse forecast	Better forecast
worse forecast	1	0
better forecast	0	1
same forecast	-1	-1

Weather alarm

	Rain alarm	Snow alarm	Icy roads alarm
rain	1	0	0
snow	0	1	0
icy roads	0	0	1
no alarm	-1	-1	-1

The last attribute level is compiled out of the values of all coefficients, as can be seen in Table 2. Dry weather for example is compiled out of the negative values of the four estimated coefficients. Effects coding was also use to code the interaction effect of the different groups that were created based on their standard modes of transport. If one of the coefficients (highway car group, non-highway car group, public transport group) is significant, this means that the utility of the group differs from the average utility. For example the alternative specific constant is the average utility and the mode coefficients determine the deviation of utility regarding the alternative specific constant.

Table 3 - Effects coding interaction effects from standard mode

Traveller groups utilitarian trips

	Highway car group	Non-highway car group	Public transport group
Highway car users	1	0	0
Non-highway car users	0	1	0
Public transport users	0	0	1
Cyclists	-1	-1	-1

Traveller groups recreational trips

	Highway car group	Non-highway car group
Highway car users	1	0
Non-highway car users	0	1
Cyclists	-1	-1

Two different models are estimated for utilitarian trips and recreational trips, since adaptation of behaviour to weather has been proven different for these trip purposes by Call (2011). This can be tested by estimating different models for these different trip purposes. Each of the three models is thus estimated twice. The models can be found in chapter 0.

4. Data analysis influence of weather conditions on travel behaviour

This section focuses on the results of the different estimated models and compares the models with each other. Firstly the utilitarian trip models are analysed and compared and after that the recreational trips are analysed. In paragraph 4.3, choice probabilities in nine different weather scenarios are presented. In section 4.4 the results of the travel behaviour analysis are converted into highway morning peak traffic demand changes. In paragraph 4.5 conclusions are provided regarding travel behaviour.

4.1 Comparison of the estimated utilitarian trip models

In this section the different estimated utilitarian trip models are compared based on their fit to the data. Then one of the models is chosen to be used in further analyses. The results of the estimated models regarding utilitarian trips can be seen in Table 4. In order to be able to understand the results, some explanation is needed. Each coefficient belongs to a certain alternative, which is presented in bold in the left column. The alternative to decide not to make a trip has been fixed to zero and thus serves as a reference alternative. The coefficient ASC is the alternative specific constant and thus resembles the utility of attributes related of alternative which are not included in the estimation (e.g. comfort related to a certain alternative). The coefficients highway car group, non-highway car group and public transport group are interaction coefficients, which determine the difference in preferences regarding the factors that are not included in the estimation (the alternative specific constant). An interaction coefficient followed by a weather coefficient (example: highway car very heavy rainfall) represents an interaction effect for differences in taste of the groups regarding those specific weather coefficients. The coefficients that are called sigma are the standard deviations of the normal distribution that was estimated for the alternative specific constant of the different alternatives. The standard deviation is only estimated for the panel grouped Mixed Logit model, since this has to do with the estimation of the panel effect. Lastly, only the significant results are presented and the non-significant results are fixed to zero. In Table 4 it becomes clear that all the alternative specific constants are positive, which indicates that travellers derive a positive utility of making a trip compared to not making a trip. This is in line with the fact that this analysis is about utilitarian trips to work, business trips or trips for educational purposes. When a traveller is expected to be at work or at an educational facility and he decides not to go, he does not meet his obligations and thus making a trip is perceived to be better than not making the trip (not taking into account the weather). All other coefficients have the expected sign, but that is elaborated upon later in section 4.3. When comparing the signs of the coefficients in the different models, it becomes clear that the sign of each coefficient is the same in all the models.

Table 4 - Comparison of the estimated utilitarian trip models

	Basic MNL		Grouped MNL		Grouped panel ML	
	coefficient	t-value	coefficient	t-value	coefficient	t-value
Highway						
ASC	2.66	22.89	n.s.	n.s.	n.s.	n.s.
snow alarm	-0.36	-3.34	-0.35	-3.01	-0.57	-2.63
icy roads alarm	-0.37	-3.77	-0.47	-3.83	-0.82	-4.05
light rain	2.29	5.31	0.89	4.42	2.20	6.61
light snow	-1.02	-6.28	-0.59	-4.86	-1.23	-6.63
heavy snow	-1.76	-10.27	-1.40	-9.81	-2.77	-12.49
highway car group	(-)	(-)	2.75	30.79	4.69	16.77
public transport group	(-)	(-)	-1.29	-3.72	-3.89	-4.75
SIGMA	(-)	(-)	(-)	(-)	-3.61	-12.92
Avoid morning peak						
better forecast	0.44	3.19	n.s.	n.s.	n.s.	n.s.
light rain	1.08	2.37	n.s.	n.s.	n.s.	n.s.
heavy snow	-1.11	-5.19	-0.63	-3.71	-0.88	-3.68
SIGMA	(-)	(-)	(-)	(-)	-1.29	-6.68
Avoid highway						
ASC	2.09	17.46	n.s.	n.s.	n.s.	n.s.
rain alarm	n.s.	n.s.	n.s.	n.s.	0.55	2.62
snow alarm	-0.34	-2.81	n.s.	n.s.	n.s.	n.s.
icy roads alarm	-0.29	-2.67	-0.39	-3.11	-1.23	-3.74
light rain	2.11	4.86	0.46	2.35	1.35	3.33
light snow	-0.78	-4.67	n.s.	n.s.	n.s.	n.s.
heavy snow	-1.64	-9.14	-1.22	-7.84	-2.43	-7.93
non-highway car group	(-)	(-)	2.77	28.11	3.97	16.95
public transport group	(-)	(-)	-3.90	-11.83	-5.82	-4.76
SIGMA	(-)	(-)	(-)	(-)	-4.30	-11.76
Bicycle						
ASC	1.12	8.33	n.s.	n.s.	n.s.	n.s.
icy roads alarm	-0.72	-5.49	-0.54	-3.28	-1.50	-4.10
light rain	2.17	4.88	0.66	2.51	2.24	4.22
very heavy rain	n.s.	n.s.	-0.87	-3.03	-2.31	-3.7
light snow	-0.95	-4.80	-0.55	-2.39	-1.10	-2.87
heavy snow	-2.09	-9.95	-1.13	-4.25	-2.84	-4.95
highway car group	(-)	(-)	-3.12	-12.06	-6.99	-7.02
highway car very heavy rainfall	(-)	(-)	-0.97	-2.27	-3.53	-3.57
public transport very heavy rainfall	(-)	(-)	0.88	2.68	2.21	3.53
SIGMA	(-)	(-)	(-)	(-)	-3.58	-7.09
Public transport						
ASC	1.65	13.28	n.s.	n.s.	n.s.	n.s.
snow alarm	-0.54	-4.54	n.s.	n.s.	n.s.	n.s.
light rain	2.00	4.54	n.s.	n.s.	1.13	3.05
light snow	-0.72	-4.07	n.s.	n.s.	n.s.	n.s.
heavy snow	-1.46	-7.81	n.s.	n.s.	-1.09	-3.46
highway car group	(-)	(-)	-1.23	-7.66	-4.18	-8.00
non-highway car group	(-)	(-)	-1.89	-9.29	-1.66	-3.34
public transport group	(-)	(-)	3.08	17.29	6.90	9.24
public transport heavy snowfall	(-)	(-)	-0.89	-3.9	-1.08	-2.73
SIGMA	(-)	(-)	(-)	(-)	3.06	9.29
Not making a trip						
ASC	0.00	reference	0.00	reference	0.00	reference
Log-likelihood	-3882.16		-2005.48		-1386.50	
Rho-square	0.200		0.587		0.714	

* n.s. means that the coefficient was not significant. (-) means that the coefficient was not estimated

There are 25 significant coefficients in the basic MNL model. The grouped MNL model has 25 different coefficients, while in the grouped panel ML model 33 coefficients turned out to be significant. The basic MNL model (LL = -3882.16) significantly improves the Null model (LL = -4855.67) and has a Rho-square value of 0.200. Grouping the respondents on the basis of their standard modes turned out to make the model fit to the data a lot better. The log-likelihood rises by 1877 points compared to the basic MNL model and the Rho-square value becomes 0.587. Adding a panel effect with the panel ML model also means a significant improvement of the model and leads to a high Rho-square value of 0.714. The grouped MNL model has a much higher model fit than the basic MNL model with the same amount of estimated coefficients. The grouped panel ML model also increases the model fit, but eight more coefficients are being estimated. The difference of 619 Log-likelihood-points is however so big that according to the Likelihood Ratio Test (Ben-Akiva & Lerman, 1985) the grouped panel ML model fits significantly better to the data than the normal grouped panel ML. As a result it has been chosen to use the grouped panel ML model for utilitarian trips in the remainder of this study.

Outcomes of the utilitarian grouped panel ML model

The most interesting outcome of the analysis is that the weather forecast does not play a significant role in the choice between the different travel alternatives. The conclusion that can be drawn regarding the weather forecast is that within the current approach of having very generic weather forecasts, this does not influence the behaviour of the traveller. It might be the case that this approach was too intangible and not specific enough for the respondents. It might also be the case that travellers are not influenced by the weather forecast in making utilitarian trips. A decisive answer can however not be provided.

In a normal situation with dry weather and no weather alarm, the utilities for the alternatives are as presented in Table 5.

Table 5 - Utilities for the alternatives with dry weather and no alarm

group / alternative	Car - highway	Car - non highway	Public transport	Cyclists
Highway	**7.886**	3.196	-0.694	2.396
Avoid morning peak	0.879	0.879	0.879	0.879
Avoid highway	1.76	**5.73**	-4.06	3.61
Bicycle	2.05	3.14	0.93	**15.66**
Public transport	-4.417	-1.897	**6.663**	-1.297
Not making a trip	0	0	0	0

A logical phenomenon arises that groups have a preference to use their standard mode of transport based on factors that are not included in the analysis. Some of the factors that are likely to play a role are for example the travel time with the different modes or the comfort related to each mode. The differences between the utilities of the alternatives are very high, while the coefficients of the other attributes are relatively small. This leads to a first insight that the weather conditions and forecasts are not likely to lead to large changes in behaviour. A more detailed explanation is provided in paragraph 4.3, where the choice probabilities of the different alternatives are treated.

The weather and rain alarm coefficients have values that can be explained easily. The travel groups, except for cyclists, seem to be more determined to use their standard modes when the current weather is light rain. The cycling group derives less utility from light rain compared to dry weather, which is a logical effect due to the fact that cycling is an open-air activity. Light snow creates a disutility for the highway and bicycle alternative. The negative influence on the bicycle usage can be explained by the fact that cycling is an open-air activity. The disutility towards the highway alternative could be explained via the average trip length of the highway trips. Travellers that normally use the highway for utilitarian trips have an average trip length of 35.9 kilometres, compared to an average of only 12.2 kilometres for non-highway users. The longer the trip is, the higher the probability of more severe snowfall in other regions and unpleasant events as a result of the weather. Travellers might know from historic events that snowfall leads to more congestion on Dutch highways which could be a reason not to use the highways. This also applies to the snow alarm which only creates a disutility for the highway alternative.

The disutility of heavy snow in the avoiding morning peak alternative is less compared to the other alternatives. Avoiding the morning peak period thus becomes more attractive compared to the normal behaviour, but due to the negative utility it is still less attractive than not making the trip. Utilitarian travellers would thus prefer to not make a trip instead of avoiding the morning peak in heavy snow conditions.

The alarm for icy roads has a negative effect on the highway alternative, the car alternative that avoids the highway and the bicycle usage. These alternatives become less attractive when this alarm is carried out. Finally a rain alarm makes using the car and avoiding the highway slightly more attractive. This could be a result of people preferring to take the car instead of the bicycle when a rain alarm is carried out. The average distance for cyclists is much shorter so there is less chance of them having to use the highway.

4.2 Comparison of the estimated recreational trip models

In this section the different estimated recreational trip models are compared to each other, after which one of the models is chosen to be used in further analyses. The results of the estimated models regarding utilitarian trips can be seen in Table 6. In a normal weather situation (dry weather and no alarm) the different traveller groups have a positive utility for their standard transportation mode and route. The influence of the weather on public transport use could however not be estimated in the grouped MNL and grouped panel ML model. The reason for this is that the public transport users were excluded from analysis due to the fact that the group was too small (see paragraph 3.4). Only few respondents of the other groups chose for public transport, which led to insignificant parameters due to the small amount of observations.

An interesting result is that some coefficients turned out to be significant in the basic MNL model, but when the grouping was introduced, the coefficients became insignificant. It is assumed that this has to do with the introduction of the coefficients highway car group, non-highway car group and public transport group, which determine the difference in utility of the groups regarding the alternative specific constant.

Table 6 - Comparison of the estimated recreational trip models

	Basic MNL		Grouped MNL		Grouped panel ML	
	coefficient	t-value	coefficient	t-value	coefficient	t-value
Highway						
ASC	-0.21	-2.09	-0.66	-5.33	-2.01	-7.24
icy roads alarm	-0.29	-2.44	-0.66	-5.43	-1.19	-5.23
better forecast	0.59	4.96	n.s.	n.s.	n.s.	n.s.
light rain	1.01	5.29	1.08	5.74	1.74	5.14
very heavy rain	(-)	(-)	n.s.	n.s.	0.49	2.11
light snow	(-)	(-)	-0.65	-3.99	n.s.	n.s.
heavy snow	-2.02	-11.26	-1.35	-7.35	-2.24	-8.28
highway car group	(-)	(-)	1.01	8.03	2.23	7.81
SIGMA	(-)	(-)	(-)	(-)	-2.38	-9.14
Avoid morning peak						
ASC	-0.45	-4.45	-0.46	-4.50	-0.78	-5.10
worse forecast	-0.40	-2.79	-0.41	-2.89	-0.56	-3.08
better forecast	0.66	5.28	0.45	4.00	0.61	3.55
light rain	0.71	3.29	0.66	3.25	0.90	3.05
heavy snow	-1.24	-7.16	-1.13	-6.72	-1.36	-5.85
SIGMA	(-)	(-)	(-)	(-)	1.15	9.50
Avoid highway						
ASC	-0.34	-3.49	-0.57	-5.17	-2.99	-8.03
icy roads alarm	n.s.	n.s.	-0.45	-3.40	-0.71	-2.92
better forecast	0.53	4.74	n.s.	n.s.	n.s.	n.s.
light rain	0.83	4.11	0.67	3.43	1.08	3.42
light snow	n.s.	n.s.	n.s.	n.s.	-1.47	-4.40
heavy snow	-1.46	-8.25	-1.13	-6.41	-1.79	-6.31
highway car group	(-)	(-)	-0.87	-6.05	-2.48	-6.69
non-highway car group	(-)	(-)	0.86	7.94	2.79	6.59
SIGMA	(-)	(-)	(-)	(-)	3.78	7.86
Bicycle						
ASC	-0.81	-6.81	-1.45	-9.04	-2.72	-7.33
snow alarm	n.s.	n.s.	-1.03	-5.71	-1.60	-4.06
better forecast	0.68	5.01	n.s.	n.s.	n.s.	n.s.
light rain	0.92	4.33	0.67	3.01	1.05	2.96
light snow	n.s.	n.s.	-0.41	-2.05	-0.72	-2.27
heavy snow	-2.39	-10.92	-1.34	-5.42	-2.07	-4.50
highway car group	(-)	(-)	-1.53	-10.32	-1.78	-6.77
highway car very heavy rainfall	(-)	(-)	0.66	3.51	1.24	4.24
SIGMA	(-)	(-)	(-)	(-)	-2.35	-11.99
Public transport						
ASC	-1.59	-10.68	-1.71	-11.81	-9.33	-4.31
light rain	0.72	2.48	n.s.	n.s.	n.s.	n.s.
heavy snow	-0.54	-2.26	n.s.	n.s.	n.s.	n.s.
SIGMA	(-)	(-)	(-)	(-)	-5.23	-5.26
Not making a trip						
ASC	0.00	reference	0.00	reference	0.00	reference
Log-likelihood	-2085.69		-1846.74		-1348.86	
Rho-square	0.118		0.219		0.430	

* n.s. means that the coefficient was not significant. (-) means that the coefficient was not estimated

There are 21 significant coefficients in the basic MNL model. The grouped MNL model has 25 different coefficients, while the grouped panel ML model resulted in 31 significant coefficients. The basic MNL model (LL = -2085.69) is a significant improvement of the Null model (LL = -2365.12) and has a Rho-square value of 0.118. Grouping the respondents on the basis of their standard modes turned out to make the model fit to the data a lot better. The Log-likelihood rises by 199 points compared to the basic MNL model and the Rho-square value becomes 0.219. Adding a panel effect on top of the grouped MNL model also means a significant improvement of the model and leads to a relatively high Rho-square value of 0.430. The grouped MNL model has a much higher model fit than the basic MNL model with the while estimating four more coefficients. The grouped panel ML model also increases the model fit compared to the basic model, but ten more coefficients are being estimated. The difference of 736 Log-likelihood-points is however so big that according to the Likelihood Ratio Test (Ben-Akiva & Lerman, 1985) the grouped panel ML model fits highly significantly better to the data than the basic MNL model. As a result, chosen was to use the grouped panel ML model for recreational trips in the remainder of this study.

Outcomes of the recreational grouped panel ML model

In a normal situation with dry weather, no weather alarm and a forecast that states the weather to be the same during the whole day, the utilities for the alternatives are as presented in Table 7.

Table 7 - Utilities for the alternatives with dry weather, no alarm and similar weather forecast

group alternative	Car - highway	Car - non highway	Cyclists
Highway	**2.895**	0.665	-1.565
Avoid morning peak	-0.319	-0.319	-0.319
Avoid highway	-4.053	**1.217**	-1.883
Bicycle	-2.4	0.62	**3.64**
Public transport	-9.33	-9.33	-9.33
Not making a trip	0	0	0

From Table 7 the conclusion can be drawn that each group derives the highest utility from using their own mode of transport, which is to be expected. The difference in the utility of alternatives is rather high within the highway users and the cyclists groups. The car users that normally avoid the highway have a smaller difference between the utilities of the alternatives. It shows that within this group, travellers are not bound to only one transportation mode and can also switch between their normal behaviour and using the highway or the bicycle rather easily. The disutility of using public transport is very high and the same for all the groups, which is a result of the exclusion of public transport users from the recreational analysis combined with the fact that travellers within the other groups do not prefer to change to public transport in many circumstances.

Compared to the utilitarian analysis the signs of the significant coefficients are similar. The difference is in the strength of the coefficients and the coefficients that are significant. For recreational trips it also holds that the travel groups, except for cyclists, seem to be more determined to use their standard modes when the current weather is light rain. The cycling group derives less utility from light rain compared to dry weather, which is understandable due to cycling being an open-air activity. A difference with the utilitarian trips is that the cycling alternative for recreational purposes is negatively influenced by a snow alarm instead of an alarm for icy roads. An interesting difference with the utilitarian trip analysis is that the weather forecast coefficients are significant for the alternative to avoid the highway morning peak. These coefficients lead to a positive approach to avoiding the morning peak when travellers know that the weather is going to improve. A part of the recreational travellers thus waits for the weather to get better before they make their trip. On the other hand, a disutility is derived from avoiding the morning peak when the weather is forecasted to get worse during the day. Travellers prefer to make the trip at this moment or not go at all when the forecasts are worse than current weather. A more detailed explanation is provided in paragraph 4.3, where the choice probabilities of the different alternatives are treated.

4.3 Travel behaviour during different weather scenarios

The outcomes of the grouped panel mixed logit models are translated into probabilities that the travellers of the different groups will choose for each of the alternatives in different weather scenarios. Via the presentation of the choice probabilities in different scenarios one can derive the adaptation of behaviour as a result of changes in the weather and weather forecasts. First the translation of the values into a probability model is briefly explained. After that the choice probabilities for nine different weather scenarios are provided. Finally conclusions are drawn based on the presented choice probability models.

4.3.1 Creation of the probability model based panel mixed logit

In this section it is elaborated upon the creation of the choice probability model, while taking the panel effect into account. As explained in section 3.1.1, simulation is needed to approximate the integral for the panel mixed logit calculation. The creation of the model and the simulation in excel is presented in this section.

An Excel model was created to translate the values of the analysis into choice probability values. For each group the values for the effects coded coefficients were recalculated into part worth utilities for the attribute levels. By filling in the kind of alarm, the current weather and the weather forecast, the model calculates the utilities that are derived from the alternatives for the different groups. To account for the different preferences of respondents regarding the alternative specific constants, the standard deviation (Sigma) of the normal distribution that was estimated for all alternatives should be added to the alternative specific constant of the different alternatives. With including this panel effect, the error term for the choice made by an individual is constant for each of the individual's choices. The error term thus does not differ within the choices of one individual, but differs between individuals. To be able to take this into account, for each constant 10000 draws from a normal distribution with the specific standard deviation (sigma) were taken. For each of the draws a random number was obtained from a uniform distribution between zero and one. After this the random number was converted into a point on the normal distribution, taking into account the standard deviation. This random draw represents the difference in preferences for the ASC's and is added to the estimated ASC mean. The ASC mean is based on the ASC (which was not significant for utilitarian trips, therefore equal to zero) combined with the interaction effects of the different groups. This resulted in the ASC to be different for each draw (representing respondents), based on the differences in the error terms of the different respondents. In each draw the total utility for the different alternatives was estimated based on the calculated constant and the part worth utilities of the attributes for that alternative for a specific weather situation. Then, for each of the simulated respondents, the choice probability for the alternatives was estimated with the approach that is shown in section 3.1.1. To approximate the resulting choice probability from the integral of the alternatives the average is taken from the 10000 simulated respondents.

The model that is created calculates the choice probabilities of the different alternatives for the different groups when the kind of alarm, the current weather and the weather forecast is filled in to the model. Also the highway traffic demand as a result of the weather conditions is presented in the created model, but more on that can be found in section 4.4.

4.3.2 Choice probabilities during different weather scenarios

In this paragraph the choice probabilities for the alternatives in nine different scenarios are elaborated upon. As a base scenario the situation of dry weather, no weather alarm and forecasted similar weather is taken. After that, scenarios with the precipitation forms light rain, very heavy rain, light snow and heavy snow are elaborated upon. The choice was made to add a heavy rain scenario as a result of the observation that the very heavy rain scenario is based on extreme rain intensity. In the very heavy rain level, respondents where shown a picture of rain during a severe rain shower which corresponded to an intensity of 120mm/hour. A rain intensity value based on interpolation between the light rain and very heavy rain scenario could be more representative for highway traffic demand during heavy rainfall. This new heavy rain scenario is estimated by using part worth rain utilities with averaging the utility of light and heavy rain. Finally extreme situations are taken into account, where a rain alarm is added to very heavy rain, and heavy snow is combined with a snow alarm and an alarm for icy roads.

Base case: dry weather, no rain alarm, similar weather forecast

In Table 8 the choice probabilities for the alternatives from the different groups of travellers can be found. For the utilitarian trips almost all the highway users, cyclists and public transport users use their standard mode of transport. The car user group that normally avoids using the highway is less bound to their standard way of transportation. There is a small chance that in dry weather conditions the car users will use the bike. The same applies to the alternatives highway usage and avoiding the morning peak. It seems that there is a bit more interchangeability between the alternatives for the car users group that normally avoids the highway.

When comparing the results of the utilitarian trips to the recreational trips it becomes clear that the recreational trip makers are less bound to their normal transportation mode. Less utility is derived from the recreational trips, since the probability of not making a trip is rather high for all traveller groups. Within the recreational trips the car users that normally avoid the highway also show the least preference of using their normal transportation mode. The probability that travellers within this group choose to use the highway or use their bicycle is fairly high (18.1% and 17.3% respectively). Recreational travellers are thus more flexible in choosing their modes.

Table 8 - Choice probabilities base scenario

	Utilitarian trips					**Recreational trips**		
	Car - highway	Car - non highway	Cyclists	Public transport		Car - highway	Car - non highway	Cyclists
Highway	**96.4%**	6.0%	0.0%	0.1%		**80.8%**	18.1%	1.4%
Avoid morning peak	0.6%	3.3%	0.0%	0.9%		3.8%	6.9%	5.2%
Avoid highway	0.3%	**76.8%**	0.0%	0.0%		0.1%	**34.7%**	1.1%
Bicycle	0.3%	5.7%	**100.0%**	0.4%		0.4%	17.3%	**73.2%**
Public transport	0.0%	0.0%	0.0%	**96.0%**		0.0%	0.0%	0.0%
Not making a trip	2.5%	8.2%	0.0%	2.7%		14.9%	22.8%	19.0%

Light rain

In the scenario where there is light rainfall, the behaviour of travellers of some groups changes slightly (Table 9). For the utilitarian trips most of the choice probabilities for the alternatives stay nearly the same. The most interesting change is that, for the highway avoiding car users the choice probability of cycling reduces from 5.7% to 0.8%. This reduction in probability is added to the car usage. There are slightly larger behavioural shifts for recreational trips. The highway user group behaves almost the same as in the base scenario. However for the highway avoiding car users the probability of cycling drops with 9.9 percentage point (pp) due to the light rainfall. For the cyclists group the probability of choosing the car increases and the probability of cycling decreases by 13.6pp. There is thus a relatively large modal shift from the bicycle to the car. The chance that cyclist will not make the trip increases by 4.2pp. The recreational trip travellers are thus more likely to change their behaviour than the utilitarian trip travellers.

Table 9 - Choice probabilities light rain scenario

	Utilitarian trips					**Recreational trips**		
	Car - highway	Car - non highway	Cyclists	Public transport		Car - highway	Car - non highway	Cyclists
Highway	**97.5%**	7.5%	0.0%	0.0%		**81.8%**	19.9%	2.9%
Avoid morning peak	0.2%	1.3%	0.0%	0.1%		4.7%	9.4%	11.4%
Avoid highway	0.2%	**81.9%**	0.1%	0.0%		0.1%	**42.6%**	2.7%
Bicycle	0.0%	0.8%	**99.4%**	0.1%		0.6%	7.4%	**59.6%**
Public transport	0.0%	0.2%	0.0%	**98.6%**		0.0%	0.0%	0.1%
Not making a trip	2.0%	8.3%	0.4%	1.1%		12.8%	20.7%	23.2%

Heavy rain

In the heavy rain scenario, the behaviour of the utilitarian travellers does not change drastically (Table 10) compared to the light rain scenario. In comparison to the light rain scenario, slightly fewer highway users will make a highway trip (-2.1pp). Non-highway car users will also use the highway less than in the light rain scenario (-2,7pp). Cyclists and public transport users are least affected by the heavy rain. Behavioural shifts are larger for the recreational travellers in comparison to the utilitarian travellers. In this scenario a smaller percentage of the recreational car user groups uses the highway (-5.7pp for highway users and -2.9pp for non-highway users). For cyclists there is no significant modal shift compared to the light rain scenario. The probability of not making a trip for all recreational travellers increase significantly as a result of the heavy rainfall, with 5.1, 6.2 and 6.0 percentage points for highway users, non-highway users and cyclists respectively.

Table 10 - Choice probabilities heavy rain scenario

	Utilitarian trips					**Recreational trips**		
	Car - highway	Car - non highway	Cyclists	Public transport		Car - highway	Car - non highway	Cyclists
Highway	**95,4%**	4,8%	0,1%	0,0%		**76,1%**	17,0%	2,5%
Avoid morning peak	0,4%	2,0%	0,1%	0,2%		4,8%	8,7%	10,3%
Avoid highway	0,4%	**82,4%**	0,3%	0,0%		0,1%	**40,3%**	2,5%
Bicycle	0,0%	0,2%	**98,4%**	0,1%		1,1%	7,0%	**55,4%**
Public transport	0,0%	0,2%	0,0%	**98,1%**		0,0%	0,1%	0,1%
Not making a trip	3,8%	10,6%	1,1%	1,6%		17,9%	26,9%	29,2%

Very heavy rain

The current weather being very heavy rain affects the choice probabilities of the alternatives more than the light and heavy rain scenario (Table 11). Compared to the light rain scenario in the utilitarian trip analysis it can be seen that the probability of using the highway by highway users reduces slightly with 5.4pp. Cyclists and public transport users are only affected to a very limited extend. The choice probability of not making a trip is relatively high for the highway avoiding car user group. A straightforward reason for this effect cannot be provided right away. It might be the case that there is a significantly higher share of travellers that can work at home in the non-highway car user group. The recreational trips are affected more by the very heavy rain than the utilitarian trips. The probability that travellers will stay at home increases significantly in very heavy rain conditions compared to light rainfall. This increase is mostly accounted for by the decrease in probability of the normal mode. There are very little modal shifts for the recreational trips compared to the light rain scenario.

Table 11 - Choice probabilities very heavy rain scenario

	Utilitarian trips				**Recreational trips**		
	Car - highway	Car - non highway	Cyclists	Public transport	Car - highway	Car - non highway	Cyclists
Highway	**92.1%**	2.9%	0.1%	0.0%	**69.6%**	14.4%	2.0%
Avoid morning peak	0.9%	2.9%	0.3%	0.3%	4.6%	7.9%	9.1%
Avoid highway	0.5%	**80.2%**	0.9%	0.0%	0.1%	**37.9%**	2.3%
Bicycle	0.0%	0.0%	**95.7%**	0.0%	2.0%	6.5%	**50.2%**
Public transport	0.0%	0.2%	0.0%	**97.2%**	0.1%	0.1%	0.2%
Not making a trip	6.4%	13.8%	3.0%	2.4%	23.6%	33.2%	36.2%

Light snow

In the light snow scenario (Table 12) there is hardly any difference in the choice probabilities for the highway avoiding car group, the cyclists and the public transport users. The highway users are however significantly affected by light snowfall. The longer the trip is, the higher the uncertainty regarding the effect of snowfall in other regions. Travellers might know from historic events that snowfall leads to more congestion on Dutch highways which could be a reason not to use the highways. Avoiding the morning peak becomes slightly more attractive, but the biggest change takes place in the probability of not making a trip. For the recreational trip travellers not making a trip becomes more favourable compared to the scenarios with rainfall. The probability to avoid the morning peak rises compared to the other scenarios, which means that travellers are more hesitant to travel during the morning peak in a scenario in light snowfall. Lastly, it can be seen that there is a relatively high modal shift in the cyclist group towards the usage of the car, with 16.9% probability of using a car alternative. A possible explanation is that traveling by car is considered to be safer than cycling in snow conditions.

Table 12 - Light snow scenario

	Utilitarian trips				Recreational trips		
	Car - highway	Car - non highway	Cyclists	Public transport	Car - highway	Car - non highway	Cyclists
Highway	**85.4%**	0.9%	0.0%	0.0%	**42.1%**	2.5%	0.5%
Avoid morning peak	2.1%	3.0%	0.3%	0.3%	12.9%	9.3%	12.6%
Avoid highway	1.8%	**81.9%**	1.0%	0.0%	0.5%	**47.4%**	3.8%
Bicycle	0.0%	0.1%	**95.4%**	0.0%	1.2%	4.0%	**39.5%**
Public transport	0.0%	0.2%	0.0%	**97.3%**	0.3%	0.1%	0.3%
Not making a trip	10.8%	14.0%	3.2%	2.4%	43.0%	36.7%	43.4%

Heavy snow

With a scenario of heavy snowfall (Table 13), the behaviour of the traveller changes more drastically compared to the other precipitation scenarios. When looking at the utilitarian trips, a fair amount of travellers will cancel their trip and stay at home as a result of the heavy snow. Interesting to see is that the car travellers are far more likely to decide not to make the trip compared to the public transport users and the cyclists. The cyclists and the public transport users seem to be less affected by the weather and have a high probability not to adapt the behaviour. It can thus be said that these groups of travellers are really persistent travellers. Another interesting observation is that the avoidance of the morning peak (leaving before 6am or after 10am) is not much preferred by the car travellers. They rather stay at home than leaving at a (very) different time. A possible explanation for this is that avoiding the morning peak drastically influences the normal workday and thus working from home or taking a day off is preferred. From the recreational trips, the most interesting result is that the chance of the travellers to decide not to make the trip lies between 57.0 and 63.5%, depending on the traveller group. More than half of the trips will thus be cancelled as a result of heavy snowfall. The probability of avoiding the morning peak is much lower compared to the light snow. Recreational travellers are thus less likely to wait with making their trip and are more likely to cancel their trip in the heavy snowfall scenario.

Table 13 - Choice probabilities heavy snow scenario

	Utilitarian trips				Recreational trips		
	Car - highway	Car - non highway	Cyclists	Public transport	Car - highway	Car - non highway	Cyclists
Highway	**77.4%**	1.4%	0.0%	0.0%	**36.4%**	3.9%	0.6%
Avoid morning peak	2.2%	4.1%	0.5%	0.3%	5.2%	5.4%	6.3%
Avoid highway	0.7%	**65.3%**	0.5%	0.0%	0.1%	**27.9%**	1.8%
Bicycle	0.0%	0.1%	**91.2%**	0.0%	0.6%	3.4%	**26.9%**
Public transport	0.0%	0.4%	0.0%	**95.5%**	0.7%	0.5%	0.9%
Not making a trip	19.6%	28.5%	7.7%	4.2%	57.0%	59.0%	63.5%

Very heavy rain and a rain alarm

This scenario represents an extreme situation in which currently there is very heavy rainfall and an alarm is carried out for extreme rainfall. When comparing this situation to the scenario with very heavy rainfall, it can be concluded that for the utilitarian trips the highway users and cyclists are affected rather strongly due to the addition of the rain alarm (Table 14). For highway users it becomes a bit more interesting to avoid the morning peak compared to the very heavy rainfall scenario. The biggest change is however in the probability not to make the trip, which increases by 5.1pp from 6.4% to 11.5%. For the cyclist it becomes more interesting to use the car and avoid the highway, which leads to a small modal shift. Also for the cyclists the biggest effect can be noticed in the increase of the probability to not make the trip from 3.0% to 6.4%. Recreational travellers are however far more affected by the addition of a rain alarm. The chance of not going increases significantly due to the addition of the rain alarm. Especially for the cyclists group the probability to make a trip with the bicycle decreases drastically from 50.2% to 26.8%. The decrease in cycling is made up for through an increase in probability of avoiding the morning peak on the highway with 8pp and not going, of which the probability increases by 14.5pp.

Table 14 - Choice probabilities very heavy rain and rain alarm scenario

	Utilitarian trips					**Recreational trips**		
	Car - highway	Car - non highway	Cyclists	Public transport		Car - highway	Car - non highway	Cyclists
Highway	**84.4%**	0.8%	0.1%	0.0%		**54.0%**	8.0%	1.6%
Avoid morning peak	2.3%	3.2%	0.9%	0.3%		9.1%	11.9%	17.1%
Avoid highway	1.8%	**81.2%**	3.2%	0.0%		0.1%	**35.4%**	3.2%
Bicycle	0.0%	0.0%	**89.2%**	0.0%		1.0%	2.4%	**26.8%**
Public transport	0.0%	0.2%	0.1%	**97.3%**		0.2%	0.2%	0.6%
Not making a trip	11.5%	14.6%	6.4%	2.4%		35.5%	42.0%	50.7%

Heavy snow and a snow alarm

A snow alarm in combination with heavy snow highly affects most of the travel groups (Table 15). In comparison to the heavy snow scenario the biggest changes in the utilitarian trips can be seen in the highway car user group, where the probability not to make a trip increases from 19.8% to 33.8%. Also avoiding the morning peak becomes marginally more attractive with an increase from 2.2% to 5.9%. The highway avoiding car users are not very much affected by the addition of the snow alarm. The group of car travellers not making the trip increases from 28.5% to 33.2%. The snow alarm being more effective on changing behaviour in the highway car user group could be explained by the average trip length of the highway car users (35.9 km) compared to the highway avoiding car users (12.2 km). The uncertainty for the highway car users concerning the trip could be higher due to the greater distance that has to be covered. For the cyclists also a considerable increase in the chance of not making the trip can be observed as a result of the snow alarm. Regarding the recreational trips it can be concluded that almost all trips are cancelled in this scenario. Based on the 2.8% probability, cyclists are not willing to perform a recreational trip in case of heavy snow and a snow alarm. The car groups will not change their behaviour in about one fifth of the cases. Lastly the alternative to avoid the morning peak becomes slightly more attractive compared to the heavy snow scenario.

Table 15 - Choice probabilities heavy snow and snow alarm scenario

	Utilitarian trips				Recreational trips		
	Car - highway	Car - non highway	Cyclists	Public transport	Car - highway	Car - non highway	Cyclists
Highway	**58.0%**	0.3%	0.0%	0.0%	**21.4%**	1.9%	0.4%
Avoid morning peak	5.9%	5.5%	1.4%	0.3%	7.9%	7.2%	11.0%
Avoid highway	2.2%	**60.3%**	1.1%	0.0%	0.1%	**22.5%**	2.4%
Bicycle	0.0%	0.1%	**83.0%**	0.0%	0.0%	0.2%	**2.8%**
Public transport	0.1%	0.7%	0.2%	**95.5%**	1.4%	0.9%	2.8%
Not making a trip	33.8%	33.2%	14.4%	4.2%	69.1%	67.4%	80.4%

Heavy snow and an alarm for icy roads

In a scenario with heavy snow and an alarm for icy roads, the travellers react even more intensely with adaptation of their behaviour in comparison to the scenario with heavy snow and a snow alarm (Table 16). For utilitarian trips a large difference can be seen in the highway avoiding group and in the cyclists group. The highway avoiders will choose less often for their normal behaviour (48.3% versus 60.3%) in comparison to the former scenario. The choice to avoid the morning peak becomes slightly more attractive to this group of travellers. For the cyclists the probability of not making the trip increases from 14.4% to 23.8%. In case of recreational trips the response to this scenario is even more intense. Using the highway and avoiding the morning peak become evenly attractive for the highway users. From the highway avoiders only 15.4% will behave like they normally do and in the cyclists group this is 11.1%. Most interesting for the recreational trips is that this scenario leads to cancellation of the trip in 72.5% to 76.2% of the cases, which are incredibly high percentages.

Table 16 - Choice probabilities heavy snow and alarm for icy roads scenario

	Utilitarian trips				Recreational trips		
	Car - highway	Car - non highway	Cyclists	Public transport	Car - highway	Car - non highway	Cyclists
Highway	**56.7%**	0.7%	0.1%	0.0%	**10.1%**	0.8%	0.1%
Avoid morning peak	6.6%	8.5%	3.2%	0.3%	10.1%	8.5%	9.6%
Avoid highway	0.8%	**48.3%**	1.3%	0.0%	0.1%	**15.4%**	0.9%
Bicycle	0.0%	0.0%	**71.1%**	0.0%	0.3%	1.5%	**11.1%**
Public transport	0.1%	1.5%	0.6%	**95.5%**	2.4%	1.4%	2.1%
Not making a trip	35.8%	41.0%	23.8%	4.2%	76.9%	72.5%	76.2%

4.4 Conversion of travel behaviour results into highway morning peak traffic demand

In this section the results of the travel behaviour analysis are converted into highway morning peak traffic demand changes to be able to link the results of the stated adaptation experiment to the highway capacity analysis (chapter 5) and come to a highway breakdown probability as a result of adverse weather conditions.

One of the alternatives in the stated adaptation experiment is making a trip on the highway during the morning peak. For the other alternatives either departure time, route choice or the mode differs, which results in the exclusion of these results for calculation of the highway traffic demand during the morning peak. This calculation has to take into account both utilitarian and recreational trip models, as well as the different traveller groups (highway car users, non-highway car users, public transport users and cyclists). The choice probabilities from the base scenario (dry weather, no alarm, similar weather forecast) are used to explain the conversion from the separate probabilities to a highway traffic demand during the morning peak.

Table 17 - Choice probabilities base scenario

	Utilitarian trips				**Recreational trips**		
	Car - highway	Car - non highway	Cyclists	Public transport	Car - highway	Car - non highway	Cyclists
	n=136	**n=72**	**n=28**	**n=35**	**n=53**	**n=45**	**n=34**
Highway	**96.4%**	6.0%	0.0%	0.1%	**80.8%**	18.1%	1.4%
Avoid morning peak	0.6%	3.3%	0.0%	0.9%	3.8%	6.9%	5.2%
Avoid highway	0.3%	**76.8%**	0.0%	0.0%	0.1%	**34.7%**	1.1%
Bicycle	0.3%	5.7%	**100.0%**	0.4%	0.4%	17.3%	**73.2%**
Public transport	0.0%	0.0%	0.0%	**96.0%**	0.0%	0.0%	0.0%
Not making a trip	2.5%	8.2%	0.0%	2.7%	14.9%	22.8%	19.0%

Firstly for both utilitarian and recreational trips the choice probability of the highway during the morning peak of the different groups have to be combined. The importance of the different groups should be based on the amount of travellers that belong to these groups in the population. Unfortunately figures about the amount of people belong to either highway car users or non-highway car users could not be retrieved from any study. Therefore the choice was made to weigh the different groups based on the number of respondents in that group in the sample. This means in the utilitarian trip model that the weight factor of the highway travellers was set to 1, while the weight factor of the non-highway car users was 0.53 (72/136), of cyclists 0.21 (28/136) and of public transport users 0.26 (35/136). The same approach has been taken for recreational trips. The weight factor is multiplied by the percentages of highway usage. The combined highway usage for utilitarian trips becomes 99.6% (96.4*1 + 6.0*0.53 + 0*0.21 + 0.1*0.26) and the highway usage for recreational trips is 96.8% (80.8*1 + 18.1*0.85 + 1.4*0.64). These two figures also have to be combined, which is done on the basis of the amount of highway morning peak trips that are made for the different purposes. Research from Ruimtelijk Planbureau (2006) shows that the utilitarian purpose accounts for 79% of the total highway morning peak trips and that the other 21% are recreational trips. These percentages are used as a weight factor and the results of the different models are added, leading to a percentage of 99.0 (99.6*0.79 + 96.8*0.21) for the base case scenario. Since this is the base case the 99.0% is indexed at 100 to make the relative difference between the different scenarios easier to interpret. For all scenarios from chapter 0 the highway traffic demand is calculated, which leads to the results in Table 18.

Table 18 - Highway morning peak traffic demand for different scenarios

Scenario	Index
Dry weather	100
Light rain	102.3
Heavy rain	97.7
Very heavy rain	92.3
Light snow	77.7
Heavy snow	70.6
Very heavy rain + rain alarm	80.6
Heavy snow + snow alarm	51.2
Heavy snow + icy roads alarm	47.6

It is interesting to see that the highway traffic demand rises by 2.3% in light rainfall due to a small route shift of non-highway travellers and a marginal modal shift of cyclists. The other scenarios result in less highway traffic demand. Highway traffic demand decreases by 2.3% in the heavy rainfall scenario. Some travellers might link heavy rainfall to an increase in probability of congestion and therefore avoid the highway. The traffic demand decreases by 7.7% compared to dry weather as a result of very heavy rainfall. The large decrease could be explained by the extreme rain intensity that was presented to the respondents in the stated adaptation experiment. It can be concluded that snowfall leads to enormous decreases in highway traffic demand. Light snowfall leads to a decrease of 22.2%, while heavy snowfall leads to a decrease of 29.4% in comparison to the dry weather traffic demand. The longer the trip length, the higher the uncertainty regarding the effect of snowfall on the highway traffic flows in other regions. Travellers might know from historic events that snowfall leads to more congestion on Dutch highways which could be a reason not to use the highways. Addition of a weather alarm results in the demand being reduced with 19.4% in case of very heavy rain and a rain alarm. Heavy snow and a snow alarm leads to a reduction of 48.8% and heavy snow in combination with an icy roads alarm results in a decrease by 52.4% of highway traffic demand in comparison with dry weather. Some travellers thus tend to accept the advice of the KNMI to avoid travelling in extreme weather situations.

4.5 Conclusions

In this paragraph the answers to the research questions are provided. The answer to the research question concerning the effect of adverse weather conditions and predictions on travel behaviour is provided by answering the following sub questions.

Which current and forecasted weather attributes are important for making travel choices?

From the attributes that were included into the analysis (current weather, weather forecast and weather alarm) it can be concluded that the weather forecast does not have an influence on the travel behaviour for utilitarian trips. The current weather and a weather alarm on the other hand can have a significant effect on the adaptation of travel behaviour. Light rain does not lead to adaptation of travel behaviour and nor does heavy rain lead to large behavioural shifts. Even in the very heavy rain scenario the utilitarian travel behaviour does not change drastically. The small behavioural changes can however have significant effect on congestion. This is analysed in chapter 6. Light snowfall mostly affects the highway car drivers, which could be explained by the fact that on an average these travellers have to make a relatively long trip. The longer the trip is, the higher the probability of being hindered by the snowfall. It is interesting to note that light snowfall is more effective on adaptation of behaviour than very heavy rainfall. Travellers are thus more willing to adapt their behaviour as a result of snowfall compared to rainfall. Heavy snowfall leads to a fair amount of travellers cancelling their trip and staying at home. The highway travel group is most affected by snowfall. The longer the trip is, the higher the uncertainty regarding the effect of snowfall in other regions. Travellers might know from historic events that snowfall leads to more congestion on Dutch highways which could be a reason to not use the highways. The alarms also have a big influence on travel choices, with the effect of a rain alarm being less than the effect of the snow and icy roads alarm. An interesting result is that cyclists and public transport users are less affected by the extreme weather conditions, but a fairly high percentage of 23.8% of the cyclists also decide not to make a utilitarian trip. The public transport users are limitedly affected which could be the result of the fact that alterations to public transport timetables are not included in the experiment.

The influence of the weather conditions on recreational trips is slightly different from the utilitarian trips. In case of a recreational trip purpose the weather forecast plays a small role in the choice to avoid the morning peak. It leads to a positive approach to avoiding the morning peak when travellers know that the weather is going to improve. On the other hand a disutility is derived from avoiding the morning peak when the weather is forecasted to get worse during the day. Travellers prefer to make the trip at this moment or not go at all when the forecasts are worse than current weather. The last interesting effect that can be seen is that both the current weather and the weather alarm more effectively influence adaptation of travel behaviour for recreational trips compared to utilitarian trips.

What is the influence of current and forecasted weather attributes on trip generation, mode choice, route choice and departure time choice for utilitarian and recreational trips?

First the influence of the weather conditions on utilitarian trips is elaborated upon. Based on the scenarios it can be concluded that trip generation could be affected by some weather conditions. Rainfall however does not have a significant effect on trip generation. Heavy snowfall, on the other hand, results in an increase in the probability of not making the trip. Especially the car users are influenced to not make a trip due to the snowfall. The biggest decreases in trip generation take place in the extreme snow scenarios. More than one third of the car travellers decide not to make the trip in case of heavy snowfall and a weather alarm. Utilitarian trip generation is thus indeed significantly affected by the weather conditions, although the weather conditions have to be extreme in order to have a significant influence.

Mode choice changes for utilitarian travellers do not occur as a result of the weather. Car users keep using their car and public transport users stay public transport users. There is a very small change in the cyclists group towards the usage of the car, but with at most 4.5% increase of car usage in the cycling group in extreme situations, this effect can be considered to be marginal. As already mentioned a small difference in highway traffic demand could have a big effect on breakdowns, which is further analysed in chapter 6.

Route choice changes for car users resulting from weather conditions are also limited. Travellers that normally use the highway will not change their route and avoid the highway in case of severe weather conditions. This can be easily explained by the rather high average distance for utilitarian trips for highway users (35.9 km). The alternative of avoiding the highway is not very attractive with such distances. Interchangeability in choice of whether or not to use the highway is more apparent for the travellers with lower trip distances (highway avoiding car users), but for this group of travellers changing the route is also not very common.

Departure time changes do not occur when only considering current weather effects. The probability of avoiding the morning peak in the scenario with heavy snow and an icy roads alarm is 6.6% for highway users and 8.5% for non-highway users. Also, a small percentage of cyclists (3.2%) decide to change to the car and avoid the morning peak in this situation. Overall, it can be concluded that the effect of weather conditions on departure time change is limited. The biggest decision that utilitarian travellers make is whether to stay at home or make their normal trip.

The influence of the weather on recreational trips is different compared to the utilitarian trips. Trip generation, for example, is a lot more influenced by adverse weather conditions. Very heavy rainfall leads to relatively high probabilities of staying at home for cyclists but also for car users (between 23.6% and 36.2%). Heavy snowfall triggers recreational travellers to stay at home even further with probabilities between 57.0% and 63.5%. In extreme weather situations more than half of the travellers decide to stay at home. Heavy snow combined with a snow or icy alarm even leads to probabilities of 67.4% to 80.4% to decide not to make the trip, which is a remarkably high probability.

Mode choice changes for recreational travellers occur more than for utilitarian travellers as a result of the weather. This can be seen in the base case scenario, where highway avoiding car users are also likely to choose the bicycle. In the rain scenario there is also a significant modal shift from cyclists towards the car. 21.9% of the cyclists will then use the car instead of the bicycle, which could be considered as a fairly high modal shift.

Route choice changes for recreational trips are comparable to utilitarian trips. Travellers that normally use the highway will not change their route and avoid the highway in case of severe weather conditions. There is a relatively high route choice change (up to 22.3%) for the non-highway users group in case of heavy rain.

The departure time is changed more often in comparison to utilitarian trips. Overall it can be said that the alternative to avoid the morning peak period is preferred by recreational trip travellers. A possible explanation for this is (to some extent) the more flexible nature of the recreational trips as compared to utilitarian trips. Grocery shopping for example is much easier to reschedule than a business meeting.

What is the effect of current and forecasted weather on highway traffic demand?

As a result of the behavioural adaptation of travellers, the highway traffic demand rises by 2.3% in light rainfall due to a small route shift of non-highway travellers and a marginal modal shift of cyclists. The other scenarios result in less highway traffic demand. Highway traffic demand decreases by 2.3% in the heavy rainfall scenario. Some travellers might link heavy rainfall to an increase in probability of congestion and therefore avoid the highway. The traffic demand decreases by 7.7% compared to dry weather as a result of very heavy rainfall. The large decrease could be explained by the extreme rain intensity that was presented to the respondents in the stated adaptation experiment. It can be concluded that snowfall leads to enormous decreases in highway traffic demand. Light snowfall leads to a decrease of 22.2%, while heavy snowfall leads to a decrease of 29.4% in comparison to the dry weather traffic demand. The longer length of the trip, the higher the uncertainty is regarding the effect of snowfall on the highway traffic flow in other regions. Travellers might know from historic events that snowfall leads to more congestion on Dutch highways which could be a reason to not use the highways. The addition of a weather alarm results in the demand being reduced by 19.4% in case of very heavy rain and a rain alarm. Heavy snow and a snow alarm leads to a reduction of 48.8% and heavy snow in combination with an icy roads alarm results in a decrease of 52.4% of highway traffic demand in comparison to dry weather. Some travellers thus tend to accept the advice of the KNMI to avoid travelling in extreme weather situations. From the stated adaptation experiment it can be concluded that a weather alarm has a significant effect on travellers.

5. The effect of precipitation on highway capacity

In this chapter the effect of precipitation on Dutch highway capacity are analysed. First, in section 5.1 the motivation for the stochastic approach and the choice of the capacity estimation method are provided. After that in section 5.2, the steps to come to capacity estimation are elaborated upon. The results of the capacity analysis and the conclusions are presented in section 5.3.

5.1 Motivation and method

There are multiple approaches to estimate highway capacity, with results being deterministic or stochastic. In this section the motivation to use a stochastic approach is presented, after which several stochastic approaches to capacity analysis are shortly compared to each other.

Traditionally highway capacity is viewed as a deterministic phenomenon, which is based on the assumption that a highway will have a breakdown if demand exceeds an identified capacity value. Where this approach is suitable in order to get an initial idea about capacity on a strategic level (to make a decision for the number of lanes on a new highway), on a tactical and operational level a higher accuracy of traffic predictions is needed. As explained in paragraph 2.1.1, multiple researchers (Elefteriadou et al. 1995; Minderhoud et al. 1997; Persaud et al. 1998; Lorenz and Elefteriadou 2001, Brilon et al., 2005) have shown that the maximum capacity of a highway varies even when the external factors are constant, resulting from unpredictable behaviour of travellers at the microscopic level. Breakdown thus does not necessarily have to occur at maximum flow and breakdown could occur at flows lower or higher than those traditionally accepted as capacity. A definition of capacity that takes the probabilistic nature of capacity into account defines capacity as *"the rate of flow along a uniform freeway segment corresponding to the expected probability of breakdown deemed acceptable under prevailing traffic and roadway conditions in a specific direction"* (Lorenz & Elefteriadou, 2001).

There are several approaches to come to a function describing the probability of breakdown. Examples are the Brilon method (2005), the method described by Minderhoud et al. (1997) and the method by van Toorenburg (1986). Brilon et al. (2005) have implemented a methodology for the derivation of capacity distribution functions for highways, based on the proposed practical capacity estimation method by van Toorenburg (1986). The estimation method of van Toorenburg (1986) has analogies with the statistics of lifetime data analysis, which in essence describes statistical properties regarding the duration of human life. It is often applied to analyse the lifetime (durability) of technical components (Lawless, 2003). An important difference of the Brilon method with the methods of van Toorenburg (1986) and Minderhoud (1997) is the definition of breakdown capacity. According to these authors breakdown capacity is the traffic volume measured downstream of a queue at a bottleneck. The Brilon method takes into account that the capacity in fluent traffic flows differs from the capacity in congested conditions. This has to do with the phenomenon of the capacity-drop, which is investigated by many authors (e.g. Hall & Agyemang-Duah, 1991, Zurlinden, 2003; Regler, 2004). The studies that measure the capacity downstream of a queue at a bottleneck (post-bottleneck) do not take the capacity drop into account. The capacity drop however can have significant magnitude. Chung et al. (2007) for example show that the magnitude of the capacity drop is location specific, but even at a certain location the capacity drop fluctuates. This study found a capacity drop between 3% and 18% in maximum traffic flow rates after the congestion compared to pre-congestion flow rates.

It is chosen to use the Brilon method in this research for estimation of freeflow capacity, because this method is based on proven theory and has, in contrast to the Minderhoud and van Toorenburg method, a clear and easy applicable definition of the free flow capacity. Next to the estimation of a capacity distribution function at free flow, the congested capacity is also estimated at a post-bottleneck location. For estimation of the capacity distribution function for congested conditions a basic empirical function is used (see 4.2.2). Due to the estimation of both freeflow and congested capacity, the capacity drop can also be investigated in this research.

5.2 Steps towards capacity estimation

In this section the four steps to come to capacity estimation are presented. First of all bottleneck locations are identified. After that breakdown observations during the morning are searched for. The observations are then filtered based on several criteria. Finally, the capacity distribution functions and estimation is elaborated upon.

5.2.1 Bottleneck location detector

Before capacity distribution functions can be estimated, one first has to identify the locations at which the capacity can be estimated. In this section the motivation for choosing static bottleneck locations is presented, the analysis of the highway data is elaborated upon and requirements to the bottleneck locations are specified. This results in 14 Dutch bottleneck locations suitable for analysis.

The estimation method relies on the occurrence of breakdowns and many breakdowns have to occur in order to be able to estimate a reliable capacity distribution function. Bottlenecks can occur at random locations due to an incident or a disruptive manoeuvre of a driver at that influences the traffic flow. The most common breakdowns are however the result of static bottlenecks, which are bottleneck locations that are the consequence of infrastructural lack of capacity or traffic flow disturbance at a certain location. The location of static bottlenecks is therefore often precisely known. Breakdowns as a result of static bottlenecks occur frequently during the traffic peak periods. Having many breakdown observations and confidence in the detected location being a bottleneck allows for accurate estimation of capacity at static bottleneck locations. Therefore it has been chosen to focus on static bottleneck locations in this research.

The bottleneck locations have to be identified by analysing data from double-induction loops at the Dutch highways. As explained by Calvert and Snelder (2013), within TNO traffic data is collected from double-induction loops that are present in the Dutch motorway network, which is known as the MONICA system (Dutch MONItoring Casco). The highway coverage of the system can be seen in Figure 9. Highways that are part of the system are presented with the measured local mean speed on a randomly chosen moment. Blue coloured highways are not part of the system as a result of a lack of loop detectors. With the Matlab tool ATOL created by TNO, for each minute data is stored regarding the average speeds (km/h), flows (veh/min) and possible lane closure for all the highways included in the MONICA system.

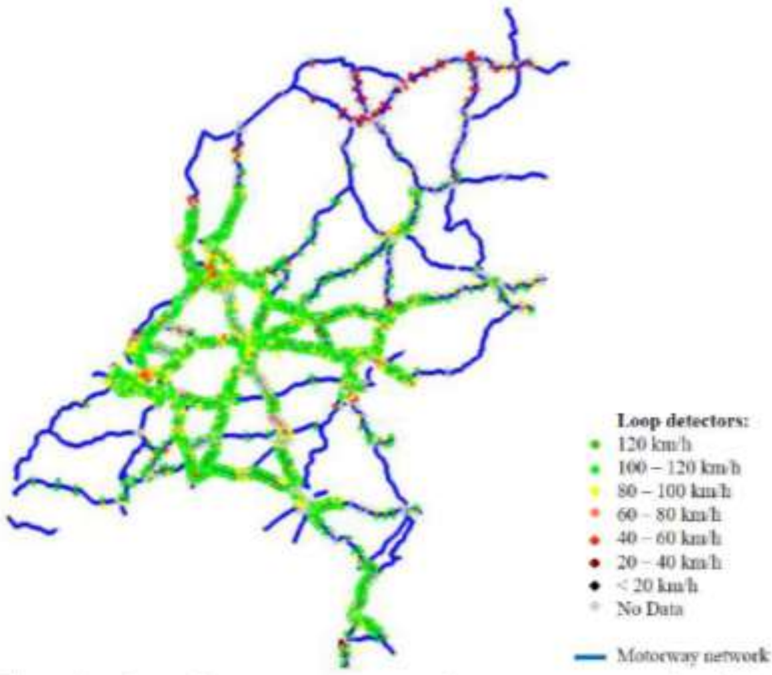

Figure 9 - Loop detector coverage on the motorway network of The Netherlands (Calvert & Snelder, 2013)

For the capacity analysis in this study, data from the years 2007, 2008 and 2009 are inspected from many Dutch highways (A2, A4, A6, A9, A15, A16, A20, A27, A50, A58 & A59). Bottleneck locations were identified by visually inspecting data of the local mean speed per one-minute time intervals for a whole year at a specific road. An example of such a figure can be seen in Figure 10.

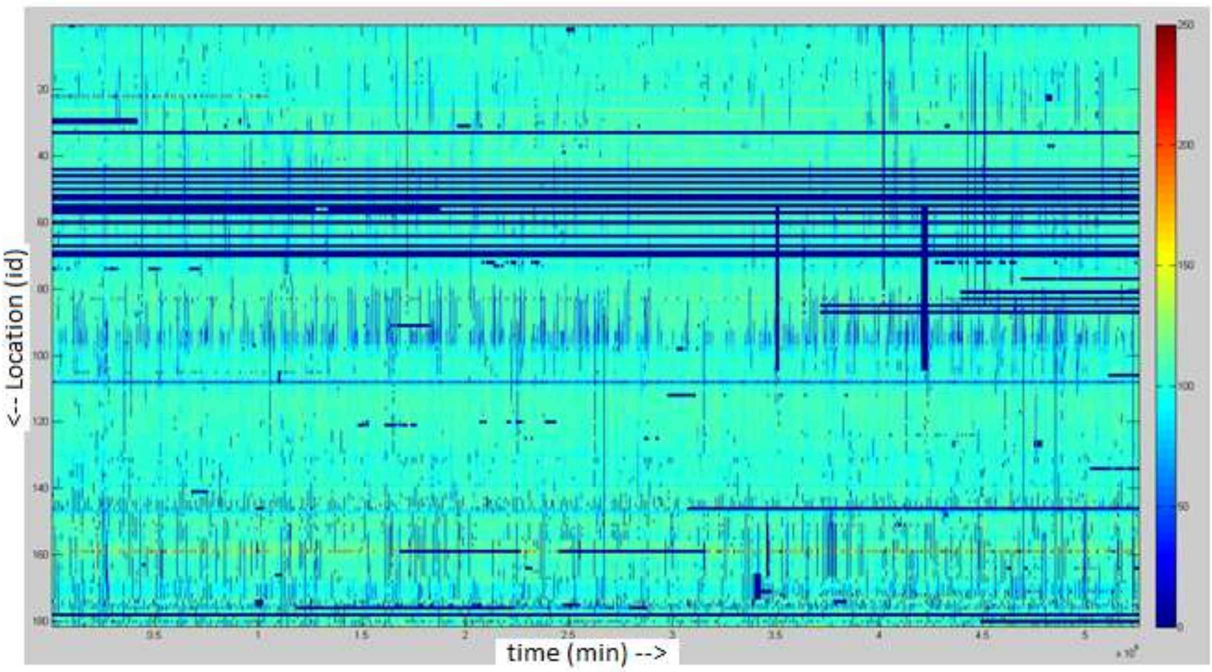

Figure 10 – Average speed at highway A4 during the year 2007

Figure 10 indicates the average speeds at the induction loops on the highway A4, with on the X-axis the time (in minutes) and on the Y-axis the induction loop locations with the identification numbers of the loops. A dark blue colour indicates that the average speed is lower than 50 km/h. When the

speed is relatively low at that location many times during the analysed year, one can conclude that the location is a structural bottleneck. There are however some requirements to a bottleneck location for making it suitable for analysis.
Firstly the induction loops at and around the bottleneck locations should work properly. If not working properly, the data obtained from the induction loop does not match the data obtained from the surrounding induction loops. The result is a (completely) different speed at that exact location compared to the other locations close by during the whole year. An example can be seen in Figure 10 between locations 40 and 70 on the y-axis, which is an indication that the induction loops do not work properly at those locations. Secondly the bottleneck location should be independent from a bottleneck downstream. If a spillback from a bottleneck downstream initializes the congestion at a certain bottleneck, the congestion is thus not solely caused by the bottleneck location itself. On top of that breakdown could not be detected by the algorithm with these kinds of observations, since the average speed difference pre and post bottleneck is rather small. Missing data and breakdown observations as a result of spillback from a bottleneck downstream are automatically filtered by the filtering algorithm. Sometimes this leads to incorrectly filtering of correct bottleneck observations, but the filters are considered necessary to come to reliable data.

Another requirement to the bottleneck location is that it may not consist of a variable amount of lanes over the day (for example peak hour lanes). A variable amount of lanes leads to a probability function that is partly based on the situation with and partly on the situation without the extra lane. In other words two different situations lead to one probability function, while for each situation a separate probability function should be estimated. Filtering bottleneck locations with a variable amount of lanes has to be done after the capacity distribution function is estimated, because at that moment the variable amount of lanes can be detected from the capacity distribution function. Bottleneck locations that did not meet any of the above mentioned three requirements were thus excluded from the analysis.

In Figure 10 a bottleneck can be detected around induction loop location 97. When zooming in to that location (Figure 11), one can see that there is a clear distinction in average speed by the distinction in colour, which indicates a bottleneck location at the red line. Figure 11 shows data over a time period of six weeks. This can be extracted from the figure by inspecting the traffic jams (vertical blue lines). One sees five traffic jams (workdays) followed by a green space in between (weekend). This pattern repeats itself six times, although some congestion effects occur in the weekends of the last three weeks in the figure. The white circle indicates a spillback from a bottleneck downstream. The breakdown observation at that moment is thus filtered by the filtering algorithm.

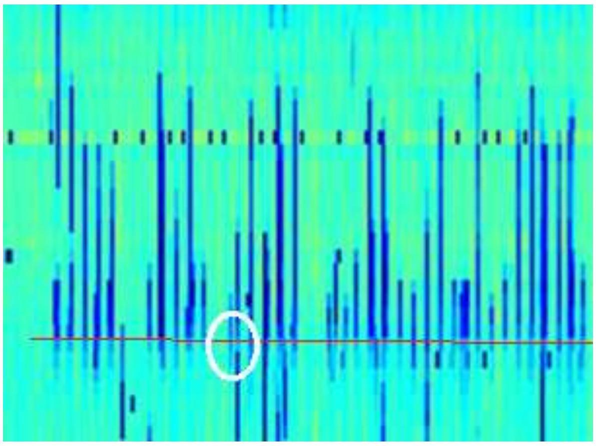

Figure 11 – Zoom-in of the average speed at highway A4 during the year 2007

The bottleneck location has to be defined by a pre-bottleneck and a post-bottleneck location. At the pre-bottleneck location the freeflow intensity that leads to a breakdown at the bottleneck is observed (see 5.2.2). It is important that the time delay between the pre-bottleneck location and the actual bottleneck is small. The defined pre-bottleneck location thus has to be close to the actual bottleneck. The bigger the time delay, the less accurate the observation is for the freeflow capacity at the bottleneck. For the post-bottleneck location it is less important to be very close to the bottleneck if the road section downstream of the bottleneck is a closed system (there are no on- and of-ramps).

In total fourteen bottleneck locations were considered suitable for the capacity analysis. The fourteen locations are presented on a map in Figure 12. From Figure 12 it follows that most bottleneck locations are in the Randstad area. Rotterdam and surroundings seems to provide most bottleneck locations that are suitable for analysis.

Figure 12 - Bottleneck locations plot in The Netherlands

The suitable bottlenecks were further investigated by analysing the number of lanes at that point. The bottleneck locations were then categorized into one of the following four categories: on-ramp, merging section, weaving section or bridge. There are some blank spaces in the table indicating that these bottleneck situations where not included into the analysis. Reasons for the exclusion are the data from that year not being available, missing data at the bottleneck location or no detection of a bottleneck at the location in that year. In total 30 bottleneck situations where suitable for analysis. The results can be found in Table 19.

Table 19- Bottleneck locations

ID	Highway	Location pre bottleneck	Location post bottleneck	2007	2008	2009	Number of lanes after bottleneck	Category
1	A4R	30.0	31.0	X	X		2	on-ramp
2	A4L	23.5	21.5	X	X	X	2	merging
3	A9R	59.8	60.5		X		2	merging
4	A9L	38.4	38.0	X		X	2	on-ramp
5	A12R	35.5	37.1	X			3	on-ramp
6	A12R	68.1	68.7		X		2	on-ramp
7	A15L	59.5	58.1		X	X	3	on-ramp
8	A15L	80.9	80.1	X	X	X	2	on-ramp
9	A20R	31.0	31.9	X	X		3	on-ramp
10	A20R	43.0	44.9	X		X	2	on-ramp
11	A20L	32.2	31.2	X	X	X	3	on-ramp
12	A27L	35.4	34.7	X	X	X	2	on-ramp
13	A50R	156.3	157.5	X	X		2	weaving
14	A50L	153.5	150.9	X	X	X	2	bridge

5.2.2 Find breakdown observations in the morning peak

In the previous step of the analysis bottleneck locations were identified and selected. In this phase of the analysis whole-year data at these bottleneck locations is analysed in order to categorise the data into different groups of observations (breakdown, uncongested and congested observations). This categorisation is needed for the capacity distribution function estimation (see 5.2.4). Also the choice is made to have five minute observation intervals in this section. Finally, the addition of precipitation data to the observation intervals is elaborated upon.

It is important that short observation intervals are used for the stochastic analysis. With large observation intervals there is only little causality between the traffic volume and the occurrence of breakdown. The observation intervals may however neither be too small in order to reduce the random fluctuations in the traffic flow. A good comprise is found to calculate the average speed over a five minute time period, in other words having five minute observation intervals (see Brilon et al., 2007). The one-minute average speeds observations are aggregated to five-minute observations. Observations outside the morning peak period are excluded from the analysis in this phase. Each of the five-minute traffic flow observations within the morning peak period (6-10am) is then placed into one of the following categories:

B: The traffic volume in this interval is viewed as a realization of the capacity due to the fact that observed flow in this interval is uncongested, but causes a breakdown in the following interval i + 1. An important threshold is the average speed during the observation interval. In this study it has been chosen that an average speed of 60 km/h is the threshold that separates observations into either congested (<60 km/h) or uncongested (>60 km/h) observations. The threshold speed can vary, but another threshold speed does not have a big influence in the range between 45 and 65km/h, as congestion has a tendency to break through these thresholds fairly quickly after the start of congestion (Calvert & Snelder, 2013). An extra requirement for this observation is that during the preceding 6 observations (30 minutes) the average speeds were higher than 60 km/h. This is added to ensure the uncongested flow before the occurrence of breakdown.

F: The traffic flow is uncongested (average speed > 60 km/h) in interval i and in interval i + 1. The information obtained from this observation is that the actual capacity in interval i is bigger than the volume q_i that is observed. In other words the capacity has not been reached during this observation. Data in this category is called censored data.

C: The traffic flow is congested in interval i and in interval i – 1, thus the average speed in both intervals is lower than the threshold value. Since the traffic volume in interval i – 1 is not congested (free flow), the observation does not provide information about the free flow capacity and is therefore excluded from the free flow capacity analysis. These congested intervals are however of use to estimate the congested capacity (see 5.2.4).

After the observations are grouped into the different categories, rain data is added to these observations. The rain data is collected from a data feed of the KNMI. The rain data feed provides data for a grid with the size of 1km by 1 km for the entire country on a one-minute basis. The rain detection and intensity estimation is performed via advanced satellite images and has realized excellent accuracy during the latest years. The one-minute rain intensity data are averaged to five-minute intervals and are mapped onto the road network with latitudinal and longitudinal coordinates (Calvert & Snelder, 2013).

This phase thus results in categorized five-minute observations to which the rain intensity of that specific moment and location is added. These categorized observations are the input for the capacity distribution function estimations, which is explained in section 5.2.4.

5.2.3 Filter observations

A database is set up in order to be able to filter observations and thereby increasing the resemblance between the results of the capacity analysis and the results of the stated adaptation experiment.

The database contains information of all days from 1 January 2007 till 31 December 2012 (anticipating on possible analysis of the years 2010-2012 in the future). Weather information was obtained from the database of the KNMI (KNMI, 2013). The weather information is based on the observations at the weather station in De Bilt. The following fourteen factors were included into the database:

- **Year**, **month** and **day**
- **Day of week**; from Monday (=1) to Sunday (=7) in order to separate working days from weekend days.
- **Season**; from spring (=1) to winter (=4). The meteorological dates are used for the beginning of a new season. Based on these dates spring starts for example on March 1st.

- **Total amount of rain** during that day (mm)
- **Rain duration**; the amount of hours it has been raining during that day
- **Total amount of snow** during that day (mm); data regarding the snow is not included in the database. To come to figures regarding snow, the rain data was combined with the maximum temperature. When the maximum temperature during that day was lower than zero degrees Celsius, the rain was considered to be snow.
- **Snow duration**; the amount of hours it has been snowing during that day. When the maximum temperature during that day was lower than zero degrees Celsius, the rain duration was considered to be the snow duration.
- **Rain peak hour**; the hour (0-24) with the highest average intensity during that day.
- **Maximum temperature** (°C)
- **Minimum temperature** (°C)
- **Weather alarm**; whether or not a specific weather alarm was carried out. Including no weather alarm (=0), storms (=1), snow (=2), thunderstorms (=3), rain + thunderstorms + storms (=4) and icy roads (=5).
- **Vacation period**; whether or not a certain part of the Netherlands will have vacation based on the advised vacation dates from the Ministry of Education, Culture and Science (Schoolvakanties Nederland, 2013). The days were categorized as non-vacation period (=0), vacation period for some regions (=1) and vacation period for all regions (=2).

On top of this the observations could be filtered based on the rain intensity values during the five-minute observations. A lower bound and a higher bound of rain intensity (mm/hour) could be used for the filtering.

It has been chosen to filter days based on the day of week in order to exclude the weekend days from analysis, because the stated adaptation experiment is about travel behaviour on weekdays. Also the vacation period has been an important filtering criterion. Only non-vacation period days were included into the analysis with the aim of taking into account only normal workweeks, as it has been done in the stated adaptation experiment. Also the five-minute rain data observations were an important filtering factor, but more on the rain data filter is explained in paragraph 5.3.1.

5.2.4 Capacity distribution functions estimation

In this study capacity distribution functions are estimated for the freeflow capacity and the congested capacity. Both capacities are estimated via a different approach. For the estimation of the freeflow capacity the Product Limit Method (PLM) by Kaplan and Meier (1958) with adaptations as described in (Brilon et al., 2005) is used. The distribution function for congested capacity is estimated differently using a more simple empirical approach. Both estimation approaches are shortly elaborated upon in this section.

In the Brilon method, after the traffic observations are classified and the data is censored, the traffic observation intervals possess information regarding the average intensity and the average speed during that interval. As explained in paragraph 5.2.2, the traffic flow is below capacity when the average speed us higher than 60 km/h. An average speed that is lower than 60km/h means that traffic flow is congested. When the traffic flow is congested during a certain observation interval, the capacity must have been exceeded during the preceding B-interval. With the information regarding the average speed, average intensity and the category of each observation interval, it is possible to

estimate a distribution function for the freeflow capacity using the Product Limit Method (PLM) by Kaplan and Meier (1958). The Product Limit Method is based on statistics of lifetime analysis and was originally used to describe the probability of death at a certain age to produce a survival function, based on observations within a sample. Due to the limited duration of experiments regarding human lifetime, individuals in the sample are likely to stay alive during the experiment. It is therefore only possible to state that these lifetimes are longer than the length of the experiment and these observations are called censored data. The Brilon method uses PLM via the analogy that breakdown probability at a certain traffic volume resembles the probability of death at a certain age. The observations where the capacity has not been reached, which are the so called F-observations, resemble the persons in the sample that outlive the duration of the experiment. According to the analogy, B-observations (intervals leading to a breakdown) are observations of the occurrence of death. The probability of a breakdown at a certain traffic volume can then be estimated based on the breakdown observations (B) and the free flow observations (F).
This leads to a freeflow capacity distribution function at the bottleneck that is estimated as follows:

$$F_c(q) = 1 - \prod_{i:qi \leq q} \frac{k_i - d_i}{k_i}; i \in \{B\}$$

where:

$F_c(q)$	= capacity distribution function
q	= traffic volume (veh/h)
q_i	= traffic volume in interval i (veh/h)
k_i	= number of intervals with a traffic volume of q ≥ qi
d_i	= number of breakdowns at a volume of qi
{B}	= set of breakdown intervals (intervals with classification B)

The calculation is made for each breakdown interval observation. Each observed breakdown is normally used as one q_i-value, which leads to d_i always being equal to 1. The factor k_i is based on all observations (thus B- and F-observations) with a traffic volume (q) that is higher than the traffic volume at the breakdown observation (q_i). The points at the capacity distribution are thus B-observations, but to come to the probability of that certain point the F-observations are also included into the estimation.

A hypothetical example is now provided to clarify the estimation of the capacity distribution function. Let us assume that there are 700 observed B- and 300 observed F-intervals. At an observation of breakdown at a traffic volume of X vehicles per hour, there are 699 observed B-intervals that led to breakdown and 300 F-intervals that did not lead to a breakdown, which all had a traffic volume higher than X. Filling this into the capacity distribution function leads to:

$$F_c(X) = 1 - \left(\frac{999 - 1}{999}\right) \approx 0.001$$

In other words the probability of breakdown at an intensity of X vehicles per hour is 0.001. The probability of a situation with 998 observed intervals having a higher traffic volume would then be calculated as follows:

$$F_c(X) = (1 - \left(\frac{999-1}{999}\right)) + (1 - \left(\frac{998-1}{998}\right)) \approx 0.002$$

Combining and linking the probability values from each of the observed intensities then leads to the capacity distribution function. It has to be said that the capacity distribution function will only reach a value of 1 if the maximum observed volume is a B-value (i.e. a breakdown was following). When this is not the case, the distribution function terminates at a value which is lower than 1 resulting in an incomplete distribution function.

The distribution function for congested capacity is estimated differently using a more simple approach. For the congested capacity only C-intervals is taken into account, which are intervals with the traffic flow being congested in interval i and in interval i − 1. For every observed C-value, the average intensity at the post-bottleneck location is stored. This results in many post-bottleneck observations, which are ranked based on the intensity. The capacity distribution function is estimated with the following formula:

$$F_c(q_i) = \frac{N_c}{N} \; ; \; i \in \{C\}$$

where:

$F_c(q)$ = capacity distribution function
q_i = traffic volume in interval i (veh/h)
N_c = number of congested observations with traffic volume ≤ q_i
N = total number of congested observations
{C} = set of congested observations (intervals with classification C)

These intensities are plotted and have a probability value depending on the total number of observations. If there are 1000 post-bottleneck observations, the observation with the lowest intensity has a value on the probability distribution function of 0.001. Due to the large number of data points, an approximation of the capacity distribution function can be estimated. The distribution function has a similar shape as the freeflow capacity distribution function, indicating that some intensity values are more likely to occur than other intensity values.

5.3 Capacity analysis

In the previous paragraph the estimation method for the freeflow and congested capacity distribution function is explained. This paragraph focuses on the analysis of the capacity distribution function. First the choices for the different scenarios are clarified. After that the results in these different scenarios are presented. Then an effort is made to validate these results based on results from other studies. Finally conclusions are drawn regarding the influence of precipitation on highway capacity.

5.3.1 Scenarios included in the capacity analysis

In this section the choice for estimating capacity distribution functions for a dry scenario, a light rain scenario and a heavy rain scenario are clarified. Also an explanation is provided for not estimating capacity distribution functions for snowfall scenarios.

A first scenario that has been used to investigate the effect of precipitation on highway capacity is the reference case of dry weather. Only observation intervals without precipitation during that interval were considered in the analysis. For all of the 30 identified bottleneck situations at the 14 bottleneck locations, capacity distribution functions could be estimated.

Next to having a reference case, it was planned to include precipitation cases like the precipitation attributes that were used in the stated adaptation experiment (light rain, heavy rain, very heavy rain, light snow and heavy snow). During the normal highway morning peak in the workweeks there were not many rainfall breakdown observations. The number of observations that could be used for the estimation of freeflow capacity was in most bottleneck situations limited to 30. Having too few breakdown observations creates difficulties in estimating a reliable distribution function. The choice was made to have two categories to resemble the categories in the stated adaptation experiment (light rain and heavy rain). Having different categories makes it also possible to compare the difference of different precipitation intensities in reducing highway capacity, which is proven by many scholars (see paragraph 2.2). In the stated adaptation experiment pictures of rainfall were shown to the respondents. The picture of light rain corresponds to rain intensity between 0 and 2mm/hour. The heavy rainfall picture corresponds to a rain shower with an intensity of 2mm/minute, which is an extremely high intensity. To have sufficient breakdown observations in both categories, it was decided to categorize breakdown observations in the category light rain if the average rain intensity during that observation was lower than 1mm/hour. This provides a good resemblance with the light rainfall in the stated adaptation experiment. The category heavy rainfall was made from observations with an average rain intensity of at least 1mm/hour. The observations in this category could thus be based on rain intensities that are lower than the rain intensity of heavy rainfall in the stated adaptation experiment. Nevertheless this division of observations led to the possibility to estimate several probability functions for both the light and heavy rainfall categories. This resulted in eight breakdown probability functions in the light rain category and fourteen breakdown probability functions in the heavy rain category.

On top of the rain categories the aim was to also include capacity estimations based on snow intensities. The first hurdle towards capacity estimations with snow is that there is no bottleneck location specific data regarding the occurrence of snow. The radar that detects rain is not able to generate (reliable) snow intensity data. The KNMI does have the precipitation amount on an hourly basis and information whether snow was detected during that hour. This precipitation amount is based on the amount of millimetres water detected when the snow is melted. Conversion factors from detected water to snow range between 1:8 and 1:20. The data regarding the precipitation was looked up for four weather stations that are close to several of the bottleneck locations, being Rotterdam, De Bilt, Schiphol and Deelen. Upon closer inspection of the data there were only several days when snow was detected in the morning peak. In the year 2007 at Schiphol for example only one day with snow during the morning peak could be detected. Even if observations from the whole day where included instead of only the morning peak, the amount of useful days was still very low. None of these days with snow resulted in a detection of breakdown by the algorithm. This could be the result of different behaviour of the car drivers on the highway (like larger time headways or decreased speed) as a result of snowfall. In the end it was decided to exclude snowfall from the capacity analysis. In chapter 8 there is a reflection on what approach could be taken in further research to include snowfall in the capacity analysis.

5.3.2 Fitting distribution functions to the empirical results

Capacity distribution functions have been estimated for three different scenarios (see 5.3.1), namely dry weather, light rainfall and heavy rainfall. In this section a mathematical distribution function is fitted to the resulting data in order to come to a complete capacity distribution function. The choice is made to use the normal distribution as an approximation of the capacity distribution function.

The capacity distribution estimation does not lead to complete distribution functions for two reasons. First of all, the estimation results in a scatter plot of the observations that are included in the analysis. Secondly, the highest intensity values observed at some capacity distribution estimations are not followed by a breakdown, leading to an incomplete capacity distribution function. In this section a mathematical distribution function is fit to the data in order to come to a complete capacity distribution function. Two plausible function types, the normal and Weibull distribution (Brilon and Zurlinden, 2003), are plotted to the data and visually tested based on the fit to the data. For the normal distribution the mean is the median capacity value and the standard deviation is the difference in traffic flow at the 50% breakdown probability value and the traffic flow at the 15.9% breakdown probability. For the Weibull distribution, the shape and scale parameter are obtained by minimizing the root mean square deviation of the Weibull distribution with the data. The corresponding parameters for the highway A4R in 2008, together with the amount of observations, are presented in Table 20.

Table 20 - Parameters distribution functions A4R-2008

	Normal distribution			**Weibull distribution**			
	Mean (veh/h)	Standard deviation (veh/h)		Scale parameter (veh/h)	Shape parameter (-)		Number of observations (-)
Freeflow							
Dry	4426	346		4543	15.1		262
Light rain	4148	214		4328	15.1		9
Heavy rain	3949	205		4107	15.1		8
Congested							
Dry	3624	324		3706	15.1		9107
Light rain	3444	284		3540	14.5		348
Heavy rain	3372	264		3487	14.0		504

From Table 20, it follows that the number of freeflow observations in rain conditions is very low. The amount of observations that can be used differs significantly between the freeflow and congested distribution function. An observation for freeflow conditions corresponds to the occurrence of one breakdown. For congested conditions multiple observations can be obtained from one breakdown. Each interval in which the bottleneck is in congested condition can be used. A traffic jam that is present for one hour provides twelve data points for congested conditions and only one data point for freeflow conditions. As a result it can be observed that in the rain scenarios there are not many data points for the freeflow capacity distribution function. In total seventeen observations during rainfall led to a breakdown. The resulting distributions are plotted to the dry, light rainfall and heavy rainfall scenario at the highway A4R in 2008. The blue lines in the figures are the distribution functions. The results can be seen in Figure 13 to Figure 18.

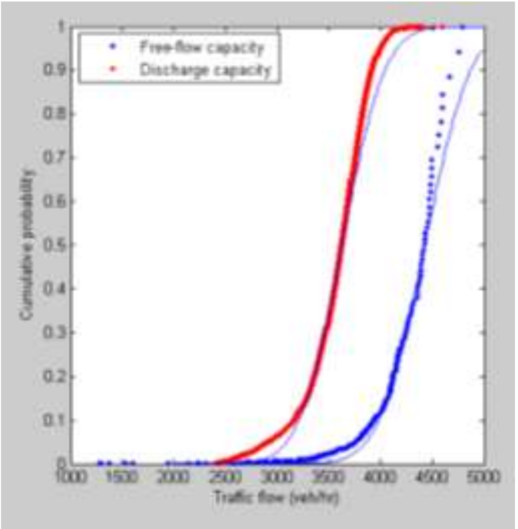

Figure 13 - A4R-2008 dry normal distribution

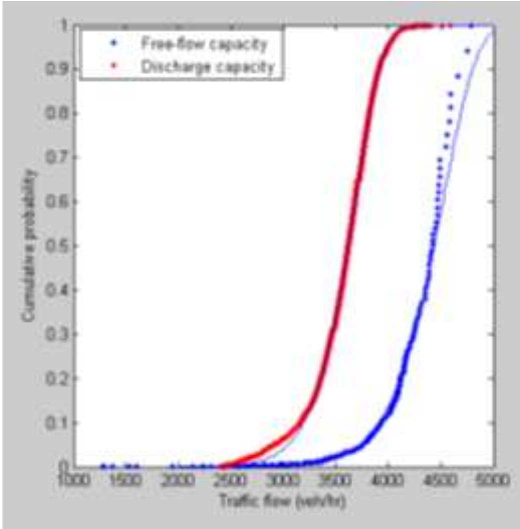

Figure 14 - A4R-2008 dry Weibull distribution

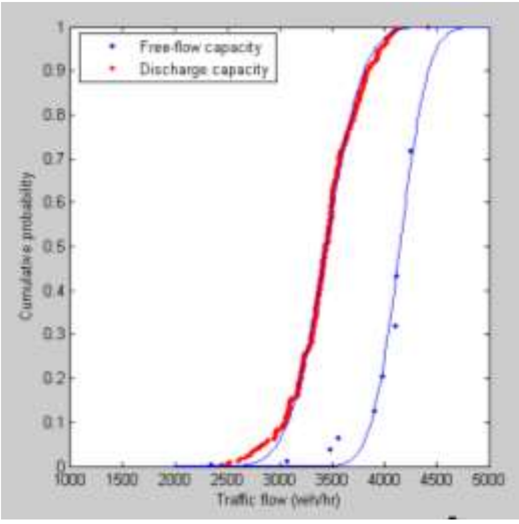

Figure 15 - A4R-2008 light rain normal distribution

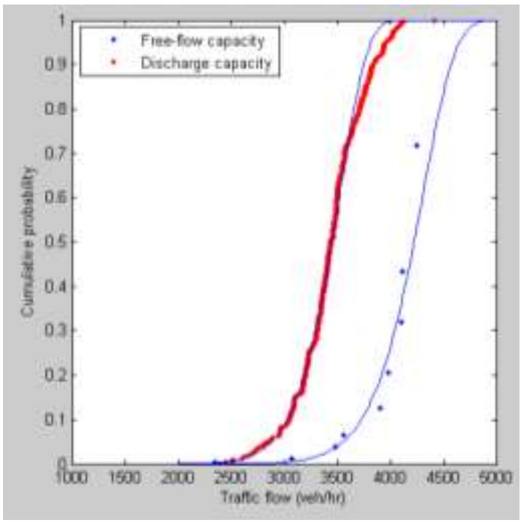

Figure 16 - A4R-2008 light rain Weibull distribution

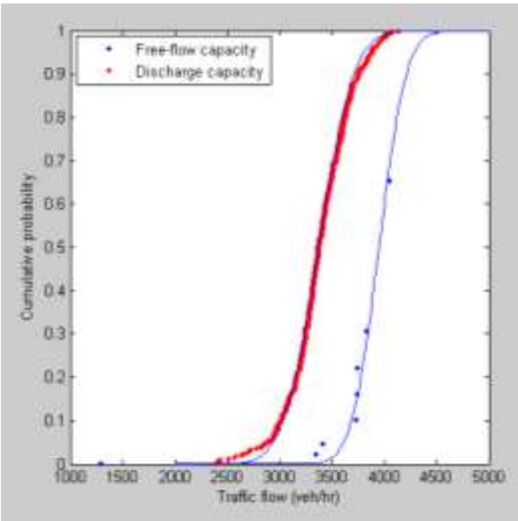

Figure 17 - A4R-2008 heavy rain normal distribution

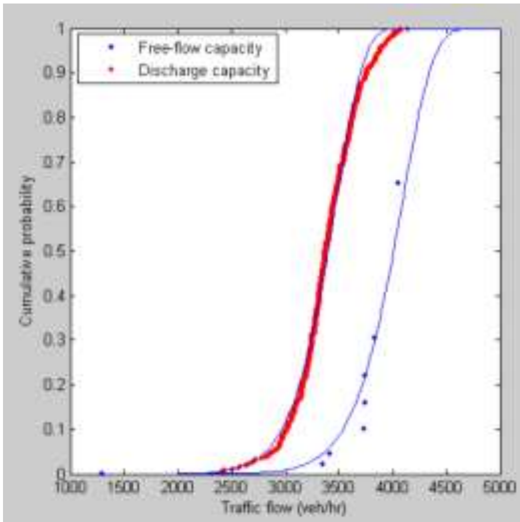

Figure 18 - A4R-2008 heavy rain Weibull distribution

When the normal and Weibull distributions are compared to each other, it can be concluded that both distributions fit fairly well to the data. This increases confidence into the validity of the result even with the limited observations. In the dry scenario the Weibull distribution fits better to the congested capacity values than the normal distribution. Both distributions however seem to overestimate the traffic flow above a breakdown probability of 0.6. In the light rain scenario the normal distribution fits perfectly for breakdown probabilities higher than 0.1, whereas the Weibull distribution fits better below 0.1, but worse above 0.1 breakdown probability. The same applies to the heavy rain scenario, where the normal distribution fits better to the data in comparison to the Weibull distribution at breakdown probability higher than 0.1.

The most important conclusion that can be drawn from the visualisations is that one distribution function is not significantly better than the other distribution function in all situations. Both the normal and Weibull distribution fit fairly well to the data. Based on an earlier assumption of the capacity function being normally distributed, it is chosen to use the normal distribution as an approximation of the capacity distribution function in the remainder of this study.

5.3.3 Results

This paragraph focuses on the results and compares the capacity in the different weather scenarios. The capacity reduction as a result of precipitation is presented in this section. The freeflow capacity values that are presented are later used in chapter 6 to estimate the probability of breakdown in certain weather conditions. The congested capacity values are only used in the intermezzo to present findings about the capacity drop phenomenon. A comparison of the results of the capacity reducing effect of rain with other studies leads to the conclusion that most other researchers have found capacity reductions that are within the same range as in this study.

The results of the capacity reduction are based on the median values of the distribution functions. The median value can be interpreted as the intensity value at which the probability of breakdown is 0.5. Since it is the median value in a cumulative probability function with a normal shape, it is also the traffic intensity value with the highest probability to occur.

Some distribution functions did not have a freeflow data point higher than 0.5, which led to the need for extrapolating. Since extrapolating leads to more uncertainty regarding the accuracy of the median, these distribution functions have been excluded from analysis. Also distribution functions based on too few data points were excluded from the analysis. Decisions regarding exclusion of capacity distribution functions were made in collaboration with an expert in the field of highway capacity distribution functions. After filtering of the results there were thirty capacity estimations for the dry scenario, eight for the light rain scenario and fourteen for the heavy rain scenario. For the dry scenario the traffic volume of the median value is presented for both freeflow and congested conditions. For the rain scenarios the values are presented as reduction of the capacity at the median in comparison to the dry situation.

To take into account the spread of the different capacity distribution functions, for each distribution function the standard deviation is computed. De standard deviation values are obtained for all the different freeflow distribution functions by looking at the corresponding traffic flow value on the capacity distribution function where the probability on breakdown is 15.9% (=median-1 standard deviation). By comparing the traffic flow values at the median value and at the 15.9% probability value the relative decrease in traffic flow can be calculated. The average change in traffic flow for one standard deviation is 8.6% in the dry weather scenario, 7.0% in de light rain scenario and 7.4% in the heavy rain scenario. These figures are later used in chapter 6 for estimating a generic capacity distribution function. The results are presented in Table 21.

Table 21 - Comparison of the median capacity values in the different scenarios

			Dry		**Light rain**		**Heavy rain**	
highway	location pre (hm)	location post (hm)	Median freeflow	Median congested	Freeflow difference (%)	Congested difference (%)	Freeflow difference (%)	Congested difference (%)
A4R-2007	30.0	31.0	4452	3612	-4.2%	-6.6%	-10.3%	-5.3%
A4R-2008	30.0	31.0	4426	3624	-6.3%	-5.0%	-10.8%	-7.0%
A4L-2007	23.5	21.5	4368	3816	-3.9%	-4.1%		
A4L-2008	23.5	21.5	4333	3852				
A4L-2009	23.5	21.5	4320	3912				
A9R-2008	59.8	60.5	4792	3960				
A9L-2008	38.4	38.0	4944	3984				
A9L-2009	38.4	38.0	4855	4056				
A12R-2007	35.5	37.1	7173	5628			-7.3%	-5.1%
A12R-2008	68.1	68.7	4690	3864	-4.1%	-6.2%		
A15L1-2008	59.5	58.1	7267	6240	-4.4%	-6.9%		
A15L1-2009	59.5	58.1	7359	6360				
A15L2-2007	80.9	80.1	4351	3768			-9.5%	-8.3%
A15L2-2008	80.9	80.1	4117	3792			-9.9%	-8.5%
A15L2-2009	80.9	80.1	4184	3768				
A20R1-2007	31.0	31.9	6072	5460	-5.8%	-3.7%		
A20R1-2008	31.0	31.9	5939	5484			-7.5%	-7.7%
A20R2-2009	43.0	44.9	4205	3432			-11.0%	-4.2%
A20L-2007	32.2	31.2	6060	5268			-3.8%	-6.2%
A20L-2008	32.2	31.2	6064	5292			-3.7%	-6.3%
A20L-2009	32.2	31.2	6121	5388			-6.0%	-5.8%
A27L-2007	35.4	34.7	3938	3624			-6.1%	-5.0%
A27L-2008	35.4	34.7	3931	3624	-7.7%	-5.0%		
A27L-2009	35.4	34.7	3996	3624				
A50R-2007	156.3	157.5	4224	3516			-11.1%	-6.1%
A50R-2008	156.3	157.5	4236	3456				
A50L-2007	153.5	150.9	4181	3732	-8.9%	-7.1%	-8.1%	-9.0%
A50L-2008	153.5	150.9	4177	3696				
A50L-2009	153.5	150.9	4108	3744				
Average					-5.7%		-8.1%	
Average change in traffic flow for one standard deviation			8.6%		7.0%		7.4%	

When looking at the median values of the capacity distribution functions without precipitation, it follows that the distribution functions that have been estimated for the same bottlenecks during different year have almost the same median values. For example when comparing the median values of the bottleneck at highway A4R for the year 2007 and 2008 results in freeflow values of 4452 and

4426, when the congested values are 3612 and 3624. The bottleneck at highway A27L has similar median congested values for three years in a row. These observations lead to an increase in confidence regarding the accuracy of the distribution functions.

Regarding the light rain results it can be seen that the average capacity reductions are similar for freeflow and congested capacity, but when looking at each situation separately there is a difference between the two reduction percentages. In some cases the freeflow capacity is reduced more than the congested capacity, but in other cases it is the other way around. Nevertheless the difference between the freeflow and congested capacity is at most 2.5 percentage points (-7.7% vs. -5.0%). Due to the limited amount of cases it is not possible to compare the results at the same location for different years. The reduction percentages for the different bottleneck locations however vary significantly. For freeflow capacity the reduction percentages vary from -3.9 to -8.9. The reducing effect of light rain on highway capacity is thus considered to be significant.

When looking at the heavy rain results, it can be seen that heavy rainfall leads on average to a higher capacity reduction than light rainfall for both freeflow and congested capacity, which is in line with the expectations. The average differences in reduction are however not very high between light and heavy rain (5.7% vs. 8.1% and 5.6% vs. 6.5%) when considering that light rain only includes observations with rain intensities less than 1mm/hour and heavy rain includes all observations higher than 1mm/hour. The difference in capacity between dry conditions and light rain are relatively big compared to the difference in capacity between light rain en heavy rain. This could indicate that the effect of rain on capacity is similar to the effect as described by Ries (1981), who concluded that the slightest amount of rain would result in an 8% reduction in capacity and every increase of 1mm/hour leads to an extra reduction of 0.2% in capacity.

Some of the heavy rain results are from the same bottleneck locations during different years. This makes comparison of the results for the same bottleneck locations possible. In Table 22 the three highways with heavy rain observations for different years are presented.

Table 22 - Comparing capacity reduction for multiple years at the same bottleneck

highway	Freeflow difference (%)	Congested difference (%)
A4R-2007	-10.3%	-5.3%
A4R-2008	-10.8%	-7.0%
A15L2-2007	-9.5%	-8.3%
A15L2-2008	-9.9%	-8.5%
A20L-2007	-3.8%	-6.2%
A20L-2008	-3.7%	-6.3%
A20L-2009	-6.0%	-5.8%

Observing the capacity reductions leads to the conclusion that the capacity reduction at one bottleneck location is very robust and does not change a lot over the years. The only outlier is the freeflow capacity at highway A20L in the year 2009, which is more than 2 percentage points higher than the other observations. Taking into account the small difference between observations at the same location and the large difference in capacity reduction between observations from different locations, it can be concluded that the huge difference between observations at different locations (between -3.7% and 11.1%) is related to the different characteristic at the different locations. This could be the result of differences in precipitation intensities during a year at the different locations, but a more plausible conclusion is that the different highway characteristics lead to the effect of heavy rainfall on highway capacity being different at those locations. The road surface at the different locations might be important factors in the reduction of highway capacity. It could be the case that the capacity reduction is smaller on highway sections with porous asphalt (in Dutch: Zeer Open AsfaltBeton). The different capacity reducing effects of rainfall at different locations is in accordance with the study of Cools et al. (2007), which concluded the existence of heterogeneity in the effect of rain on different traffic count locations and the homogeneity of the rain effects on the upstream and downstream side of a certain location.

The results can be validated by comparing them with results from other studies. A sample of the studies conducted to the effect of rain on highway capacity is provided in Table 23.

Table 23 - Overview of selected literature on capacity reduction due to rain

Publication	Country	Rain intensity (mm/hr)	Capacity reduction
Maze et al. (2005)	USA	0-2.5 2.5-6 >6	2% 7% 14%
Agarwal et al. (2006)	USA	0.25-6 >6	5-10% 10-17%
Ries (1981)	USA	>0.1	8% +(0.2% per mm/hour) capacity reduction
Okamoto et al (2004)	Japan	0.1-1.2 1.3-2.4 2.5-4.8 5-10	5-11% 14% 25% 33%
Chung et al. (2006)	Japan	1-3 3-5 5-10 10-20	4-9% 5-11% 8-12% 9-14%

Comparing the results obtained in the analysis with findings from other studies, leads to the conclusion that most other researchers have found capacity reductions that are within the same range as in this study. The only outlier is the study from Okamoto et al. (2004), which reported capacity reductions up to 33%. The results from the other studies used as ballpark figures, leads to an increase in confidence concerning the results in this study.

Intermezzo - The capacity drop at the investigated bottleneck locations

By estimating both the freeflow and congested capacity distribution function the capacity drop phenomenon can be quantified in this study. The capacity drop shows the existence of different capacities under freeflow and congested conditions. Some hypotheses for the existence of the capacity drop phenomenon were provided by (Brilon et al., 2005):

- Driver behaviour: in fluent traffic conditions drivers will accept shorter time headways since it is expected that they can pass the vehicles in front. In congested conditions drivers will switch to a more safety-conscious driving style and will keep longer time headways.
- Differences in vehicle population: when leaving the congested area drivers need to accelerate. Some vehicles have limited acceleration power which leads to a bigger headway in front of the drivers.

Many researchers have made an attempt to identify capacity drop causes by investigating the microscopic traffic flow behaviour. Conclusions from these studies are that lane-changing

manoeuvres, heterogeneous lane behaviour and vehicles that enter a merging section with low speed are considered to enlarge the capacity drop phenomenon (Srivastave & Geroliminis, 2013).
The capacity drop is also related to the hysteresis phenomenon. Hysteresis means that the deceleration pattern for approaching and acceleration pattern for leaving the congestion are different. Generally, when a driver moves into a region with increasing densities the speed is higher than the equilibrium speed. On the other hand when a driver moves into a region with decreasing densities the speed will be lower than the equilibrium speed (Hoogendoorn, 2007). On top of that microscopic traffic flow behaviour plays an important role and thus the capacity drop is dependent of the location and situation. In the study of Chung et al. (2007) this can be seen through the capacity drop that fluctuates at the same location and is different for other locations. At a bottleneck location with five lanes a capacity drop was found between 5% and 18%, where a 3 lane bottleneck led to a drop of 3% to 12% and a two lane location resulted in 5.1% to 8.5% drop in capacity. The results of the capacity drop in this study are based on the differences in the median values for the freeflow and the congested capacity distribution function for the same scenario. The results for each analysed bottleneck location and can be found in Table 24.

Table 24 - Capacity drop at the investigated bottleneck

Highway	location pre bottleneck (hm)	location post bottleneck (hm)	Dry	Light rain	Heavy rain
A4R-2007	30.0	31.0	-18.9%	-20.9%	-14.4%
A4R-2008	30.0	31.0	-18.1%	-17.0%	-14.6%
A4L-2007	23.5	21.5	-12.6%	-12.8%	
A4L-2008	23.5	21.5	-11.1%		
A4L-2009	23.5	21.5	-9.4%		
A9R-2008	59.8	60.5	-17.4%		
A9L-2008	38.4	38.0	-19.4%		
A9L-2009	38.4	38.0	-16.5%		
A12R-2007	35.5	37.1	-21.5%		-19.7%
A12R-2008	68.1	68.7	-17.6%	-19.4%	
A15L1-2008	59.5	58.1	-14.1%	-16.4%	
A15L1-2009	59.5	58.1	-13.6%		
A15L2-2007	80.9	80.1	-13.4%		-12.2%
A15L2-2008	80.9	80.1	-7.9%		-6.5%
A15L2-2009	80.9	80.1	-9.9%		
A20R1-2007	31.0	31.9	-10.1%	-8.1%	
A20R1-2008	31.0	31.9	-7.7%		-7.8%
A20R2-2009	43.0	44.9	-18.4%		-12.2%
A20L-2007	32.2	31.2	-13.1%	-11.0%	-15.2%
A20L-2008	32.2	31.2	-12.7%	-8.4%	-15.1%
A20L-2009	32.2	31.2	-12.0%	-7.9%	-11.8%
A27-2007	35.4	34.7	-8.0%		-6.9%
A27-2008	35.4	34.7	-7.8%	-5.0%	
A27-2009	35.4	34.7	-9.3%		
A50R-2007	156.3	157.5	-16.8%		-12.1%
A50R-2008	156.3	157.5	-18.4%		
A50L-2007	153.5	150.9	-10.7%	-8.9%	-11.6%

A50L-2008	153.5	150.9	-11.5%		
A50L-2009	153.5	150.9	-8.9%		
		Average	-13.3%	-12.3%	-12.3%
		Standard deviation	4.1%	5.3%	3.7%

From Table 24 it can be seen that there are considerable differences in effects between bottleneck locations and situation. If the phenomenon at the same location and in the same scenario is compared for different years, it follows that the effect is relatively stable over the years. An example is the bottleneck A4R where in dry conditions the capacity drop is 18.9% and 18.1% for 2007 and 2008. Even within the same bottleneck and situation there can however still be some fluctuations with the example of bottleneck A4R in light rain conditions (20.9% in 2007 vs. 17.0% in 2008). This is in accordance with findings of Chung et al. (2007) that capacity drop fluctuates at the same location. The range between the minimum capacity drop (5.0%) and the maximum capacity drop (21.5%) is rather big. For validation these results are compared to results in other studies. Srivastava and Geroliminis (2013) found a capacity drop between 10% and 20% at the Trunk Highway 169 in the United States. Chung et al. (2007) found capacity drop values between 3% and 18%. Brilon and Zurlinden (2003) indicated that the capacity drop could be even higher with an average capacity reduction of 24% on the German highways, which is very high compared to other researchers' results. In comparison with these different studies the confidence in the validity of the result is increased. The main conclusion that can be drawn regarding the capacity drop phenomenon is that still a lot is unknown about the causes and the relation to the magnitude of the effect. The results from this analysis also show that the effect differs per bottleneck and situation, but also between different years as at the same location in the same situation considerable differences can be observed.

5.3.4 Conclusions

In this paragraph the answers to the research questions are provided regarding the influence of precipitation on highway capacity. First the sub sub research questions are answered, after which the answer to the sub research question is elaborated upon.

What are requirements for a bottleneck location to be suitable for capacity analysis?

The estimation method relies on the occurrence of breakdowns and many breakdowns have to occur in order to be able to estimate a reliable capacity distribution function. Bottlenecks can occur at random locations due to an incident or a disruptive manoeuvre of a driver that influences the traffic flow. The most common breakdowns are, however, the result of static bottlenecks, which are bottleneck locations that are the consequence of infrastructural lack of capacity at a certain location. The location of static bottlenecks is therefore often precisely known. Breakdowns as a result of static bottlenecks occur frequently during the traffic peak periods. Having many breakdown observations and confidence in the detected location being a bottleneck allows for accurate estimation of capacity at static bottleneck locations. Therefore it has been chosen to focus on static bottleneck locations in this research.

There are three criteria for static bottleneck locations to become suitable for analysis. Firstly the induction loops at and around the bottleneck locations should work properly. Secondly the bottleneck location should be independent from a bottleneck downstream. Thirdly the bottleneck may not consist of a variable amount of lanes over the day (for example, peak hour lanes). In total fourteen bottleneck locations were considered suitable for the capacity analysis, which are shown in Table 25.

Table 25 - Dutch highway sections that are suitable for capacity analysis

ID	Highway	Location pre bottleneck (hm)	Location post Bottleneck (hm)
1	A4R	30.0	31.0
2	A4L	23.5	21.5
3	A9R	59.8	60.5
4	A9L	38.4	38.0
5	A12R	35.5	37.1
6	A12R	68.1	68.7
7	A15L	59.5	58.1
8	A15L	80.9	80.1
9	A20R	31.0	31.9
10	A20R	43.0	44.9
11	A20L	32.2	31.2
12	A27L	35.4	34.7
13	A50R	156.3	157.5
14	A50L	153.5	150.9

Which capacity estimation approach is most suitable for analysing the effect of precipitation on highway capacity?

There are several approaches to arrive at a function describing the probability of breakdown. Some examples are the Brilon method (2005), the method described by Minderhoud et al. (1997) and the method by van Toorenburg (1986). Brilon et al. (2005) have implemented a methodology for the derivation of capacity distribution functions for highways, based on the proposed practical capacity estimation method by van Toorenburg (1986). An important difference between the Brilon method and the methods of van Toorenburg (1986) and Minderhoud (1997) is the definition of breakdown capacity. According to the former authors breakdown capacity is the traffic volume measured downstream of a queue at a bottleneck. The Brilon method takes into account that the capacity in fluent traffic flows differs from the capacity in congested conditions. This deals with the phenomenon of the capacity-drop, which is investigated by many authors (e.g. Hall & Agyemang-Duah, 1991, Zurlinden, 2003; Regler, 2004; Chung et al., 2007). The studies that measure the capacity downstream of a queue at a bottleneck (post-bottleneck) do not take the capacity drop into account. The capacity drop, however, can have significant magnitude. Chung et al. (2007), for example, show that the magnitude of the capacity drop is location specific, but even at a certain location the capacity drop fluctuates. This study found a capacity drop between 3% and 18% in maximum traffic flow rates after the congestion compared to pre-congestion flow rates. It is chosen to use the Brilon method in this research for estimation of freeflow capacity, because this method is based on proven theory and has, in contrast to the Minderhoud and van Toorenburg method, a clear and easy applicable definition of the free flow capacity. Along with the estimation of a capacity distribution function at free flow, the congested capacity is also estimated at a post-bottleneck location. For the estimation of the capacity distribution function for congested conditions a basic empirical function is used.

Which distribution function fits best with the empirical results of the capacity estimation?

The capacity distribution estimation does not lead to complete distribution functions as a consequence of the estimation resulting in a scatter plot of the observations that are included in the analysis. In addition, the highest intensity values observed at some capacity distribution estimations are not followed by a breakdown. Two plausible mathematical distribution function types, the normal and Weibull distribution, were fitted to the data to arrive at a complete capacity distribution function. Despite the low number of freeflow observations in rain conditions, both the normal and Weibull distributions fit well with the data. This increases confidence in the validity of the result even with the limited observations. In the dry scenario the Weibull distribution fits better with the congested capacity values than the normal distribution. Both distributions, however, seem to overestimate the traffic flow above a breakdown probability of 0.6. In the light rain scenario the normal distribution fits perfectly for breakdown probabilities higher than 0.1, whereas the Weibull distribution fits better below 0.1, but worse above 0.1 breakdown probability. The same applies to the heavy rain scenario, where the normal distribution fits better to the data in comparison to the Weibull distribution at breakdown probability higher than 0.1. The most important conclusion that can be drawn from the visualisations is that one distribution function is not significantly better than the other distribution function in all situations. Based on an earlier assumption of the capacity function being normally distributed, it is chosen to use the normal distribution as an approximation of the capacity distribution function in this study.

What is the effect of precipitation on highway capacity?

Light rainfall results in an average capacity reduction of 5.7% as compared to dry weather. There is a significant difference in the capacity reduction if the results from different bottleneck locations are analysed, with the capacity reductions ranging from 3.9% to 8.9%. It is interesting to note that heavy rainfall leads on average to a higher capacity reduction than light rainfall for freeflow capacity, which is in accordance with the expectations. There is a significant difference, but the average difference in reduction is not extremely high between light and heavy rain (5.7% vs. 8.1%) when considering that light rain only includes observations with rain intensities less than 1mm/hour and heavy rain includes all observations higher than 1mm/hour. The difference in capacity between dry conditions and light rain is relatively large compared to the difference in capacity between light rain and heavy rain.

Observations of the capacity reductions for the same scenario at the same location lead to the conclusion that the capacity reduction at one bottleneck location is very robust and does not change a lot over the years. The only outlier is the freeflow capacity at highway A20L in the year 2009, which is more than 2 percentage points higher than the other observations. Taking into account the small difference between observations at the same location, it can be concluded that the huge difference between observations at different locations (between -3.7% and 11.1%) is related to the different characteristics at the different locations. This could be the result of differences in precipitation intensities during a year at the different locations, but a more plausible conclusion is that the different highway characteristics lead to the effect of heavy rainfall on highway capacity being different at those locations. The road surface at the different locations might be important factors in the reduction of highway capacity. It could be the case that the capacity reduction is smaller on highway sections with porous asphalt. This is in accordance with the study of Cools et al. (2007) to the effect of rain on different locations, which concluded the existence of heterogeneity in the effect of rain on different traffic count locations and the homogeneity of the rain effects on the upstream and downstream side of a certain location. Comparing the results obtained in the analysis with findings from other studies leads to the conclusion that most other researchers have found capacity reductions that are within the same range as in this study, which leads to an increase in confidence concerning the results of this study.

Conclusions regarding the effect of precipitation on highway capacity should not be based on the average reduction in capacity, since there is a high variety in capacity reductions at different locations for both the light rain and heavy rain scenario. In chapter 6, a generic approach is introduced that can provide information regarding each of the analysed Dutch highways and also includes the highway traffic demand change as a result of the weather.

6. Combined effect of changes in travel behaviour and highway capacity as a result of weather conditions on highway breakdown probability

In this chapter the findings from the travel behaviour analysis and the results for the capacity analysis are combined in order to gain insights into the effect of weather conditions on the occurrence of breakdowns at Dutch highways. In section 6.1 a highway specific approach to the breakdown probability in different weather scenarios is presented. After that a generic approach to breakdown probability is developed in section 6.2. Conclusions regarding the effect of weather conditions on the probability of breakdown are presented in section 6.3.

6.1 A highway specific approach to breakdown probability

In this section the approach to investigate the influence of the weather on the probability of breakdown is explained. The highway capacity changes and the highway traffic demand changes are both taken into account in this approach to come to a breakdown probability at the Dutch highways. An example is provided to clarify the highway specific approach to breakdown probability.

Elements that are needed to examine the influence of the weather are the capacity distribution function for dry weather, the capacity distribution function for the rain scenario (here light rain), and the highway traffic demand change as a result of the weather which is +2.3%. The starting situation is a certain traffic flow in dry conditions, leading to a probability of breakdown from the capacity distribution function of dry weather. The first step is to project the same traffic flow on the capacity distribution function of light rain to account for the limited capacity in light rain conditions. This leads to a higher probability of breakdown compared to the dry weather scenario. The second step is to account for the demand change as a result of the weather. This results in a different traffic flow value, which leads to another probability of breakdown. With these two steps the probability of breakdown in the dry situation is converted into a probability of breakdown in the light rain scenario. This approach is clarified by using the capacity distribution functions of the dry and light rain scenario of the bottleneck location at highway A4R in 2007 in an example:

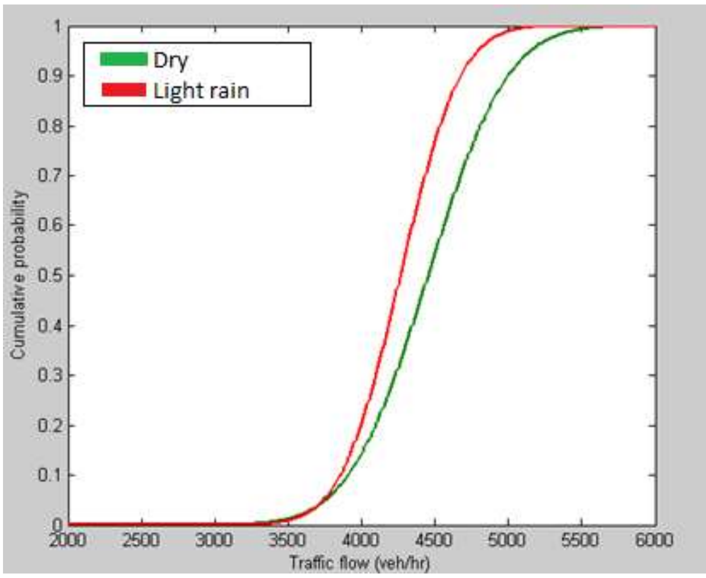

Figure 19 - Capacity distribution functions dry weather and light rain for highway A4R in 2007

In this example, the starting situation is a certain random chosen traffic flow of 4200 veh/h in dry conditions, leading to a probability of breakdown of 27.9% from the capacity distribution function of dry weather. The first step towards investigating the effect of light rain is to find the probability of breakdown on the capacity distribution function of light rain with the same traffic flow of 4200 veh/h. The probability of breakdown becomes 42.9%. The second step is to incorporate the demand change, which is +2.3% in the light rain scenario. A traffic flow value of 4297 (4200*1.023) veh/h thus has to be used on the capacity distribution function of light rain to come the combined effect of changes in traffic demand and capacity as a result of the light rain, which leads in this case to a breakdown probability of 53.9%. Comparison of the probability with the initial probability of breakdown in dry conditions of 27.9% leads to the conclusion that the probability of breakdown increases drastically with 26.0 percentage points as a result of light rain.

6.2 A generic approach to breakdown probability

While the approach as explained in the previous section is a suitable approach, the used capacity distribution is specific for the bottleneck at highway A4L and the calculation is on the basis of a specific traffic flow in dry conditions. It would add value to the results if a generic model that could provide information regarding all Dutch highways can be made. This can be done with a 3D-function that incorporates the traffic demand and the capacity and results in a probability of breakdown, which is explained in this section.

In the generic 3D-function, the variable demand is on the x-axis and the variable median capacity is on the Y-axis. The Z-axis is then the probability of breakdown. Seven lines are drawn in the 3D-plot, which are connected to each other to come to a function. The starting point is drawing the first line in the plot, which is the median line with a Z-value of 50%. At the median value of a capacity distribution function is the value where the traffic flow meets the capacity. At this line the Y-values of the median capacity are thus the same as the X-values of the traffic flow at the median capacity. For example the X and Y-coordinates of the median capacity of 4000 veh/h and the traffic demand of 4000 veh/h leads to the Z-value of 50%.

The other six lines in the 3D-plot are based on the standard deviation of the capacity distribution functions. De standard deviation values are obtained for all the different distribution functions by looking at the corresponding traffic flow value on the capacity distribution function where the probability on breakdown is 15.9% (=median-1 standard deviation). By comparing the traffic flow values at the median value and at the 15.9% probability value the relative decrease in traffic flow can be calculated. An example is a traffic flow of 4400 veh/h that corresponds to 50% probability of breakdown and 4092 veh/h that corresponds to 15.9% probability of breakdown. This means that in this specific example one standard deviation relates to 7% difference (=1 – (4092/4400)) in traffic flow. The difference in traffic flow relating to one standard deviation is computed for all bottleneck situations and scenarios, and the average of these values is taken. This results in corresponding traffic flow changes at one standard deviation of 8.6% for dry weather, 7.0% for light rainfall and 7.4% for heavy rainfall. Due to the different standard deviations for the different rain scenarios, one function and plot has to be made for each of the scenarios. This explanation focuses on the dry weather scenario. When the corresponding traffic flow change that leads to a probability of breakdown at a distance of 1 standard deviation is known, all six lines can be made based on these figures. The probability of breakdown for these six lines is fixed based on the standard deviation from the median, being 34.1% at one standard deviation, 47.7% at two standard deviations and 49.8% at three standard deviations. This results in the Z-values of 0.2%, 2.3%, 15.9%, 50%, 84.1%, 97.7% and 99.8%. The traffic flow change relating to one standard deviation is 8.6%, which should be interpreted as follows: If the traffic flow is 8.6% lower than the median capacity value, the probability of breakdown drops from 50% (median) to 15.9% (median – 1 standard deviation). Based on this a function can be made for the corresponding values of the capacity and demand at these Z-values. The information regarding the seven functions for all scenarios, with x being the median capacity and y the traffic flow, is presented in Table 26.

Table 26 - Generic capacity distribution function values

	Z-value	Functions dry scenario	Functions light rain scenario	Functions heavy rain scenario
Median	50%	x = y	x = y	x = y
Median – 1 STDEV	15.9%	x = y*(1 – 1*0.086)	x = y*(1 – 1*0.070)	x = y*(1 – 1*0.074)
Median – 2 STDEV	2.3%	x = y*(1 – 2*0.086)	x = y*(1 – 2*0.070)	x = y*(1 – 2*0.074)
Median – 3 STDEV	0.2%	x = y*(1 – 3*0.086)	x = y*(1 – 3*0.070)	x = y*(1 – 3*0.074)
Median + 1 STDEV	84.1%	x = y* (1 + 1*0.086)	x = y*(1 + 1*0.070)	x = y*(1 + 1*0.074)
Median + 2 STDEV	97.7%	x = y* (1 + 2*0.086)	x = y*(1 + 2*0.070)	x = y*(1 + 2*0.074)
Median + 3 STDEV	99.8%	x = y* (1 + 3*0.086)	x = y*(1 + 3*0.070)	x = y*(1 + 3*0.074)

There are seven functions in the 3D-plot at this moment. This gives the opportunity to match the median capacity to a corresponding traffic flow based on a known probability of breakdown. The aim is however to come to a function in which the probability of breakdown at a certain traffic flow is the result of a known median capacity and a traffic flow value. The 3D-plot is complete for a probability of breakdown between 0.2% and 99.8%. Values outside this range would occur in very little occasions, but to be able to deal with percentages below 0.2% and above 99.8% the values at 0.2% and 99.8% are taken. With the function and 3D-plot the probability of breakdown of any Dutch highway can be calculated if the median capacity of the highway is known for any traffic flow. The intersection with the surface at a certain traffic demand and median capacity values is the probability of breakdown. The functions for the dry scenario, light rain scenario and heavy rain scenario are present and the corresponding grid plots are as follows:

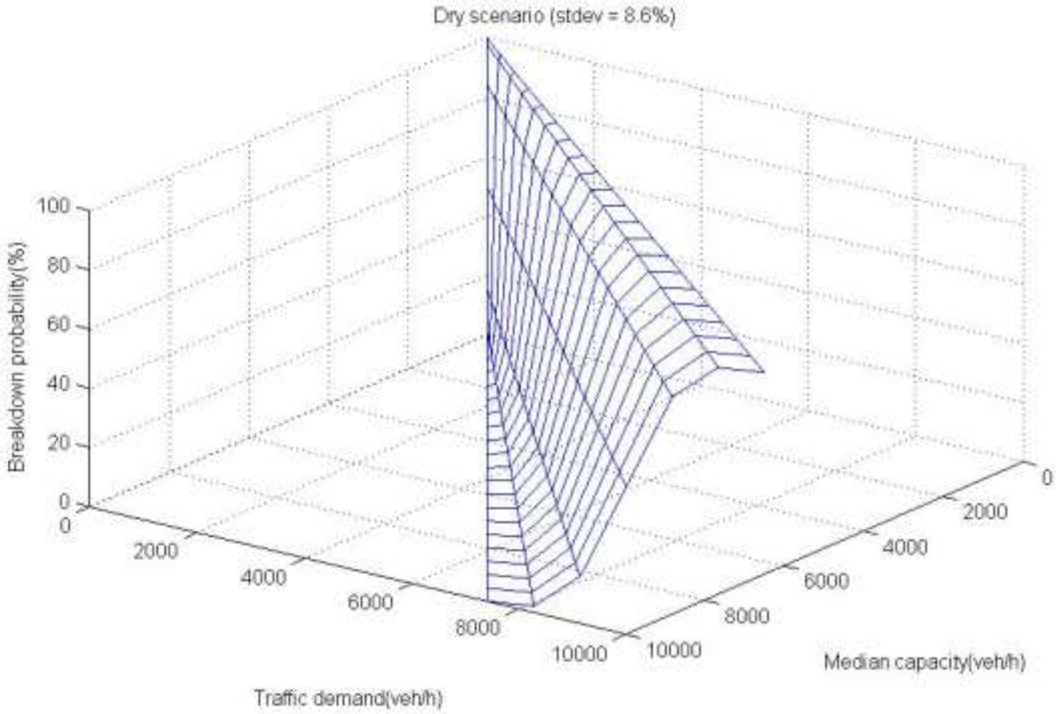

Figure 20 - Breakdown probability dry scenario in 3D

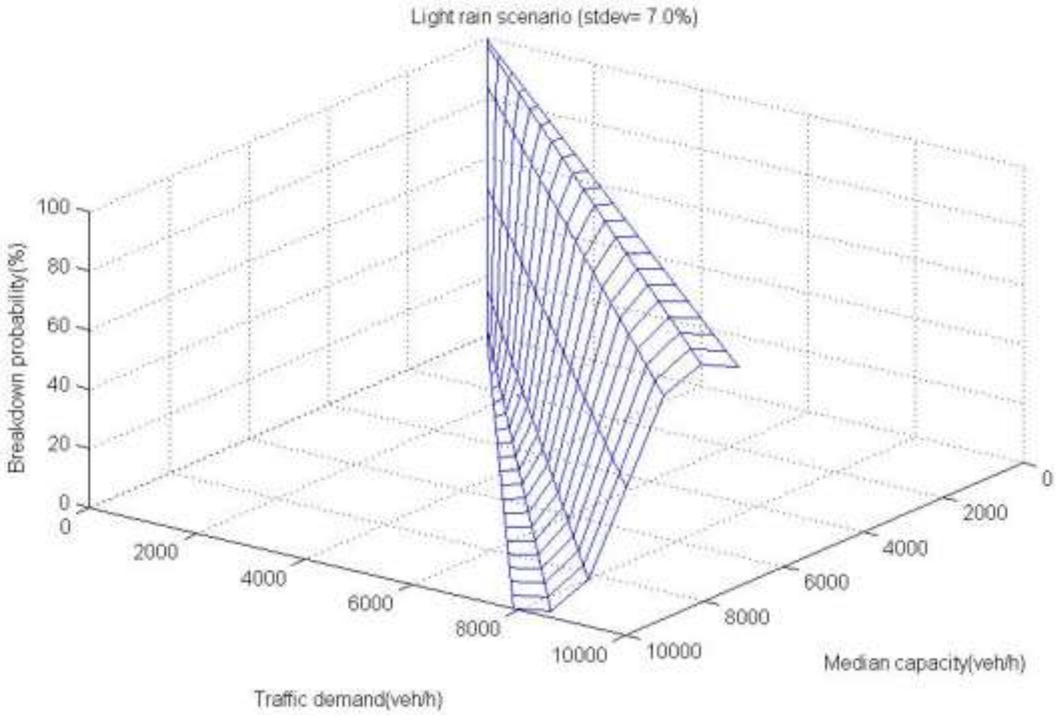

Figure 21 - Breakdown probability light rain scenario in 3D

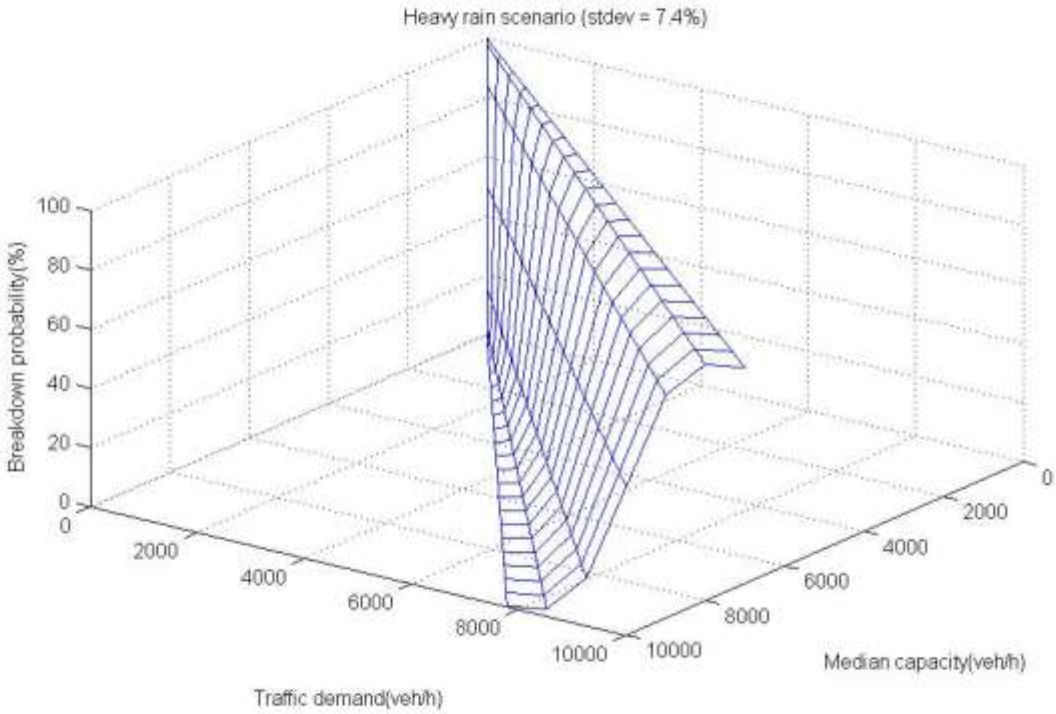

Figure 22 - Breakdown probability heavy rain scenario in 3D

In the 3D-plots it can be seen that the function consists of cumulative normal distribution, which corresponds to the two dimensional plot in Figure 19. The curve is tight with low capacity and traffic demand values, and becomes wider as capacity and traffic demand values increase. This is the result of the relative demand change corresponding to one standard deviation in combination with the absolute scales for traffic demand and median capacity.

6.3 Results and conclusion

In this section the approach to calculate the changes in breakdown probability as a result of rainfall is briefly presented. After that, the results of the effect of rain on breakdown probability and the corresponding conclusions are elaborated upon.

A script has been written in Matlab that makes it possible to calculate the corresponding breakdown probability when the traffic demand and median capacity are entered. Due to the different functions for the scenarios, it is not possible to assess the change in breakdown probability in one function. The dry scenario is the starting point, where the known median capacity (based on the results in chapter 5) and a certain traffic flow can be entered. The breakdown probability for these values is then provided. Then the adjusted traffic flow (reference traffic flow with the demand change) has to be entered into the function of the other scenario. This results in a new breakdown probability, which can be compared to the breakdown probability in the reference case. This approach has been carried out, with the median capacity and the corresponding traffic demand in the dry scenario. The results can be found in Table 27.

Table 27 - The effect of rain on breakdown probability

highway	traffic flow median capacity dry (veh/h)	traffic flow light rain (veh/h)	median capacity light rain (veh/h)	breakdown probability light rain (%)	traffic flow heavy rain (veh/h)	median capacity heavy rain (veh/h)	breakdown probability heavy rain (%)
A4R-2007	4452	4554	4264	83.2%	4350	3993	87.0%
A4R-2008	4426	4528	4148	88.4%	4324	3949	88.1%
A4L-2007	4368	4468	4196	81.7%	4268		
A12R-2007	7173	7338			7008	6648	75.2%
A12R-2008	4690	4798	4497	82.7%	4582		
A15L-2008	7267	7434	6944	84.2%	7100		
A15L-2007	4351	4451			4251	3937	85.2%
A15L-2008	4117	4212			4022	3710	86.0%
A20R-2007	6072	6212	5721	87.3%	5932		
A20R-2008	5939	6076			5802	5491	76.3%
A20R-2009	4205	4302			4108	3744	88.5%
A20L-2007	6060	6199			5921	5827	57.7%
A20L-2008	6064	6203			5925	5839	57.0%
A20L-2009	6121	6262			5980	5756	68.2%
A27L-2007	3938	4029			3847	3698	68.9%
A27L-2008	3931	4021	3627	91.7%	3841		
A50R-2007	4224	4321			4127	3756	88.8%
A50L-2007	4181	4277	3807	94.6%	4085	3843	79.2%
			average	86.7%		average	77.4%
			STDEV	4.6%		STDEV	11.4%

In Table 27 the traffic flow corresponding to the median capacity is used as a reference value. If the traffic flow is equal to the median capacity, this results in a breakdown probability of 50%. The traffic demand changes of +2.3% for light rain and -2.3% (see Table 18) lead to the traffic flow values per bottleneck location in these scenarios. In addition, the median capacity values for the bottleneck locations in the different scenarios are presented. These values can be entered into the generic formula, which leads to a breakdown probability for these specific locations in the different scenarios. The breakdown probabilities in the light rain scenario are based on the generic formula for light rain and the results for heavy rain are based on the formula for the heavy rain scenario.

As can be seen in Table 27 the average breakdown probability increases from 50% to 86.7% due to light rain. This is the result of the decreased capacity and an increasing traffic demand in this scenario. The range of breakdown probabilities for the different locations is between 81.7% and 94.6%, which can be explained by the different capacity reductions for the bottleneck locations as seen in section 5.3.3. In the heavy rain scenario the average breakdown probability is increased from 50% to 77.4%. There is a bigger range in the breakdown probability for heavy rain scenario resulting from the relatively low breakdown probability at highway A20L and A27L. The average probability of breakdown is lower than in the light rain scenario, while the average capacity reduction in the heavy rain scenario is bigger than in the light rain scenario due to the decreased traffic demand in the heavy rain scenario.

The first conclusion that can be drawn is that rain on average leads to a significant increase in probability at bottleneck locations. A breakdown probability of 50% in dry weather leads to an average breakdown probability of 86.7% in light rain and 77.4% in heavy rain conditions. Since the magnitude of the capacity reductions differs at different bottleneck locations, the increase in breakdown probabilities should be analysed location specific. Another interesting conclusion is that a small change in demand can have significant effect. Referring to the example with Figure 19, it can be seen that an increase in demand of 2.3% leads to an increase in breakdown probability of 11 percentage points. Consequently, the conclusion can be drawn that an analysis solely based on the capacity reduction without incorporating the demand change would lead to incorrect results and thus a possible highway traffic demand change should always be concluded in the capacity analysis to arrive at accurate predictions regarding the effect of the weather on highway breakdown probability.

7. Conclusions and recommendations

This chapter provides the conclusions and recommendations based on the analyses in the report. First of all, answers to the sub-research questions are provided in section 7.1. After that in section 7.2 the answer to the main research question is elaborated upon. Section 7.3 presents the implications of the results and conclusions for relevant actors. Finally, in section 7.4, recommendations for further research are provided.

7.1 Answers to the sub-research questions

In this section the sub-research questions are answered based on the findings regarding the effect of the weather on travel behaviour and highway capacity.

How can the highway traffic demand and capacity change as a result of adverse weather be combined into a probability of congestion?

To be able to answer the main research question, the highway traffic demand and highway capacity should be linked to each other. Insight is needed into the stochastic approach towards highway capacity to link these factors. With the stochastic approach towards capacity a certain traffic volume leads to a probability of breakdown. The higher the traffic volume is, the higher the breakdown probability becomes ceteris paribus. The link between highway capacity and highway traffic demand is based on the influence that both factors have on the probability of breakdown. Probability density functions can be estimated for scenarios with and without precipitation to arrive at a capacity reduction by comparing the different functions. The result of precipitation on capacity is that the probability of a breakdown increases if the intensity stays the same. At this part, the highway traffic demand also influences the probability of breakdown. The travel demand, whether increasing or decreasing, affects the flow rate at the highway. The difference in flow rate at the highway as a result of weather conditions affects the probability of a breakdown. The steep curve of the capacity distribution function suggests that small changes in travel behaviour could have a significant effect on the breakdown probability. With both highway traffic demand and highway capacity being affected by adverse weather conditions, and the significant effect highway traffic demand changes can have, both traffic demand and highway capacity should always be incorporated in the analysis to arrive at accurate predictions regarding breakdown probabilities.

What is the effect of current and forecasted weather on travel behaviour?

In this study a distinction was made between utilitarian trips (business trips, commuter trips and educational trips) and recreational trips (visiting family or friends, grocery shopping, shopping, a day-out, going to sports et cetera) during the morning peak. First the results for utilitarian trips are elaborated upon, after which the results concerning the recreational trips are presented.

From the attributes that were included into the analysis (current weather, weather forecast and weather alarm) it can be concluded that the weather forecast does not have an influence on the travel behaviour for utilitarian trips. The current weather and a weather alarm on the other hand can have a significant effect on the adaptation of travel behaviour. Light rain does not lead to adaptation of travel behaviour nor does heavy rain lead to large behavioural shifts. Even in the very heavy rain scenario the utilitarian travel behaviour does not change drastically. Travellers are more willing to adapt their behaviour as a result of snowfall than as compared to rainfall. Light snowfall mostly affects the highway car drivers, which could be explained by the fact that on average these travellers have to make a relatively long trip (35.9 km). The longer the trip is, the higher the uncertainty regarding the effect of snowfall in other regions. Heavy snowfall leads to a fair amount of travellers cancelling their trip and staying at home. The alarms also have a big influence on the travel choices, with the effect of a rain alarm being less than the effect of the snow and icy roads alarm. An interesting result is that cyclists and public transport users are less affected by the extreme weather conditions, but a fairly high percentage of 23.8% of the cyclists also decide not to make a utilitarian trip in case of heavy snow and a icy roads alarm. The public transport users are limitedly affected which could be the result of the fact that alterations in public transport timetables are not included in the experiment.

Trip generation could be affected by some weather conditions. Rainfall, however, does not have a significant effect on trip generation. Heavy snowfall, on the other hand, results in an increase in the probability of not making the trip. The car users, especially, are influenced to not make a trip due to the snowfall. The biggest decreases in trip generation take place in the extreme snow scenarios. More than one third of the car travellers will decide not to make the trip in case of heavy snowfall and a weather alarm. Mode choice changes for utilitarian travellers do not occur a lot as a result of the weather. There is a very small change in the cyclists group towards the usage of the car, but this effect can be considered marginal. Route choice changes for car users resulting from weather conditions are also limited. Travellers who normally use the highway will not change their route and avoid the highway in case of severe weather conditions. Also, changing the route is not very common for non-highway travellers. Departure time changes only occur if there is a weather alarm. Overall, it can however be concluded that the effect of weather conditions on departure time change is limited. The biggest decision that utilitarian travellers make is whether to stay at home or to make their normal trip.

The influence of the weather conditions on recreational trips is slightly different from the utilitarian trips. In case of a recreational trip purpose, the weather forecast plays a small role in the choice to avoid the morning peak. It leads to a positive approach to avoiding the morning peak when travellers know that the weather is going to improve. On the other hand, a disutility is derived from avoiding the morning peak when the weather is forecasted to get worse during the day. Travellers prefer to make the trip at this moment or do not want to go at all when the forecasts are worse than current weather. The last interesting effect that can be seen is that both the current weather and the weather alarm more effectively influence adaptation of travel behaviour for recreational trips compared to utilitarian trips.

Trip generation of recreational trips is significantly influenced by adverse weather conditions. Very heavy rainfall leads to relatively high probabilities of staying at home not only for cyclists but also for car users (between 23.6% and 36.2%). Heavy snowfall triggers recreational travellers to stay at home even further with probabilities between 57.0% and 63.5%. In extreme weather situations more than half of the travellers decide to stay at home. Heavy snow combined with a snow or icy roads alarm even leads to probabilities of 67.4% to 80.4% to decide to not make the trip, which are remarkably high probabilities.

Mode choice changes for recreational travellers occur more than for utilitarian travellers as a result of the weather. This can be seen in the base case scenario, where highway avoiding car users are also likely to choose the bicycle. In the rain scenario there is also a significant modal shift from cyclists towards the car. 21.9% of the cyclists will then use the car instead of the bicycle, which could be considered as a fairly high modal shift.

Route choice changes for recreational trips are mostly comparable to utilitarian trips. Travellers that normally use the highway will not change their route and avoid the highway in case of severe weather conditions. There is a relatively high route choice change (up to 22.3%) for the non-highway users group in case of very heavy rain.

The departure time is changed more often in comparison to utilitarian trips. Overall it can be said that the alternative to avoid the morning peak period is preferred by recreational trip travellers. A possible explanation for this is (to some extent) the more flexible nature of the recreational trips compared to utilitarian trips. Grocery shopping, for example, is easier to reschedule than a business meeting.

As a result of the behavioural adaptation of travellers, the highway traffic demand rises by 2.3% in light rainfall due to a small route shift of non-highway travellers and a marginal modal shift of cyclists. The other scenarios result in less highway traffic demand. Highway traffic demand decreases by 2.3% in the heavy rainfall scenario. Some travellers might link heavy rainfall to an increase in probability of congestion and therefore avoid the highway. The traffic demand decreases by7.7% compared to dry weather as a result of very heavy rainfall. The large decrease could be explained by the extreme rain intensity that was presented to the respondents in the stated adaptation experiment. It can be concluded that snowfall leads to enormous decreases in highway traffic demand. Light snowfall leads to a decrease of 22.2%, while heavy snowfall leads to a decrease of 29.4% in comparison to the dry weather traffic demand. Travellers might know from historic events that snowfall leads to more congestion on Dutch highways, which could be a reason to not use the highways. The addition of a weather alarm results in the demand being reduced by 19.4% in case of very heavy rain and a rain alarm. Heavy snow and a snow alarm leads to a reduction of 48.8% and heavy snow in combination with an icy roads alarm results in a decrease of 52.4% of highway traffic demand in comparison with dry weather. Some travellers thus tend to accept the advice of the KNMI to avoid travelling in extreme weather situations.

What is the effect of precipitation on highway capacity?

For the capacity analysis a reference case of dry weather was used to investigate the effect of precipitation. In addition to a reference case, the scenarios of light rain (rain intensity < 1mm/h) and heavy rain (rain intensity ≥ 1mm/h) were analysed. Along with the rain scenarios, the aim was to also include capacity estimations based on snow intensities. Due to limited data regarding snowfall and limited observations of congestion during snowfall, it was decided to exclude snowfall from the capacity analysis. A normal and Weibull distribution were fitted to the results to come to complete distribution functions. Both distribution functions fit well with the data. It is chosen to use the normal distribution as an approximation of the capacity distribution function in this study.

Light rainfall results in an average capacity reduction of 5.7% as compared to dry weather. There is a significant difference in the capacity reduction if the results from different bottleneck locations are analysed, with the capacity reductions ranging from 3.9% to 8.9%. It is interesting to note that heavy rainfall, on an average, leads to a higher capacity reduction than light rainfall for freeflow capacity, which is in accordance with the expectations. There is a significant difference, but the average difference in reduction is not extremely high between light and heavy rain (5.7% vs. 8.1%) while considering that light rain only includes observations with rain intensities less than 1mm/hour and heavy rain includes all observations higher than 1mm/hour. The difference in capacity between dry conditions and light rain is relatively large compared to the difference in capacity between light rain and heavy rain.

Observations of the capacity reductions for the same scenario at the same location lead to the conclusion that the capacity reduction at one bottleneck location is very robust and does not change a lot over the years. The only outlier is the freeflow capacity at highway A20L in the year 2009, which is more than 2 percentage points higher than the other observations. Taking into account the small difference between observations at the same location, it can be concluded that the huge difference between observations at different locations (between -3.7% and 11.1%) is related to the different characteristics at the different locations. This could be the result of differences in precipitation intensities during a year at the different locations, but a more plausible conclusion is that the different highway characteristics lead to the effect of heavy rainfall on highway capacity being different at those locations. The road surface at the different locations might be an important factor in the reduction of highway capacity. It could be the case that the capacity reduction is smaller on highway sections with porous asphalt. This is in accordance with the study of Cools et al. (2007) on the effect of rain on different locations, which concluded the existence of heterogeneity in the effect of rain on different traffic count locations and the homogeneity of the rain effects on the upstream and downstream side of a certain location. Comparing the results obtained in the analysis with findings from other studies leads to the conclusion that most other researchers have found capacity reductions that are within the same range as in this study, leadings to an increase in confidence concerning the results of this study.

The main conclusion that can be drawn from the capacity analysis is that the conclusions regarding the effect of precipitation on highway capacity should not be based on the average reduction in capacity, since there is a high variety in capacity reductions for both the light rain and heavy rain scenario.

7.2 Answer to the main research question

Using the main findings and the sub-conclusions from this research project allows the main research question to be answered in this paragraph. The main research question posed is:

What is the influence of adverse weather conditions on the probability of congestion on Dutch highways?

The elements that were needed to examine the influence of precipitation on highway breakdown probability are the capacity distribution functions for dry weather, light rain and heavy rain and the highway demand change compared to the dry scenario as a result of light rain and heavy rain. A script has been written in Matlab that makes it possible to calculate the corresponding breakdown probability when the traffic demand and median capacity are entered. With the development of a generic model based on a cumulative normal distribution, breakdown probabilities can be calculated for any given traffic demand and median capacity. The resulting breakdown probability in the dry scenario can be used as a reference value. Inserting the adjusted traffic flow (reference traffic flow with the demand change) and the reduced median capacity into the model leads to a probability of breakdown in that scenario for that specific highway.

Based on the analysed bottleneck locations, the combined effect of demand and capacity change as a result of the weather leads to the average breakdown probability to increase from 50% in the dry scenario to 86.7% due to light rain. This is the result of the decreased capacity and an increasing traffic demand in this scenario. In the heavy rain scenario the average breakdown probability is increased from 50% to 77.4%. The average probability of breakdown is lower than in the light rain scenario, while the average capacity reduction in the heavy rain scenario is larger than in the light rain scenario due to the decreased traffic demand in the heavy rain scenario. The range of breakdown probabilities for the different locations is between 81.7% and 94.6% in the light rain scenario, which can be explained by the location specific capacity reductions. In the heavy rain scenario there is a bigger range in the breakdown probability (between 57.0% and 88.8%) resulting from the relatively high capacity reduction at the highways A20L and A27L that are included in the heavy rain scenario.

The first conclusion that can be drawn is that rain on average leads to a significant increase in probability at bottleneck locations. A breakdown probability of 50% indry weather leads to an average breakdown probability of 86.7% inlight rain and 77.4% in heavy rain conditions. Since the magnitude of the capacity reductions differs at different bottleneck locations, the breakdown probabilities should be analysed location specific. Another interesting conclusion is that a small change in demand can have a significant effect due to the steep curve of the probability distribution functions. The relatively small influence of rain on highway traffic demand in the morning peak thus significantly influences the breakdown probability at the highways. An increase in demand of only 2.3% could for example lead to an increase in breakdown probability of 11 percentage points at a specific bottleneck location. An analysis solely based on the capacity reduction without incorporating the demand change would lead to incorrect results. In addition, it can be concluded that the breakdown probabilities vary for the different locations as a result of the different capacity reductions at these locations. Consequently, the conclusion can be drawn that both traffic demand and location specific highway capacity should always be incorporated in order to arrive at accurate predictions regarding breakdown probabilities as a result of adverse weather conditions.

7.3 Implications of the results

This section deals with the possible consequences that the results of the study can have on different actors. The actors that are taken into account are TNO, the Ministry of Infrastructure and the Environment, Rijkswaterstaat, companies in the navigation market, the KNMI, the public transport sector and the highway travellers.

For TNO these results are, in the first place, an addition to their knowledge of the effect of weather conditions on travel behaviour and breakdown probability of highways. Along with the increase in knowledge, these results can be used to incorporate stochasticity into the traffic models that are used by TNO. The influence of the weather is one of the stochastic factors that could be incorporated into TNO's traffic models. One should include distribution functions to create stochasticity into the traffic models. This research can contribute to this by serving as input for estimation of these distribution functions and could provide an opportunity towards the increase of accuracy of the traffic models at TNO.

Observations of the capacity reductions for the same scenario at the same location lead to the conclusion that the capacity reduction at one bottleneck location is very robust and does not change a lot over the years. There are, however, relatively large differences in capacity reduction as a result of precipitation between observations at different locations due to different highway characteristics at those locations. Rijkswaterstaat could analyse the underlying factors for the different capacity reducing effects at different locations as a result of rainfall. A characteristic that should be taken into account in the analysis is the effect of the road surface on capacity reduction. It might be the case that the capacity reduction is smaller on highway sections with porous asphalt (in Dutch: Zeer Open AsfaltBeton). When different road surfaces lead to other capacity reductions, Rijkswaterstaat should take into consideration changing the road surface at the bottleneck locations to the surface that reduces capacity the least. The Ministry of Infrastructure and the Environment could benefit if the results of the study of Rijkswaterstaat lead to more cost-efficient reduction of congestion than constructing new highways. This way the probability of the Ministry reaching the goals of reduction of congestion will increase. The results regarding the different increases in breakdown probability at different locations as a result of precipitation can also be taken into account in the decision to assign the budgets to highway improvement projects. Investing in the bottleneck locations at which rain leads to the biggest increase in breakdown probability could be more interesting. This should, however, not be a decisive criterion for the Ministry, since many other factors play a role in the decision making process. More insight into the breakdown probability at bottleneck locations should be seen as an addition to the current knowledge of the Ministry.

Companies in the navigation market (like TomTom and Garmin) can be positively affected by the results in this study due to the insights that are provided regarding the effect of (extreme) weather situations on the probability of breakdown at certain highway sections. Data regarding the effect of extreme weather situations is scarce, but is needed in order to create accurate traffic predictions. These companies could use these insights as a first step towards smarter routing of travellers in order to decrease the probability of congestion.

For the KNMI the results regarding the weather alarms can be useful. The KNMI initiates a weather alarm when a weather situation could lead to a heavy nuisance and disruption of the community. The weather alarm has led to some debate over the past years. In 2010 the criteria for initiating a weather alarm were changed and in January 2013 the criteria had to be revised again. The effect of the heavy rain alarm, the heavy snow alarm and the icy roads alarm were tested in this study. The rain alarm is only marginally effective for utilitarian travellers with at most a reduction of trips of 5.1 percentage points (pp), but more effective for recreational travellers (up to 14.5pp reduction in trips). The heavy snow alarm is more effective as compared to the heavy rain alarm, with up to 14.2pp utilitarian trip reduction and up to 16.9pp recreational trip reduction. The icy roads alarm has the biggest effect on utilitarian trips (up to 16.2pp reduction) and also could decrease the recreational trips up with 16.9pp. It can thus be concluded that, despite the debate, the weather alarm still has a significant effect on travellers. This should create more confidence in the effectiveness of the weather alarms.

The implications of this study for the public transport sector are relatively limited. There is only a very small effect of the weather on public transport trips. Public transport users seem to stick to the public transport under any condition, while other travellers will not shift towards public transport in adverse weather conditions. The effect of adverse weather on the amount of public transport trips seems to be marginal based on this study. The results are, however, only based on a small group of 35 utilitarian public transport travellers and the recreational public transport group was not included into the analysis. For accurate insights into the effect of adverse weather on public transport travel behaviour it is advised to conduct a study that focuses more on the public transport sector.

In the end, the travellers using the highway could become the biggest beneficiaries of the efforts of the other parties. The likely result of those efforts is better circulation of traffic and less congestion at static bottleneck locations, leading to travel times and travel time uncertainty related to congestion to decrease. The congestion effects due to precipitation could be reduced if utilitarian drivers would avoid the morning peak more or work more at home. According to the experiment at most 6.6% of the utilitarian highway users would avoid the morning peak and 35.8% would not make a trip in the extreme situation of heavy snowfall and an icy roads alarm. More flexibility in working hours or the possibility to work at home could result in more utilitarian travellers to avoid travelling during the morning peak in adverse weather conditions. It could be valuable to test if more flexibility provided by employers would lead to higher behavioural adaptation of employees and thereby reduce congestion during the morning peak in adverse weather conditions.

7.4 Recommendations for further research

The results regarding the effect of rain on highway breakdown probability can eventually be used to incorporate stochasticity into the traffic models that are used by TNO. It should first be investigated how stochasticity can be best incorporated into the traffic models. When the best approach towards including stochasticity into the model is known, the results from this study can contribute by serving as input for estimation of the capacity distribution functions.

It would be an addition to analyse the effect of snow on highway capacity, which could not be carried out in this research. The first hurdle towards capacity estimations with snow was that there is no bottleneck location specific data regarding the occurrence of snow available at TNO. In addition, there were very limited days with snow within the examined years (2007, 2008 and 2009). An analysis of the effect of snow on highway capacity could however provide valuable additions to the results of this study. In order to come to sufficient breakdown observations on days with snowfall, it is advised to combine the traffic data from different years at the same bottleneck location. The snow analysis would be more accurate if reliable location specific snowfall information could be obtained. Lastly, it might be valuable to analyse whether or not the filtering algorithm can cope with breakdown observations at snow conditions.

From the conclusions, it can be inferred that the capacity reductions and breakdown probabilities at different bottleneck locations are location specific. The increase in breakdown probability as a result of rainfall at one specific location does not have to be an accurate estimate for bottleneck locations that are not included in this study. It is therefore not recommended to apply the average results in this study to other Dutch highway bottleneck locations. Further research into the capacity reducing effect of rainfall at other bottleneck locations is therefore advised.

The results obtained regarding the demand changes in this research have three limitations. Firstly, the results are based on stated behaviour instead of revealed behaviour. Disadvantages might be that stated behaviour differs from actual behaviour and that hypothetical weather situations were differently interpreted by respondents. Secondly, the results of the travel behaviour analysis are average changes in highway traffic demand. With the high importance of small changes in travel demand, it should be considered to investigate the effect of rain location specific on the highway traffic demand. Thirdly, there was no data available of the number of travellers in the different travel groups (car highway, car non-highway, public transport and bicycle). In this study the importance of the groups was based on the number of respondents in the groups. Data regarding the division of the groups in the population could have increased the accuracy of the traffic demand predictions.

The three limitations can be overcome through travel data that will become available in the near future. TNO is developing a smartphone application that can track the trips made by travellers via GPS. Such an application has already been used by TNO in a project in Assen. There are, however, plans for an application to be used by 500.000 Dutch travellers. In the future, revealed data from 500.000 travellers can provide information regarding location specific demand changes as a result of the weather. In addition, the standard mode of each traveller could be investigated by analysing the GPS data (see, for example, Bohte, 2010) to be able to weigh the travel groups based on the share of the travel groups in the population. This data from TNO's smartphone tracking application project can be an addition to the results obtained in this study.

8. Epilogue

In the epilogue a reflection on the project and the choices made in the project are presented. First of all something can be said regarding the project planning. The project planning turned out to be less relaxed than anticipated, but due to the absence of large setbacks or disappointments I was able to complete the project within the planned timeframe. Considering the execution of the project planning, I noticed that during the process my personal deadlines slowly faded away and different tasks were carried out at the same time. Therefore, I had less of an overview of whether I met the personal deadlines. This led to an accumulation of the workload towards the end of the project, which to some extent could have been avoided.

When reflecting on the choices made in the project, I would have made some different choices related to the stated adaptation experiment if I would have had the knowledge that I have now. First of all, the relatively high correlations of the temperature attribute with the other attributes led to the inability to come to good model estimation. These correlations were known at the start of the experiment. Nevertheless, I chose to incorporate temperature into the experiment. When temperature would have been excluded at the beginning, a more efficient design for the other attributes could probably have been made. In addition, too many questions were asked in the survey, with some of them not being included in the analysis. It would have been better to have fewer questions and more respondents, but considering the short time of the thesis project the resulting survey was acceptable. Finally, too little information was acquired about the viable travel options of the different respondents. This information could have been beneficial to the estimation of the models.

A final remark can be made regarding the order of the analysis. In the project I first carried out the survey and after that I analysed the capacity reductions. This created some problems in linking the different scenarios to each other, which might not have occurred if the capacity analysis was carried out first.

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Appendix 1 – Scientific article

The influence of adverse weather conditions on the probability of congestion on Dutch highways

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ABSTRACT
This is the first paper that incorporates both the highway traffic demand change and the highway capacity reduction in the estimation of the congestion probability at Dutch highways as a result of adverse weather conditions. Congestion effects at the Dutch highways account for serious economic damage. Between May 2010 and April 2011 there were 68 million vehicle loss hours as a result of congestion (TNO, 2011). The external factor weather is widely acknowledged to contribute to the occurrence of congestion in two different ways. Firstly, weather conditions can influence traffic supply through a temporal reduction of capacity due to changes in driving behaviour. Secondly, weather conditions can influence highway traffic demand. A stated adaptation experiment has been conducted and a Panel Mixed Logit model is estimated to arrive at a highway traffic demand as a result of adverse weather. To examine the influence of precipitation on highway capacity it was chosen to estimate capacity distribution functions for dry weather, light rain and heavy rain based on the Product Limit Method. With the development of a generic model based on a cumulative normal distribution, breakdown probabilities can be calculated for any given traffic demand and capacity. Rainfall leads to a significant increase in probability of breakdown at bottleneck locations. A breakdown probability of 50% in dry weather will lead to an average breakdown probability of 86.7% in light rain and 77.4% in heavy rain conditions. The higher breakdown probability with light rainfall is the result of the increased traffic demand. The conclusion that can be drawn is that both traffic demand and highway capacity should always be incorporated in the analysis to come to accurate predictions regarding breakdown probabilities.

INTRODUCTION

Congestion effects at the Dutch highways account for serious economic damage. Between May 2010 and April 2011 there were 68 million vehicle loss hours as a result of congestion (TNO, 2011). The external factor weather is widely acknowledged to contribute to the occurrence of congestion in two different ways. Firstly, weather conditions can influence the traffic supply through a temporal reduction of capacity. One of the most well-known studies to the effect of weather on traffic flow is presented in the Highway Capacity Manual (2000). The manual suggests the inclusion of capacity reductions between 0% and 15% as a result of precipitation. Highway capacity reduction is traditionally regarded as a deterministic phenomenon, but multiple researchers (Elefteriadou et al. 1995; Minderhoud et al. 1997; Persaud et al. 1998; Lorenz and Elefteriadou 2001, Brilon et al., 2005) have shown that the maximum capacity of a highway varies even when the external factors are constant, resulting from the unpredictable behaviour of travellers at the microscopic level. With a stochastic approach to capacity, the probability of a breakdown is also dependent on the traffic demand at a certain highway section.

Highway traffic demand is also influenced by weather conditions, but the effect of weather on traffic demand has received much less attention than the effect on highway capacity according to Böcker et al. (2012). In their literature review, Böcker et al. show that many studies have found different effects of precipitation, temperature and wind on traffic demand. Call (2011), amongst others, reported considerable reductions in trip-making with snowfall. Car traffic reductions are also reported as a consequence of rainfall, for example by Hassan and Barker (1999) in Scotland. Where most studies show negative percepitation effects on trip generation, a Dutch study from Sabir (2011) shows a positive relationship between precipitation and car and public transport usage. This is the result of the large number of cyclists in the Netherlands, from which some switch to motorized transport modes in response to precipitation.

Surprisingly though, a study towards the combined effect of changes in highway capacity and highway traffic demand as a result of the weather has not been carried out yet. This study focuses on the probability of breakdown at Dutch highways as a result of adverse weather conditions, including both highway capacity reductions and traffic demand changes resulting from adverse weather. A stated adaptation experiment is conducted and a Panel Mixed Logit model is estimated to arrive at a highway traffic demand as a result of adverse weather. To examine the influence of precipitation on highway capacity it was chosen to estimate capacity distribution functions for dry weather, light rain and heavy rain based on the Product Limit Method. To get accurate predictions of the traffic demand change and have sufficient observations with congestion, it is chosen to limit this study to the morning peak period (between 6:00 and 10:00 am). With the development of a generic model based on a cumulative normal distribution, breakdown probabilities can be calculated for any given traffic demand and capacity.

METHODOLOGY

The relation between highway traffic demand and highway capacity

In this section a relation between highway morning peak traffic demand and highway capacity is made explicit to provide insights into the possibility of linking both factors later in the analysis. For the capacity analysis, a stochastic approach to capacity is used based on the following definition of capacity: *"the rate of flow along a uniform freeway segment corresponding to the expected probability of breakdown deemed acceptable under prevailing traffic and roadway conditions in a specific direction*" (Lorenz & Elefteriadou, 2001). Applying the concept of stochasticity to the highway capacity leads to a probability density function that provides the probability of breakdown given a certain traffic flow, which is shown in Figure 4.

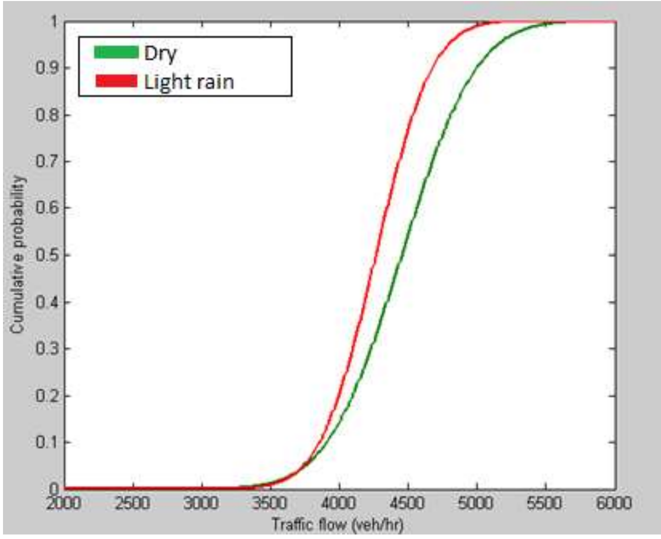

Figure 23 - Breakdown probability at highway A4 in dry and heavy rain conditions

Figure 4 shows the capacity distribution function at highway A4 in 2007 in dry weather conditions (bottom line) and in heavy rain weather conditions (top line). A comparison is made between the breakdown probability based on the estimated capacity distribution functions for scenarios with and without precipitation. The highway travel demand, whether increasing or decreasing in these scenarios, also affects the breakdown probability. The link between highway capacity and highway traffic demand is thus based on the influence that both factors have on the probability of breakdown.

Capacity Analysis

Choice capacity estimation method

In this research the Product Limit Method (PLM) by Kaplan and Meier (1958) with adaptations as described in Brilon et al. (2005), is used in the capacity analysis to come to a function describing the probability of breakdown. The PLM method by Brilon uses observations upstream of a bottleneck location, which is the main difference between this approach and the others (van Toorenburg, 1986; Minderhoud, 1997). Measurement upstream of a bottleneck location takes into account that the capacity in uncongested traffic flows differs from the capacity in congested conditions, which is the result of the so-called capacity drop phenomenon (Zurlinden, 2003; Regler, 2004; Chung et al., 2007).

Bottleneck location detection

The estimation method relies on the occurrence of many breakdowns to arrive at a reliable capacity distribution function based on many data points. Therefore, only static bottleneck locations with many congested morning peaks during the year are analysed in this research. The bottleneck locations are identified by analysing data from double-induction loops at the Dutch highways. Traffic data is collected from double-induction loops that are present in the Dutch motorway network, which is known as the MONICA system (Dutch MONItoring Casco). For each minute data is stored regarding the average speeds (km/h), flows (veh/min) and possible lane closure for all the highways included in the MONICA system. For the capacity analysis in this study, data from the years 2007, 2008 and 2009 are inspected of various Dutch highways (A2, A4, A6, A9, A15, A16, A20, A27, A50, A58 & A59).

There are three criteria for static bottleneck locations to become suitable for analysis. Firstly, the induction loops at and around the bottleneck locations should work properly. Secondly, congestion at the bottleneck location should not be initialized by spillback from a bottleneck downstream. Thirdly, the bottleneck may not consist of a variable amount of lanes over the day (for example peak hour lanes). In total fourteen bottleneck locations met all three requirements and were considered suitable for the capacity analysis (see Table 1).

Table 1 - Bottleneck locations included in the capacity analysis

ID	Highway	Location pre bottleneck	Location post bottleneck	2007	2008	2009	Number of lanes after bottleneck	Category
1	A4R	30.0	31.0	X	X		2	on-ramp
2	A4L	23.5	21.5	X	X	X	2	merging
3	A9R	59.8	60.5		X		2	merging
4	A9L	38.4	38.0	X		X	2	on-ramp
5	A12R	35.5	37.1	X			3	on-ramp
6	A12R	68.1	68.7		X		2	on-ramp
7	A15L	59.5	58.1		X	X	3	on-ramp
8	A15L	80.9	80.1	X	X	X	2	on-ramp
9	A20R	31.0	31.9	X	X		3	on-ramp
10	A20R	43.0	44.9	X		X	2	on-ramp
11	A20L	32.2	31.2	X	X	X	3	on-ramp
12	A27L	35.4	34.7	X	X	X	2	on-ramp
13	A50R	156.3	157.5	X	X		2	weaving
14	A50L	153.5	150.9	X	X	X	2	bridge

Categorization of the traffic flow observations

To arrive at a capacity distribution function, the traffic flow observations are categorized into three different classes. Observation intervals of five minutes are used, since this is a good compromise between reducing the random fluctuations in the traffic flow and accuracy in the average intensity values (see Brilon et al., 2007). Only observations within the morning peak period (6am-10am) are included in the analysis. Additionally, observations of weekend days and vacation periods are also excluded. Each of the remaining five-minute traffic flow observations are placed into one of the following categories:

B: The traffic volume in this interval is viewed as a realization of the capacity due to the fact that observed flow in this interval is uncongested, but causes a breakdown in the following interval i + 1. In this study, an average speed of 60 km/h is the threshold that separates observations into either congested (<60 km/h) or uncongested (>60 km/h) observations. The threshold speed can vary, but another threshold speed does not have a big influence in the range between 45 and 65km/h, as congestion has a tendency to break through these thresholds fairly quickly after the start of congestion (Calvert & Snelder, 2013). An extra requirement for this observation is that during the preceding 6 observations (30 minutes) the average speeds were higher than 60 km/h. This is added to ensure the uncongested flow before the occurrence of breakdown.

F: The traffic flow is uncongested in interval i and in interval i + 1. The information obtained from this observation is that the actual capacity in interval i is bigger than the volume q_i that is observed. In other words, the capacity has not been reached during this observation. Data in this category is called censored data.

C: The traffic flow is congested in interval i and in interval i – 1, thus the average speed in both intervals is lower than the threshold value. Since the traffic volume in interval i – 1 is not congested (free flow), the observation does not provide information about the free flow capacity and is therefore excluded from the free flow capacity analysis.

After the observations are grouped into the different categories, rain data is added to these observations. The rain data is collected from a data feed of the Royal Netherlands Meteorological Institute. The rain data feed provides data for a grid with the size of 1km by 1 km for the Netherlands on a one-minute basis. The rain detection and intensity estimation is performed via advanced satellite images and has realized excellent accuracy during the latest years. The one-minute rain intensity data is averaged to five-minute intervals and these intervals are mapped onto the road network with latitudinal and longitudinal coordinates (Calvert & Snelder, 2013).

Capacity distribution function estimation
With the traffic observations being classified and filtered, the traffic observation intervals possess information regarding the average intensity and the average speed during that interval. With the information regarding the average speed, average intensity and the category of each observation interval, it is possible to estimate a distribution function for the freeflow capacity using the Product Limit Method (PLM) by Kaplan and Meier (1958). This leads to a freeflow capacity distribution function at the bottleneck that is estimated as follows:

$$F_c(q) = 1 - \prod_{i:qi \leq q} \frac{k_i - d_i}{k_i}; i \in \{B\}$$

where:
$F_c(q)$ = capacity distribution function
q = traffic volume (veh/h)
q_i = traffic volume in interval i (veh/h)
k_i = number of intervals with a traffic volume of $q \geq qi$
d_i = number of breakdowns at a volume of qi
{B} = set of breakdown intervals (intervals with classification B)

The calculation is made for each breakdown interval observation. Each observed breakdown is normally used as one q_i-value, which leads to d_i always being equal to 1. The factor k_i is based on all observations (thus B- and F-observations) with a traffic volume (q) that is higher than the traffic volume at the breakdown observation (q_i). The points at the capacity distribution are thus B-observations, but in order to arrive at the probability of that certain point the F-observations are also included into the estimation.

Stated adaptation experiment

Selection of attributes
In this section, the attributes are discussed that are varied in the stated adaptation experiment. In the experiment, whether the respondent will adapt his behaviour given a hypothetical weather situation is examined. The trade-off in this experiment is between the different travel options given a certain weather situation.

The precipitation attribute reflects the current precipitation at the decision moment, thus in the morning at the moment that the decision about a trip in the highway morning peak will be taken. This attribute consists of five levels, which are dry, light rainfall, very heavy rainfall, light snowfall and heavy snowfall. Pictures are included to the precipitation levels in order to make the terms light and heavy more concrete. This is done in order to mitigate the effect that these precipitation conditions are differently interpreted among different respondents.

The second attribute is the weather alarm that is sometimes carried out by the Royal Netherlands Meteorological Institute. A weather alarm with code red will be carried out at most twelve hours in advance and if the probability of occurrence of the event is at least 90%. It is only used if the area that is confronted with the weather at least has a length of 50 kilometres (KNMI, 2011). There are several different alarms applicable to the weather events in this experiment, which are code red for heavy rainfall (at least 75mm in 24 hours), code red for snow (at least 3cm per hour or 10cm per 6 hours) and code red for icy roads. The fourth attribute level that is included in the experiment is the event of no weather alarm.

The third attribute is the weather forecast, which is included in the experiment as a result of the hypothesis that the weather forecast for the return trip influences the travel choices of the traveller in the morning. The forecasts on the news broadcasting did not provide very specific information regarding the weather during the coming day. Based on this it was chosen to create a weather forecast for the rest of the day by having the following attribute levels: during the day the weather conditions can improve, get worse or stay the same as the current weather conditions.

Lastly, information regarding the temperature related to the different precipitation forms is included into the experiment to provide a more complete sketch of the weather conditions. This was mainly done to avoid potential heterogeneity due that different respondents make different guesses with respect to temperature based on the presented precipitation forms.

Construction of choice sets

The selected attributes are combined to arrive at weather situation alternatives in which respondents make their choices for highway use. Following a pilot study with 30 respondents, an efficient design was selected to construct 20 choice sets of weather situations. These choice sets were split into two blocks of 10 sets each in order to limit the choice task for each respondent. Each respondent was randomly assigned to one of the two blocks.

In this study, two different categories of trip purposes are distinguished. The first category consists of business trips, commuter trips and educational trips. This category is named utilitarian trips. The second category consists of trips for visiting family or friends, grocery shopping, shopping, a day-out, going to sports etc. This category is defined as the recreational category. If the respondent makes utilitarian and recreational trips in the morning peak during a normal workweek, the respondent is asked what he would do if he had planned a utilitarian trip in the morning peak and is confronted with a given weather situation. For the same given weather situation a second question is asked what he would do if he had planned a recreational trip in the morning peak. A respondent that only makes utilitarian or recreational trips is asked what he would do if he had planned a trip with the corresponding purpose. The following alternatives were provided:

- Travel by car on the highway in the morning peak
- Travel by car, but avoiding the morning peak (before 06:00 or after 10:00am)
- Travel by car, but avoiding the highway
- Travel by bicycle
- Travel by public transport
- Decide not to make the trip

The decision of not making the trip is used as the reference alternative in this experiment and therefore was by definition given a utility of zero.

Questionnaire and sample

The stated adaptation experiment was included in an online questionnaire and was preceded by socio-demographic characteristics and questions regarding the normal behaviour of the travellers. To gain insight into normal travel behaviour, questions were asked regarding the number of utilitarian and recreational trips that are made in a normal workweek (Monday-Friday) in the morning peak, the mode that is most often used during a normal workweek for both purposes, the distance from home to work, the possibility to avoid the morning peak and the possibility to work at home.

In collaboration with RespondentenDatabase.nl 1550 panel members were invited to fill out the survey. Before entering the survey the respondents needed to answer two filtering questions. The first question asked whether the respondent had a driving license and the second question whether or not the respondent used the highway during the morning peak in the last month. Respondents that did not have a driver's licence or had not been on the highway in the morning peak during the last month were excluded from the survey. In total 342 respondents filled out the survey completely (response rate of 22%), which is considered relatively low for a paid survey. This led to a sample of 132 respondents (1320 observations) for the recreational trip analysis and 271 respondents (2710 observations) for the utilitarian trip analysis.

Model estimation

Effects coding is applied to the attribute levels in order to be able to incorporate a test for non-linearity in utility between the attribute levels and for coding of interval and ratio attribute levels. Another advantage of effects coding is that the strength of the estimated coefficients can be directly compared in terms of the impact of the attributes on overall utility if all attributes are effects coded (Molin, van Stralen & van Wee, 2012). There are four current weather indicator variables, two weather forecast and three weather alarm indicator variables. The effects coding applied to the attribute levels can be seen in Table 2.

Table 2 - Effects coding attribute levels

Current precipitation

	Light rainfall	Very heavy rainfall	Light snowfall	Heavy snowfall
light rainfall	1	0	0	0
very heavy rainfall	0	1	0	0
light snowfall	0	0	1	0
heavy snowfall	0	0	0	1
dry	-1	-1	-1	-1

Weather forecast

	Worse forecast	Better forecast
worse forecast	1	0
better forecast	0	1
same forecast	-1	-1

Weather alarm

	Rain alarm	Snow alarm	Icy roads alarm
rain	1	0	0
snow	0	1	0
icy roads	0	0	1
no alarm	-1	-1	-1

The last attribute level is compiled out of the values of all coefficients, as can be seen in Table 2. Dry weather for example is compiled out of the negative values of the four estimated coefficients. Effects coding was also use to code the interaction effect of the different groups that were created based on their standard modes of transport. If one of the coefficients (highway car group, non-highway car group, public transport group) is significant, this means that the utility of the group differs from the average utility in the sample.

Separate models were estimated in Biogeme (Bierlaire, BIOGEME: A free package for the estimation of discrete choice models, 2003) for utilitarian and recreational travel behaviour. For utilitarian travel behaviour analysis, the basic MNL model (LL = -3882.16) has a Rho-square value of 0.200. In the second model, the respondents are sorted into four groups based on their standard mode of transport for utilitarian and recreational trips. Interaction effects are estimated for each of the groups. The four groups are car users that use the highway, car users that do not use the highway, public transport users and cyclists. Grouping the respondents on the basis of their standard modes for utilitarian trips improved the model fit. The log-likelihood rises to -2005.48 and the Rho-square value becomes 0.587. An unlikely assumption of the MNL model is that all observed choices are independent. This is unlikely since multiple choices are observed from the same respondent, which are to a certain extent correlated as a result of the preferences of the respondent. To take this into account a Mixed Logit model for panel data can be estimated. Based on the assumption of heterogeneity of the alternative specific constant for respondents in the sample, the alternative specific constants are estimated as normal distributions (with a mean and a standard deviation). The error term for the choice made by an individual is constant for each of the individual's choices with the panel effect. Including the panel effect means a significant improvement of the model (LL= -1386.50) and leads to a high Rho-square value of 0.714. According to the Likelihood Ratio Test (Ben-Akiva & Lerman, 1985) the grouped Panel Mixed Logit model fits significantly better to the data than the normal grouped MNL model. For the recreational travel behaviour analysis, the basic MNL model (LL = -2085.69) has a Rho-square value of 0.118. Grouping the respondents on the basis of their standard modes made the Log-likelihood rise to -1846.74. The grouped Panel Mixed Logit model also means a significant improvement of the grouped MNL model (LL = -1348.86) and leads to a relatively high Rho-square value of 0.430. As a result, the grouped Panel Mixed Logit model for both utilitarian and recreational travel behaviour analysis was chosen in this study. The final grouped Panel Mixed Logit models that included only significant coefficients were estimated by applying 500 Halton draws.

RESULTS

Capacity analysis

This section compares the capacity in different weather scenarios. The first scenario is the reference case of dry weather. Secondly, the effect of light rain on highway capacity is investigated by only analysing traffic flow intervals with precipitation intensities between 0.01 and 1 millimetre per hour. The third scenario is the heavy rainfall scenario, which included all traffic flow intervals with precipitation intensities higher than 1 millimetre per hour. Analysis on the effect of snow on highway capacity could not be carried due to very limited days with snow within the examined years (2007, 2008 and 2009) and the absence of location specific snowfall data. A cumulative normal distribution function is fitted to the resulting data in order to arrive at a complete capacity distribution function. The comparison of the capacity is made based on the median value of the capacity distribution functions. Since it is the median value in a normal cumulative probability function, along with it is the traffic intensity value with the highest probability to occur and therefore the most representative capacity value. The results can be found in Table 3.

Table 3 - Comparison of the median capacity values in the different scenarios

			Dry		**Light rain**		**Heavy rain**	
highway	Location pre-bottleneck (hm)	location post-bottleneck (hm)	Median capacity Freeflow conditions (veh/h)	Median capacity Congested conditions (veh/h)	Freeflow difference (%)	Congested difference (%)	Freeflow difference (%)	Congested difference (%)
A4R-2007	30.0	31.0	4452	3612	-4.2%	-6.6%	-10.3%	-5.3%
A4R-2008	30.0	31.0	4426	3624	-6.3%	-5.0%	-10.8%	-7.0%
A4L-2007	23.5	21.5	4368	3816	-3.9%	-4.1%		
A12R-2007	35.5	37.1	7173	5628			-7.3%	-5.1%
A12R-2008	68.1	68.7	4690	3864	-4.1%	-6.2%		
A15L1-2008	59.5	58.1	7267	6240	-4.4%	-6.9%		
A15L2-2007	80.9	80.1	4351	3768			-9.5%	-8.3%
A15L2-2008	80.9	80.1	4117	3792			-9.9%	-8.5%
A20R1-2007	31.0	31.9	6072	5460	-5.8%	-3.7%		
A20R1-2008	31.0	31.9	5939	5484			-7.5%	-7.7%
A20R2-2009	43.0	44.9	4205	3432			-11.0%	-4.2%
A20L-2007	32.2	31.2	6060	5268			-3.8%	-6.2%
A20L-2008	32.2	31.2	6064	5292			-3.7%	-6.3%
A20L-2009	32.2	31.2	6121	5388			-6.0%	-5.8%
A27L-2007	35.4	34.7	3938	3624			-6.1%	-5.0%
A27L-2008	35.4	34.7	3931	3624	-7.7%	-5.0%		
A50R-2007	156.3	157.5	4224	3516			-11.1%	-6.1%
A50L-2007	153.5	150.9	4181	3732	-8.9%	-7.1%	-8.1%	-9.0%
				Average	-5.7%	-5.6%	-8.1%	-6.5%
				Standard deviation	1.9%	1.3%	2.6%	1.5%

Light rainfall results in an average capacity reduction of 5.7% compared to dry weather. There is a significant difference in the capacity reduction if the results from different bottleneck locations are analysed, with the capacity reductions ranging from 3.9% to 8.9%. It is interesting to note that heavy rainfall, on an average, leads to a higher capacity reduction than light rainfall for freeflow capacity, which is in accordance with the expectations. There is a significant difference, but the average difference in reduction is not extremely high between light and heavy rain (5.7% vs. 8.1%) when one considers the fact that light rain only includes observations with rain intensities less than 1mm/hour and heavy rain includes all observations equal or higher than 1mm/hour. The difference in capacity between dry conditions and light rain is relatively large compared to the difference in capacity between light rain and heavy rain.

Observations of the capacity reductions for the same scenario at the same location lead to the conclusion that the capacity reduction at one bottleneck location is very robust and does not change a lot over the years. Taking into account the small difference between observations at the same location, it can be concluded that the huge difference between observations at different locations (between -3.7% and 11.1%) is related to the different characteristics at the different locations. This could be the result of differences in precipitation intensities during a year at the different locations, but a more plausible conclusion is that the different highway characteristics lead to the effect of heavy rainfall on highway capacity being different at those locations. The road surface at the different locations might be an important factor in the reduction of highway capacity. It could be the case that the capacity reduction is smaller on highway sections with porous asphalt. This is in accordance with the study of Cools et al. (2007) on the effect of rain on different locations, which concluded the existence of heterogeneity in the effect of rain on different traffic count locations and the homogeneity of the rain effects on the upstream and downstream side of a certain location. Comparing the results obtained in the analysis with findings from other studies leads to the conclusion that most other researchers have found capacity reductions which are within the same range as that of this study, leading to an increase in confidence concerning the results of this study.

Stated adaptation experiment

As a result of the trade-off between the different travel options given a certain weather situation in the experiment, the parameters for the six alternatives need to be estimated alternative specific. The significant coefficients of the estimated utilitarian and recreational trip Panel Mixed Logit models are presented in Table 4.

Table 4 – Results of the estimated Panel Mixed Logit models

	Utilitarian trip analysis			**Recreational trip analysis**	
	coefficient	t-value		coefficient	t-value
Highway			***Highway***		
snow alarm	-0.57	-2.63	ASC	-2.01	-7.24
icy roads alarm	-0.82	-4.05	icy roads alarm	-1.19	-5.23
light rain	2.20	6.61	light rain	1.74	5.14
light snow	-1.23	-6.63	very heavy rain	0.49	2.11
heavy snow	-2.77	-12.49	heavy snow	-2.24	-8.28
highway car group	4.69	16.77	highway car group	2.23	7.81
public transport group	-3.89	-4.75	SIGMA	-2.38	-9.14
SIGMA	-3.61	-12.92			
Avoid morning peak			***Avoid morning peak***		
heavy snow	-0.88	-3.68	ASC	-0.78	-5.10
SIGMA	-1.29	-6.68	worse forecast	-0.56	-3.08
			better forecast	0.61	3.55
			light rain	0.90	3.05
			heavy snow	-1.36	-5.85
			SIGMA	1.15	9.50
Avoid highway			***Avoid highway***		
rain alarm	0.55	2.62	ASC	-2.99	-8.03
icy roads alarm	-1.23	-3.74	icy roads alarm	-0.71	-2.92
light rain	1.35	3.33	light rain	1.08	3.42
heavy snow	-2.43	-7.93	light snow	-1.47	-4.40
non-highway car group	3.97	16.95	heavy snow	-1.79	-6.31
public transport group	-5.82	-4.76	highway car group	-2.48	-6.69
SIGMA	-4.30	-11.76	non-highway car group	2.79	6.59
			SIGMA	3.78	7.86
Bicycle			***Bicycle***		
alarm3	-1.50	-4.10	ASC	-2.72	-7.33
light rain	2.24	4.22	snow alarm	-1.60	-4.06
very heavy rain	-2.31	-3.7	light rain	1.05	2.96
light snow	-1.10	-2.87	light snow	-0.72	-2.27
heavy snow	-2.84	-4.95	heavy snow	-2.07	-4.50
highway car group	-6.99	-7.02	highway car group	-1.78	-6.77
highway car very heavy rainfall	-3.53	-3.57	highway car very heavy rainfall	1.24	4.24
public transport very heavy rainfall	2.21	3.53	SIGMA	-2.35	-11.99

SIGMA	-3.58	-7.09			
Public transport			***Public transport***		
light rain	1.13	3.05	ASC	-9.33	-4.31
heavy snow	-1.09	-3.46	SIGMA	-5.23	-5.26
highway car group	-4.18	-8.00			
non-highway car group	-1.66	-3.34			
public transport group	6.90	9.24			
public transport heavy snowfall	-1.08	-2.73			
SIGMA	3.06	9.29			
Not making a trip			***Not making a trip***		
ASC	0.00	reference	ASC	0.00	reference
Log-likelihood	-1386.50			-1348.86	
Rho-square	0.714			0.430	

First, the results for utilitarian trips are discussed. The attribute temperature was excluded from the analysis because temperature was too highly correlated with the current weather and weather forecast, leading to misspecification of the model. From the attributes that were included into the analysis (current weather, weather forecast and weather alarm) it can be concluded that the weather forecast does not have an influence on the travel behaviour for utilitarian trips. The current weather and a weather alarm, on the other hand, have significant effects on the adaptation of travel behaviour. Rainfall, however, does not have a significant effect on trip generation. Heavy snowfall, on the other hand, results in an increase in the probability of not making the trip. Mode choice changes for utilitarian travellers do not occur a lot as a result of the weather. There is a very small change in the cyclists group towards the usage of the car, but this effect can be considered marginal. Route choice changes for car users resulting from weather conditions are also limited. Travellers that normally use the highway will not change their route and will avoid the highway in case of severe weather conditions. Also, changing the route is not very common for non-highway travellers. Departure time changes only occur if there is a weather alarm. Overall, it can be concluded that the effect of weather conditions on departure time change is limited. The biggest decision that utilitarian travellers make is whether to stay at home or make their normal trip.

The influence of the weather conditions on recreational trips is slightly different from the utilitarian trips. In the case of a recreational trip purpose, the weather forecast plays a small role in the choice to avoid the morning peak. It leads to a positive approach to avoiding the morning peak when travellers know that the weather is going to improve. Both the current weather and the weather alarm influence adaptation of travel behaviour more effectively for recreational trips compared to utilitarian trips. Trip generation of recreational trips is a significantly influenced by adverse weather conditions. Heavy rainfall leads to relative high probabilities of staying at home. Heavy snow combined with a snow or icy roads alarm even leads to probabilities of 67.4% to 80.4% to decide not to make the trip; these are remarkably high probabilities. Mode choice changes for recreational travellers occur more than for utilitarian travellers as a result of the weather. In the rain scenario there is a significant modal shift from cyclists towards the car. Route choice changes for recreational trips are mostly comparable to utilitarian trips. There is however a relatively high route choice change (up to 22.3%) for the non-highway users group in case of heavy rain. The departure time is changed more often in comparison to utilitarian trips. Overall, it can be said that the alternative to avoid the morning peak period is preferred by recreational trip travellers. A possible explanation for this is (to some extent) the more flexible nature of the recreational trips as compared to utilitarian trips.

As a result of the behavioural adaptation of travellers, the highway traffic demand increases by 2.3% with light rainfall. Highway traffic demand decreases by 2.3% in the heavy rainfall scenario and by 7.7% compared to dry weather as a result of very heavy rainfall. Light snowfall leads to a decrease of 22.2%, while heavy snowfall leads to a decrease of 29.4% in comparison to the dry weather traffic demand. The addition of a weather alarm results in the demand being reduced by 19.4% in case of heavy rain and a rain alarm. Heavy snow and a snow alarm leads to a reduction of 48.8% and heavy snow in combination with an icy roads alarm results in a decrease of 52.4% of highway traffic demand in comparison with dry weather.

Effect of precipitation on breakdown probability

A generic model is developed that provides information regarding the breakdown probability of all Dutch highways. Input that is necessary to arrive at the breakdown probability is the median capacity value and the traffic flow in the different precipitation scenarios. The difference in traffic flow relating to one standard deviation in breakdown probability is computed for all bottleneck situations and scenarios, and the average of these values is taken. This results in corresponding traffic flow changes at one standard deviation of 8.6% for dry weather, 7.0% for light rainfall and 7.4% for heavy rainfall. Due to the different standard deviations for the different rain scenarios, one function and plot is made for each of the scenarios, which can be seen in figure 2, 3 and 4.

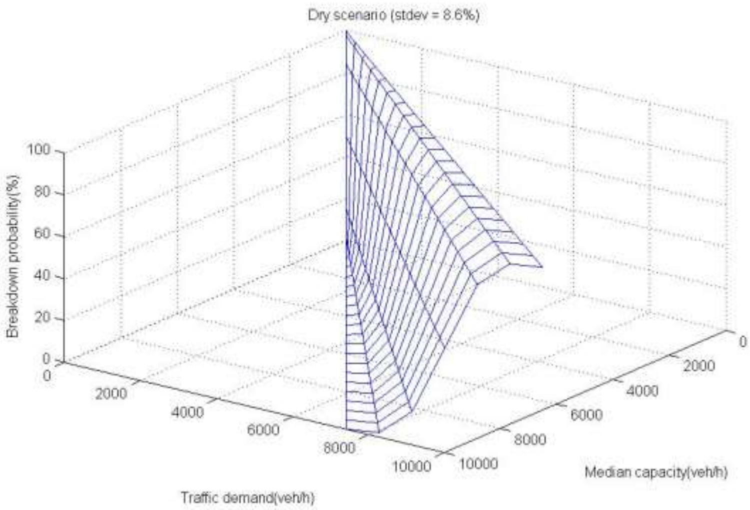

Figure 24 - 3D-plot breakdown probability dry scenario

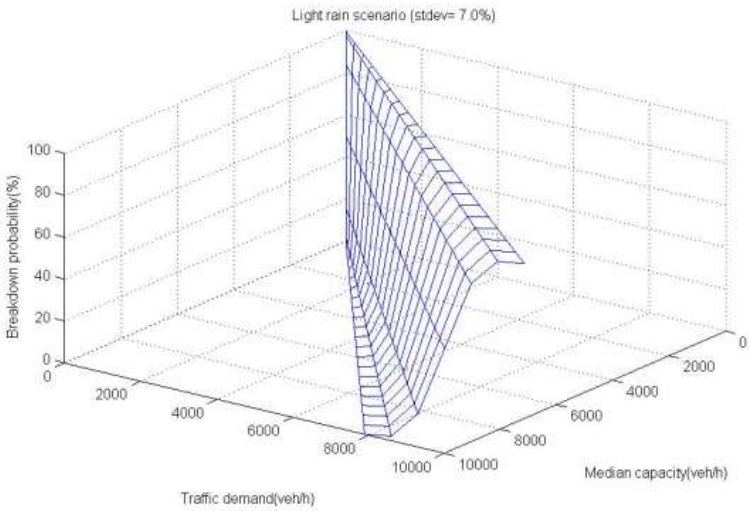

Figure 25 - 3D-plot breakdown probability light rain scenario

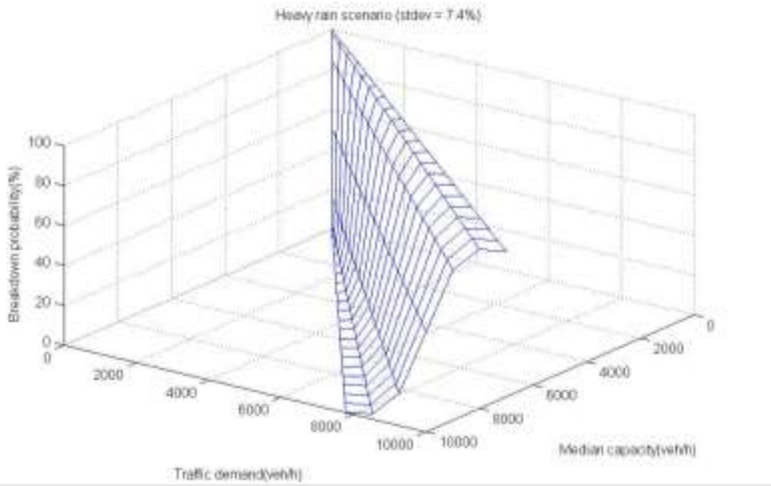

Figure 26 - 3D-plot breakdown probability heavy rain scenario

With the development of the three generic models, breakdown probabilities can be calculated for any given traffic demand and median capacity. When the median capacity value of a certain bottleneck and the traffic demand are known, the intersection of this point with the function leads to the breakdown probability value. The resulting breakdown probability in the dry scenario can be used as a reference value. Inserting the adjusted traffic flow (reference traffic flow with the demand change) and the reduced median capacity into the model leads to a probability of breakdown in that scenario for that specific highway. The results are shown in Table 5.

Table 5 - The effect of rain no breakdown probability

highway	traffic flow median capacity dry (veh/h)	traffic flow light rain (veh/h)	median capacity light rain (veh/h)	breakdown probability light rain (%)	traffic flow heavy rain (veh/h)	median capacity heavy rain (veh/h)	breakdown probability heavy rain (%)
A4R-2007	4452	4554	4264	83.2%	4350	3993	87.0%
A4R-2008	4426	4528	4148	88.4%	4324	3949	88.1%
A4L-2007	4368	4468	4196	81.7%	4268		
A12R-2007	7173	7338			7008	6648	75.2%
A12R-2008	4690	4798	4497	82.7%	4582		
A15L-2008	7267	7434	6944	84.2%	7100		
A15L-2007	4351	4451			4251	3937	85.2%
A15L-2008	4117	4212			4022	3710	86.0%
A20R-2007	6072	6212	5721	87.3%	5932		
A20R-2008	5939	6076			5802	5491	76.3%
A20R-2009	4205	4302			4108	3744	88.5%
A20L-2007	6060	6199			5921	5827	57.7%
A20L-2008	6064	6203			5925	5839	57.0%
A20L-2009	6121	6262			5980	5756	68.2%
A27L-2007	3938	4029			3847	3698	68.9%
A27L-2008	3931	4021	3627	91.7%	3841		
A50R-2007	4224	4321			4127	3756	88.8%
A50L-2007	4181	4277	3807	94.6%	4085	3843	79.2%
			average	86.7%		Average	77.4%
			STDEV	4.6%		STDEV	11.4%

In Table 5, the traffic flow corresponding to the median capacity is used as a reference value. If the traffic flow is equal to the median capacity, this results in a breakdown probability of 50%. The traffic demand changes of +2.3% for light rain and -2.3% result in the traffic flow values per bottleneck location in these scenarios. Next to that, the median capacity values for the bottleneck locations in the different scenarios are presented. These values can be entered into the generic formula, which leads to a breakdown probability for these specific locations in the different scenarios. The breakdown probabilities in the light rain scenario are based on the generic formula for light rain and the results for heavy rain are based on the formula for the heavy rain scenario.

As seen in Table 5, the average breakdown probability increases from 50% to 86.7% due to light rain. This is the result of the decreased capacity and an increasing traffic demand in this scenario. The range of breakdown probabilities for the different locations is between 81.7% and 94.6%, which can be explained by the different capacity reductions for the bottleneck locations. In the heavy rain scenario the average breakdown probability is increased from 50% to 77.4%. There is a bigger range in the breakdown probability for heavy rain scenario resulting from the relative low breakdown probability at highway A20L and A27L. The average probability of breakdown is lower than in the light rain scenario, while the average capacity reduction in the heavy rain scenario is bigger than in the light rain scenario. This is the result of the decreased traffic demand in the heavy rain scenario.

CONCLUSIONS

This paper reports on the first study that incorporates both the highway traffic demand change and the highway capacity reduction in the estimation of the congestion probability as a result of adverse weather conditions for the Dutch highways. A stated adaptation experiment has been conducted and a Panel Mixed Logit model is estimated to arrive at a highway traffic demand as a result of adverse weather. To examine the influence of precipitation on highway capacity, distribution functions were estimated for dry weather, light rain and heavy rain based on the Product Limit Method. With the development of a generic model based on a cumulative normal distribution, breakdown probabilities can be calculated for any given traffic demand and capacity.

Capacity reductions at one bottleneck location are very robust and do not change significantly over the years. The difference in capacity reduction between observations at different locations could be the result of differences in precipitation intensities during a year at the different locations, but a more plausible conclusion is that the different highway characteristics lead to the effect of rainfall on highway capacity being different at those locations. The road surface at the different locations might be an important factor in the reduction of highway capacity. When research leads to the conclusion that different road surfaces lead to other capacity reductions, the road authorities could take into consideration changing the road surface at the bottleneck locations to the surface that reduces capacity the least.

The most important result of the stated adaptation experiment is that the highway traffic demand increases by 2.3% with light rainfall and decreases by 2.3% in the heavy rainfall scenario as a result of the behavioural adaptation of travellers. The relatively small influence of rain on highway traffic demand in the morning peak significantly influences the breakdown probability at the highways. An increase in demand of only 2.3% could lead to an increase in breakdown probability of 11 percentage points at a specific bottleneck location.

Combining both the traffic demand change and the capacity reduction leads to the conclusion that rainfall leads to a significant increase in probability of breakdown at bottleneck locations. A breakdown probability of 50% in dry weather leads to an average breakdown probability of 86.7% in light rain and 77.4% in heavy rain conditions. The higher breakdown probability in light rainfall is the result of the increased traffic demand. It can be concluded that both traffic demand and highway capacity should always be incorporated in the analysis to arrive at accurate predictions regarding breakdown probabilities. The results regarding the different increases in breakdown probability at different locations as a result of precipitation can be taken into account by the Ministry of Infrastructure and the Environment in the decision to assign budgets to highway improvement projects. Investing in the bottleneck locations at which rain leads to the biggest increase in breakdown probability could be more interesting. This way the Ministry's chances of reaching the goals of reduction of congestion will increase.

DISCUSSION

The results obtained regarding the demand changes in this research have three limitations. Firstly, the results are based on stated behaviour instead of revealed behaviour. The disadvantages might be that the stated behaviour differs from actual behaviour and that hypothetical weather situations were differently interpreted by respondents. Secondly, the results of the travel behaviour analysis are average changes in highway traffic demand. With the high importance of small changes in travel demand, investigating the effect of rain location specific on the highway traffic demand should be considered. Thirdly, there was no data available of the number of travellers in the different travel groups (car highway, car non-highway, public transport and bicycle). In this study the importance of the groups was based on the number of respondents in the groups. Data regarding the division of the groups in the population could have increased the accuracy of the traffic demand predictions. The three limitations can be overcome through travel data that will become available in the near future. TNO is developing a smartphone application that can track the trips made by the travellers via GPS. Such an application has already been used by TNO in a project in Assen. Furthermore, there are plans for an application to be used by 500.000 Dutch travellers. In the future, revealed data from 500.000 travellers can provide information regarding location specific demand changes as a result of the weather. In addition, the standard mode of each traveller could be investigated by analysing the GPS data to be able to weigh the travel groups based on the share of the travel groups in the population. This data from the smartphone tracking application project of TNO can be an addition to the results obtained in this study.

From the conclusions, it can be inferred that the capacity reductions and breakdown probabilities at different bottleneck locations are location specific. The increase in breakdown probability as a result of rainfall at one specific location does not have to be an accurate estimate for bottleneck locations that are not included in this study. It is therefore not recommended to apply the average results in this study to other highway bottleneck locations. Further research into the capacity reducing effect of rainfall at other bottleneck locations is therefore advisable.

An analysis of the effect of snow on highway capacity could provide a valuable addition to the results of this study. In order to come to sufficient breakdown observations on days with snowfall, it is advised to combine the traffic data from different years at the same bottleneck location. The snow analysis would be more accurate if reliable location specific snowfall information could be obtained. Lastly, it might be valuable to analyse whether the filtering algorithm can cope with breakdown observations at snow conditions.

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Appendix 2 – Online survey

1. Wat is uw geslacht?
   - Man
   - Vrouw

2. Ik ben in ______ geboren (voorbeeld: 1980)

3. De vier cijfers van mijn postcode zijn ______

4. Wat is uw werksituatie?
   - Werkend
   - Niet werkend
   - Student
   - Gepensioneerd

5. Hoeveel dagen in een normale werkweek (maandag t/m vrijdag) reist u in de ochtendspits (tussen 06:00 en 10:00) met als reden **werk** (woon-werk, werk of opleiding)?
   - 0 dagen
   - 1 dag
   - 2 dagen
   - 3 dagen
   - 4 dagen
   - 5 dagen

6. Hoeveel dagen in een normale werkweek (maandag t/m vrijdag) reist u in de ochtendspits (tussen 06:00 en 10:00) met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc)?
   - 0 dagen
   - 1 dag
   - 2 dagen
   - 3 dagen
   - 4 dagen
   - 5 dagen

7. Welk vervoermiddel gebruikt u in een normale week in de meeste gevallen voor een rit met reden **werk** (woon-werk, werk of opleiding) gedurende de ochtendspits (tussen 6:00 en 10:00)?
Let op: Indien u gebruik maakt van meerdere vervoermiddelen gedurende één reis, kiest u dan het vervoermiddel waarmee u de meeste kilometers aflegt.

- de auto (of motor) over de snelweg
- de auto (of motor) niet over de snelweg
- het openbaar vervoer
- de fiets

8. De afstand naar mijn werk (of opleiding) is ____ kilometer.

9. Hoeveel van de ingevulde **X** dagen per normale week in de ochtendspits gebruikt u **niet** de auto (of motor) over de snelweg voor reizen met reden **werk** (woon-werk, werk of opleiding)?

- 0 dagen
- 1 dag
- 2 dagen
- 3 dagen
- 4 dagen
- 5 dagen

10. Hoeveel van de ingevulde **X** dagen per week bent u door flexibele indeling van de starttijd van uw werk in staat om de ochtendspits mijden (voor 06:00 of na 10:00)?

- 0 dagen
- 1 dag
- 2 dagen
- 3 dagen
- 4 dagen
- 5 dagen

11. Hoeveel van de ingevulde **X** dagen per week die u reist in de ochtendspits met als reden **werk** heeft u de mogelijkheid om thuis te werken?

- 0 dagen
- 1 dag
- 2 dagen
- 3 dagen
- 4 dagen
- 5 dagen

12. Welk vervoermiddel gebruikt u in een normale week in de meeste gevallen voor een rit met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) gedurende de ochtendspits (tussen 6:00 en 10:00)?
Let op: Indien u gebruik maakt van meerdere vervoermiddelen gedurende één reis, kiest u dan het vervoermiddel waarmee u de meeste kilometers aflegt.

- de auto (of motor) over de snelweg
- de auto (of motor) niet over de snelweg
- het openbaar vervoer
- de fiets

13. Hoeveel van de ingevulde **X** dagen per normale week in de ochtendspits gebruikt u **niet** de auto (of motor) niet over de snelweg voor reizen met reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc)?

- 0 dagen
- 1 dag
- 2 dagen
- 3 dagen
- 4 dagen
- 5 dagen

14. Hoeveel van de ingevulde **X** dagen per week met de reden **sociaal-recreatief** bent u in staat om de ochtendspits te mijden (voor 06:00 of na 10:00)?

- 0 dagen
- 1 dag
- 2 dagen
- 3 dagen
- 4 dagen
- 5 dagen

Uitleg deel twee van de enquête

In het volgende deel van de enquête wordt onderzocht wat de invloed van het weer en weersvoorspellingen is op uw reisgedrag.
Hieronder kunt u een voorbeeldsituatie vinden:

Huidige temperatuur	25°C
Huidige weer	Zware regenbui 
Weerbericht	Het blijft de hele dag soortgelijk weer
Weeralarm	Code rood voor zware regenbuien

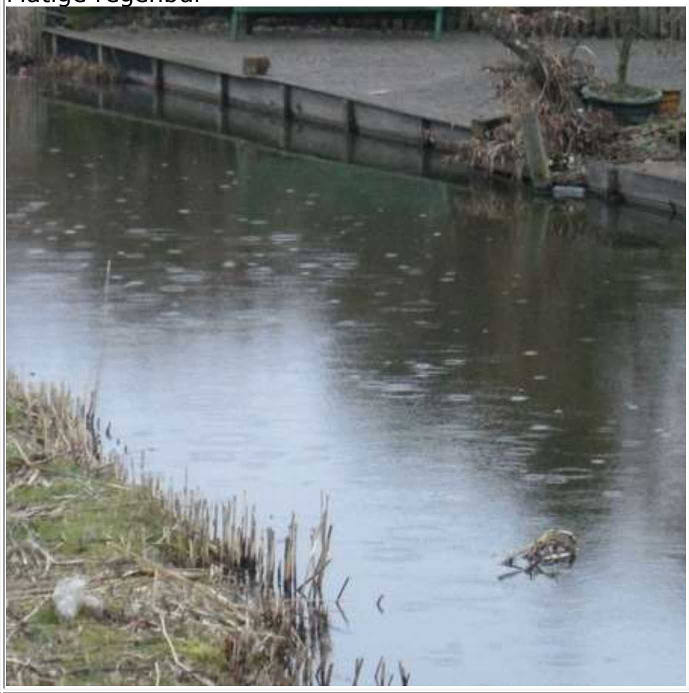
De uitgangspositie is dat u een reis heeft gepland in de ochtendspits.
Aan u wordt de vraag gesteld wat u zou doen in de voorgelegde weersituatie.
Dit kan gaan om een reis met de reden werk of met de reden sociaal-recreatief.

- De **huidige temperatuur** kan -5, 10 en 25 graden Celsius zijn.
- Het **huidige weer** kan droog, matige regenbui, zware regenbui, matige sneeuwbui en zware sneeuwbui zijn.
- Het **weerbericht** geeft aan dat het weer kan verbeteren en verslechteren in de loop van de dag, of kan gelijk zijn aan het huidige weer.
- Het **weeralarm** is het alarm dat het KNMI in extreme weerssituaties uitgeeft. Code rood voor zware regenbuien, zware sneeuwbuien of gladheid kunnen voorkomen.

○ Ik heb de uitleg gelezen

Questions survey 1

16. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	25°C
Huidige weer	Matige regenbui 
Weerbericht	In de loop van de dag zal het weer verbeteren
Weeralarm	Geen weeralarm

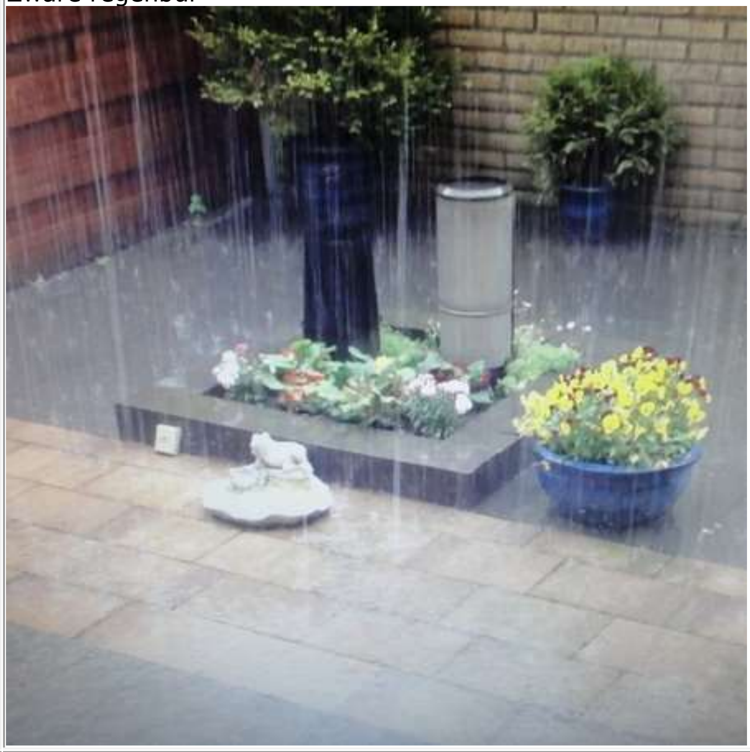
Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

17. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

18. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	10°C
Huidige weer	Zware regenbui 
Weerbericht	In de loop van de dag zal het weer verbeteren
Weeralarm	Code rood voor zware regenbuien

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

19. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

20. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	-5°C
Huidige weer	Zware sneeuwbui 
Weerbericht	In de loop van de dag zal het weer verbeteren
Weeralarm	Code rood voor zware sneeuwbuien

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

21. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

22. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	25°C
Huidige weer	Droog
Weerbericht	In de loop van de dag zal het weer verslechteren
Weeralarm	Code rood voor zware regenbuien

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- ○ Ik ga met de auto over de snelweg
- ○ Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- ○ Ik ga met de auto, maar ik mijd de snelweg
- ○ Ik ga met de fiets
- ○ Ik ga met het openbaar vervoer
- ○ Ik besluit om niet te gaan

23. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- ○ Ik ga met de auto over de snelweg
- ○ Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- ○ Ik ga met de auto, maar ik mijd de snelweg
- ○ Ik ga met de fiets
- ○ Ik ga met het openbaar vervoer
- ○ Ik besluit om niet te gaan

24. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	-5°C
Huidige weer	Matige sneeuwbui 
Weerbericht	De hele dag blijft het soortgelijk weer
Weeralarm	Code rood voor gladheid

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

25. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

26. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	-5°C
Huidige weer	Zware sneeuwbui 
Weerbericht	In de loop van de dag zal het weer verbeteren
Weeralarm	Geen weeralarm

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
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27. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

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- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

28. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	10°C
Huidige weer	Matige regenbui 
Weerbericht	In de loop van de dag zal het weer verslechteren
Weeralarm	Code rood voor zware regenbuien

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
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- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

30. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	-5°C
Huidige weer	Droog
Weerbericht	In de loop van de dag zal het weer verbeteren
Weeralarm	Geen weeralarm

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
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- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

31. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

32. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	25°C
Huidige weer	Matige regenbui 
Weerbericht	In de loop van de dag zal het weer verslechteren
Weeralarm	Geen weeralarm

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

33. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

34. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	-5°C
Huidige weer	Zware sneeuwbui 
Weerbericht	De hele dag blijft het soortgelijk weer
Weeralarm	Code rood voor zware sneeuwbuien

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

35. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

Questions survey 2

16. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	10°C
Huidige weer	Droog
Weerbericht	De hele dag blijft het soortgelijk weer
Weeralarm	Geen weeralarm

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

17. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

18. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	25°C
Huidige weer	Zware regenbui 
Weerbericht	In de loop van de dag zal het weer verbeteren
Weeralarm	Code rood voor zware regenbuien

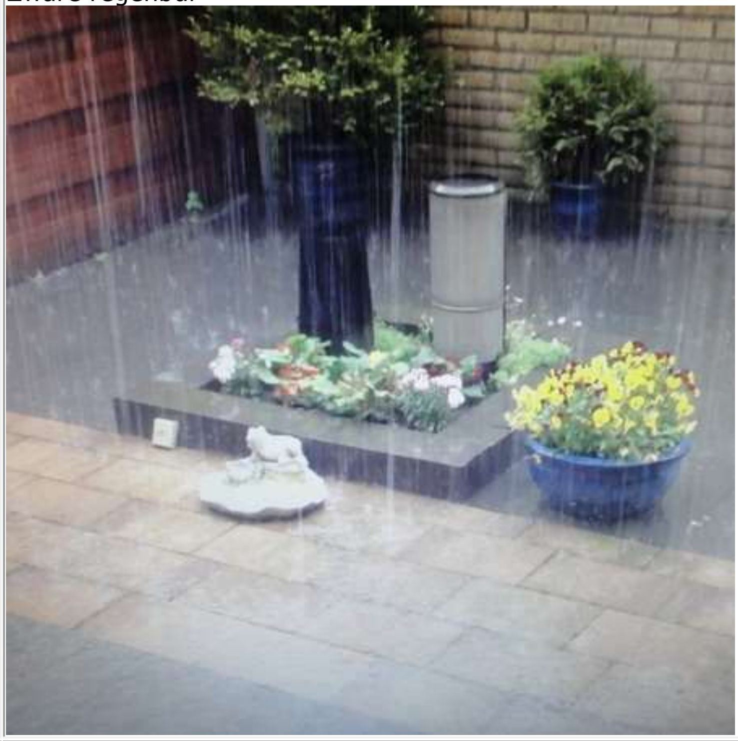
Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

19. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

20. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	25°C
Huidige weer	Zware regenbui 
Weerbericht	De hele dag blijft het soortgelijk weer
Weeralarm	Code rood voor zware regenbuien

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

21. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

22. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	-5°C
Huidige weer	Matige sneeuwbui 
Weerbericht	In de loop van de dag zal het weer verslechteren
Weeralarm	Geen weeralarm

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

23. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

24. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	10°C
Huidige weer	Matige regenbui 
Weerbericht	In de loop van de dag zal het weer verbeteren
Weeralarm	Geen weeralarm

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

25. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

26. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	-5°C
Huidige weer	Droog
Weerbericht	De hele dag blijft het soortgelijk weer
Weeralarm	Code rood voor gladheid

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
- Ik ga met de auto, maar ik mijd de snelweg
- Ik ga met de fiets
- Ik ga met het openbaar vervoer
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27. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

- Ik ga met de auto over de snelweg
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- Ik besluit om niet te gaan

28. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	-5°C
Huidige weer	Zware sneeuwbui 
Weerbericht	In de loop van de dag zal het weer verbeteren
Weeralarm	Code rood voor gladheid

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

- Ik ga met de auto over de snelweg
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- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

30. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	**-**5**°**C
Huidige weer	Matige sneeuwval 
Weerbericht	In de loop van de dag zal het weer verslechteren
Weeralarm	Code rood voor zware sneeuwbuien

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

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- Ik ga met de auto, maar ik mijd de spits (voor 06:00 of na 10:00)
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32. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	10°C
Huidige weer	Zware regenbui 
Weerbericht	In de loop van de dag zal het weer verbeteren
Weeralarm	Geen weeralarm

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

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33. Wat doet u als dit een reis met de reden **sociaal-recreatief** (visite, boodschappen, winkelen, uitstapjes, sport, etc) betreft?

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34. Stel dat u op een ochtend een reis gepland heeft in de ochtendspits en de weersituatie ziet er als volgt uit:

Huidige temperatuur	**-**5**°**C
Huidige weer	Matige sneeuwbui 
Weerbericht	In de loop van de dag zal het weer verbeteren
Weeralarm	Geen weeralarm

Wat doet u als dit een reis met reden **werk** (woon-werk, werk of opleiding) betreft?

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- Ik ga met de fiets
- Ik ga met het openbaar vervoer
- Ik besluit om niet te gaan

Appendix 3 – Design syntax

In this appendix the design syntax of the MNL design to minimize the number of respondents that is used is presented.

```
Design
;alts = alt1,alt2
;rows = 20
;block = 2
;eff = (mnl,s)

;cond:
?als de huidige temperatuur 5 graden is, dan kan het niet regenen
if(alt2.temp = 0, alt2.weer = [0.3.4] and alt2.alarm = [0.2.3]),
?als de huidige temperatuur 10 of 25 graden is, dan kan het niet sneeuwen
if(alt2.temp = [1.2], alt2.weer = [0.1.2] and alt2.alarm = [0.1]),
? als er een regenalarm is en het huidige weer is regen, dan moet het weerbericht slechter zijn
if(alt2.alarm = 1 and alt2.weer = 1, alt2.weerbericht = 0),
? als er een sneeuwalarm is en het huidige weer is sneeuw, dan moet het weerbericht slechter zijn
if(alt2.alarm = 2 and alt2.weer = 3, alt2.weerbericht = 0),
?als huidige weer is veel sneeuw en bericht is gelijk of slechter, dan alarm code rood sneeuw
if(alt2.weer = 4 and alt2.weerbericht = [0.1], alt2.alarm = 2),
?als huidige weer is veel regen en bericht is gelijk of slechter, dan alarm code rood regen
if(alt2.weer = 2 and alt2.weerbericht = [0.1], alt2.alarm = 1),
?als het droog is en weerbericht is gelijk of beter, dan kan er geen sneeuw of regen alarm zijn
if(alt2.weer = 0 and alt2.weerbericht = [1.2], alt2.alarm = [0.3])

;model:
U(alt2) =  b1[-0.864] + b2.effects[1.09|-0.554]*temp[0.2.1] +
b3.effects[0|0|0|0.443]*weer[1.2.3.4.0] + b4.effects[-0.193|0.305]*weerbericht[0.2.1]+
b5.effects[0|0.638|-0.395]*alarm[1.2.3.0] + b6*temp*weer + b7*temp*alarm + b8*weer*alarm
$
```