QUANTIFYING THE FULL RELIABILITY BENEFITS OF ROAD NETWORK IMPROVEMENTS

Maaike Snelder, TNO, Van Mourik Broekmanweg 6, P.O. Box 49, 2600 AA Delft, The Netherlands, maaike.snelder@tno.nl; TRAIL research school PhD Student.

Lori Tavasszy, TNO, Van Mourik Broekmanweg 6, P.O. Box 49, 2600 AA Delft, The Netherlands, lori.tavasszy@tno.nl; Delft University of Technology, Faculty of Technology, Policy and Management, Transport and Logistics' Organization.

ABSTRACT

Assessing travel time reliability and the robustness of networks (especially road networks in major urban areas) is becoming more important as networks become more vulnerable. Especially in the Netherlands, the interconnectivity of networks of different scale is low and the level of usage is high, which leads to low spare capacities for unfavorable conditions. Also, the number of incidents is high and increasing. The Randstad area, lying between Amsterdam, The Hague, Utrecht and Rotterdam, experiences about 1750 incidents a year with a clearance time of over one hour. Already small disturbances can cause major disruptions on large parts of the network. As such we can expect that major benefits could be gained from measures that improve the stability of operating conditions of the road network under unfavorable circumstances.

In 2008 the Dutch Ministry of Transport, Public Works and Water Management published the "MobiliteitsAanpak" (Mobility Approach) (Ministry of Transport, Public Works and Water Management, 2008). This policy document proposes investments in the Dutch road, rail, regional public transport and waterways network to improve travel times and their reliability and reduce negative external effects of transport. By assignment of the Dutch Ministry of Transport TNO evaluated the benefits of the Euro 30bn's worth of investment in the road network between 2020 and 2028. New in this analysis was that, in addition to travel time gains, we assessed the full reliability benefits of transport projects, where, next to the small travel time variations we also included the effects of major disruptions, where the robustness of the transport network is critical.

Traditionally benefits related to improved travel time reliability were assessed using crude rules of thumb which are not related to the present or the future state of the network. In the Netherlands, a 25% markup is applied to travel time benefits. This number is based on expert judgment. Instead of using this fixed markup we chose to assess the benefits of improved robustness of the network by using Monte Carlo simulation to compute the reduction of travel time losses under disturbed travel times (reliability analysis). We included both small, frequent and large, infrequent variations in travel time. Furthermore, we proposed a second method that focuses more on the effects of large disturbances (vulnerability analysis).

One important outcome of the analyses is that the reliability benefits of the proposed road projects are similar in magnitude as the benefits from reduction of average travel times. We also find that the outcomes are overall positive for the complete set of measures, but that effects can be negative in individual cases. In other words, there are specific situations in which the travel times become less reliable for certain travelers, despite a clear gain in average travel time under normal operating conditions. As the projects were not evaluated before with robustness in mind, an important implication of this is that the proposed set of projects in the Dutch road network strategy can be optimized further, bearing in mind that a trade-off between travel time and reliability may lead to different projects.

Finally, we showed that splitting through traffic from local traffic, upgrading the secondary road network and completing ring roads makes the network more robust against large disturbances. Of course, the extent to which the robustness improves depends on the amount of spare capacity that is created, the usage of the roads under regular conditions and the distance between the original route and the fall back options.

Keywords: robustness of road networks; travel time reliability; benefits of robustness measures for road networks

INTRODUCTION

Assessing travel time reliability and the robustness of networks (especially road networks in major urban areas) is becoming more important as networks become more vulnerable. Especially in the Netherlands, the interconnectivity of networks of different scale is low and the level of usage is high, which leads to low spare capacities for unfavorable conditions. Also, the number of incidents is high and increasing. The Randstad area, lying between Amsterdam, The Hague, Utrecht and Rotterdam, experiences about 1750 incidents a year with a clearance time of over one hour. Already small disturbances can cause major disruptions on large parts of the network. As such we can expect that major benefits could be gained from measures that improve the stability of operating conditions of the road network under unfavorable circumstances.

In 2008 the Dutch Ministry of Transport, Public Works and Water Management published the “MobiliteitsAanpak” (Mobility Approach). This policy document proposes investments in the Dutch road, rail, regional public transport and waterways network to improve travel times and their reliability by improving the robustness of the networks and reduce negative external effects of transport. By assignment of the Dutch Ministry of Transport TNO evaluated the benefits of the Euro 30 billions worth of investment in the road network between 2020 and 2028.

Traditionally, in cost-benefit analysis (CBA) reliability benefits are not considered or only in a very simplified way. In the Netherlands, benefits related to improved travel time reliability were sometimes assessed using a rule of thumb (a 25% markup is applied to travel time benefits) which is not related to the present or the future state of the network. However, since the "MobiliteitsAanpak" focuses on measures that make the network more robust the question rose what the reliability/robustness benefits of these measures is. Therefore, in addition to travel time gains, we assessed the full reliability benefits of transport projects, where, next to the small travel time variations we also included the effects of major disruptions, where the robustness of the transport network is critical. Furthermore, we analyzed the benefits of a set of combined projects on a program level. Of course, the different projects in a program can not be considered independently, since the projects also have an impact on each other. Nevertheless, some projects are more beneficial than others. Therefore, we analyzed some example projects, to get a better understanding of the impacts of different projects. As far as the authors are aware this is the first large scale impact study reported in the literature in which reliability/robustness benefits are explicitly computed, not using a rule of thumb.

Computing the reliability benefits for an investment program that covers the whole Netherlands is both a methodological and computational challenge since the effects of many different disturbances have to be forecasted on many different locations. This is especially difficult since forecasting the effects of a single disturbance is already a complex task in itself due to the inherent uncertain nature of disturbances and the uncertain response of humans in case of disturbances.

This paper aims to give an example of how the reliability benefits of robustness related measures can be computed on a large scale network. In this paper we start by introducing some definitions and indicators for robustness and reliability. Thereafter, we describe the two methods that we use for the evaluation of these indicators. In the section thereafter we describe the proposed measures of the "MobiliteitsAanpak" and their impacts on a program level. Furthermore, we zoom in to a few specific example projects that indicate that the reliability benefits differ per project. In the last section we conclude the paper with the main findings and recommendations.

DEFINITION AND INDICATORS FOR ROBUSTNESS AND RELIABILITY

We define robustness as the extent to which a network is able to maintain the function where it was originally designed for under pre-specified circumstances. Vulnerability is the opposite of robustness. A network that is vulnerable is not robust, and vice versa.

This definition has three components which are explained below:

- Function: The most general function of a road network is to enable trips from origins to destinations. To achieve an adequate road network design it has to be known for which kind of trip a network link or network node has a function. Trips can be subdivided by the length of a trip, but also by passenger and freight transport and even trip purpose. The level at which a network has to function is usually defined by government organizations.

- Pre-specified circumstances: A network can be made robust against all kind of circumstances. It is up to the policy makers and network managers to decide how robust the network should be made against which disturbances. In this paper we focus on short term variations in supply and demand. The different disturbances that can occur are described below.

- The extent to which: The definition includes the words “the extent to which”. This implies that in case of disturbances the network doesn’t have to function just as well as it would without disturbances. From an economical perspective it is not advisable to make a network 100% robust against all disturbances. The costs of creating such a network would exceed the benefits. However, this does raise the question to which extent the network should maintain its function. This is a question that needs to be addressed by policy makers and network managers as well. A balance has to be found between investments in robustness measures and reliability benefits for travelers. Cost-benefit analysis can offer the insights to make a balanced decision.

Disturbances like accidents, special weather conditions, road works, events and seasonality’s, lead to short term variations in demand and supply. The effect of these variations depends on the behavior of drivers and network managers and on the robustness of the network. For instance, in a robust network deviations from the regular demand and supply pattern will result in less variation in travel time compared to a network with a lower robustness level.

Besides the effects, also the chances on these disturbances are relevant. In risk theory this is expressed as follows: risk = probability x effect. The above mentioned disturbances lead to a travel time distribution which is shown in figure 1. In this figure both the probability (frequency) and the effect (horizontal axis) are shown. If robustness issues are discussed, it is advisable to clearly indicate against which disturbances a network is to be made robust. In this paper we focus in principle on the entire travel time distribution. However, extreme circumstances like earthquakes and flooding are not considered since they have a very low probability of occurrence.

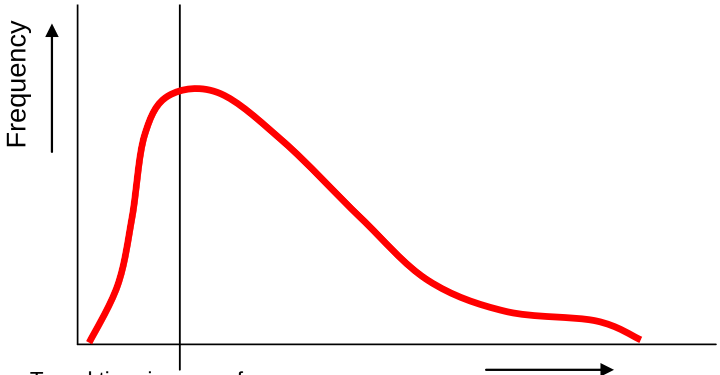

Figure 1 – Travel time distribution.

The travel time distribution that is shown above brings us to the concept of reliability. The most accepted definition of the network reliability is given by (Billington and Allan, 1992) and (Wakabayashi and Iida, 1992): *Reliability is the probability of a road network performing its proposed service level adequately for the period of time intended under the operating conditions encountered.*

Although reliability and robustness have a strong relation, they are not identical. It is clear that robustness is a property of the system. By contrast, the reliability of the travel time is something that the traveler experiences. Immers et al. (2004) expressed this as follows: reliability is a user oriented quality while robustness is a characteristic of the system itself. In addition to this distinction, there are three other distinctions we can make:

1. Where reliability is concerned, the emphasis lies on disturbances that occur at regular intervals, whereas with robustness the emphasis lies on disturbances that occur unexpectedly and that have a large impact. However, a strict distinction can not be made because road networks can be made robust against all kind of disturbances (disturbance with small and large effects) and all disturbances have an influence on the reliability of travel times.

2. Reliability is geared towards an average spread in the travel time and must therefore be determined over a longer period (ranging from several days to a year). With robustness, the emphasis lies on the period in which the effect of a specific disturbance is noticeable and focuses on the impact of single disturbances and not so much on probabilities that these disturbances occur.

3. In the case of reliability, the emphasis lies on the chance that a specific disturbance occurs, and with robustness the emphasis lies on the effect as was also noted by others. Husdal (2004) noted that probability or predictability is a major concern in network reliability studies. The impacts or consequences of disturbances are the focus of vulnerability studies. D'Este and Taylor (2003) note that vulnerability and reliability are two related concepts, but emphasize that network vulnerability relates to network weaknesses and the economic and social consequences of network failure,

not so much to the probability of failure. This distinction is of course dependent on the two previous points taken together.

Now that we have defined robustness and reliability, the question can be asked which indicators we should use to evaluate those concepts. So far, no generally accepted indicator for robustness has been introduced. In (Chen et al., 200) the indicator capacity reliability is introduced, which includes connectivity reliability as a special case and also provides travel time reliability as a side product. In (Murray-Tuite and Mahmassani, 2004, Tampère et al., 2007, Li, 2008) different other indicators can be found. Of course, also others use similar or other indicators. These indicators usually focus on non predictable disturbances like incidents. In this paper we focus on the complete travel time distribution which implies that the regularly occurring disturbances that are usually included in reliability analysis should also be considered. Reliability indicators are often categorized as follows (Texas Transportation Institute and Cambridge systems Inc., 2006, Lomax et al., 2003):

1. Statistical range methods like the standard deviation.
2. Buffer time methods: the extra percentage travel time due to travel time variability on a trip that a traveler should take into account in order to arrive on time.
3. The so-called ‘‘tardy-trip’’ measures like the misery index which takes the difference between the average travel time of the 20% worst trips with the overall travel time average.
4. Probabilistic measures like the probability that a trip can be made in time.

Van Lint et al. (2008) argue that these indicators are not consistent and show that there are empirically underpinned arguments to prefer measures that include the skew of the travel time distribution. The fact that this paper focuses on including risk analysis in cost-benefit analysis requires that the indicator that is chosen can be valued. In general there are two concepts for valuation. The first is by using a value of time. It is well known that the values of times that are used in cost-benefits analyses do not reflect unexpected delays. In those situations travel time losses are valued higher. At the moment, there are no values of time specified for non-regular situations. However, a choice could be made to just use a specific value of time and vary that assumption in a sensitivity analysis. The second concept is the concept of reliability ratios. Reliability ratios are used to value one minute of standard deviation compared to one minute of travel time. The reliability ratios that are used in literature vary between 0.3 and 2.5 (RAND, 2005). In the Netherlands, expert workshops have been organized to define appropriate reliability ratios (RAND, 2005, Kouwenhoven et al., 2005). For passenger transport a reliability ratio of 0.8 is chosen and for freight transport a reliability ratio of 1.2 is chosen. In this paper we use these values as well. Since using reliability ratios is advocated in the guidelines for cost-benefit analysis that are used in the Netherlands (Eijgenraam et al., 2000) we chose to use that method. The question can be asked whether or not using standard deviations is appropriate for valuing all disturbances. As is argued by Van Lint (2009) the effects of disturbances with extremely long delays might be underestimated if only the standard deviation is considered. Therefore, we apply a second method that focuses on the disturbances with a large effect. In the following section we turn to this method and to the method that is needed to evaluate the indicator standard deviation.

A METHOD FOR EVALUATING ROBUSTNESS

When transportation projects and policies are evaluated within cost-benefit analysis, different methods can be applied that predict the effect of these policies on travel time reliability. Ideally, the method should comply with the following 6 criteria:

1. Spill back effects should be taken into account (Knoop et al., 2007). Spill back effects occur when the queue caused by congestion or a traffic jam blocks cars that don't have to pass by the bottleneck. Spill back effects are the cause of the fact that the effects of local disturbances spread all over the network. In a robust network these effects are minimized.

2. Alternative routes should be included in the route choice. A network is more robust if alternative routes are available since they offer spare capacity that can be used in case of disturbances.

3. Time dynamics should be included, since the speed at which network performance drops during disturbances and the speed at which the network recovers after disturbances is important for the robustness.

4. The method should be able to evaluate a network of realistic size within a reasonable amount of time: since assessing robustness and reliability requires a lot of analysis of different disturbances on different locations, a method with a short computation time must preferably be used.

5. The method should be able to deal with all kind of disturbances in such a way that the complete travel time distribution is modeled.

6. The method should be able to deal with intersection delays, because in a robust road network, regional (and local) roads are an important element.

To the best of our knowledge, there is no model that covers all six requirements completely. In particular, applications in practice of reliability evaluation are scarce, mostly due to a lack of practicable models that can predict future accessibility levels resulting from policies. The main dilemma in the model choice is between accuracy and computation time. The most accurate models take in general the longest computation time. Using a network level rule of thumb takes hardly any computation time, but is the least accurate of all options and relatively unresponsive to policies. For some applications, a rule of thumb can be good enough to get a quick impression of the robustness of a network. However, to make a well balanced decision about robustness measures in network design it would be better to look for a method/model that deals with the above mentioned requirements in the best possible way.

Several researchers have noted that if the standard deviation σ (or $σ^2$) is plotted against the mean for successive time intervals, an anti-clockwise loop is often generated. This appears to be the impact of serial correlation in the data caused by the persistence of queues, and can be reproduced by dynamic assignment processes (Bates, 2009). Therefore, ideally a dynamic model is used, with a detailed congestion modeling, with multiple types of route choice behavior during incidents and with an accurate intersection modeling. Sometimes these macro- or mesoscopic dynamic models like Marple, Dynasmart, Dynameq, Madam and Indy are already used in robustness analysis. However, since they have a high computation time, especially when hundreds or thousand different disturbances on different locations have to be considered, they are not yet applied in robustness and reliability evaluation of large scale networks. The computation time problem can partly be overcome by the marginal incident computation model (MIC) (Corthout et al., 2009) by which an estimate of the impact of hundreds of incidents can analytically be obtained in a few minutes after an equilibrium run with a dynamic model has been carried out. The MIC model approximates (additional) congestion caused by an incident by superimposing it on a single base simulation of Indy (without incidents). Drivers are assumed to make the same journey (no changes in departure time, destination or route) in case of an incident as they would make in the base situation. However, this module can only simulate the effects of incidents. Therefore, the effects of other disturbances can not yet be computed within a short computation time.

Alternatives for dynamic modeling to assess the impacts of policy on reliability are the following:

1. Rules of thumb that assume a fixed relationship between time gains and reliability gains. This category includes the “multiplier” approach for travel time benefits, assuming that the product of values of reliability and reliability gains is constant. In Dutch cost-benefit analyses an additional 25% of the travel time benefits was taken as markup value to represent the benefits of reliability gains in various national project evaluations (Besseling et al, 2004).

2. A second category of methods also assumes that reliability gains follow the same patterns as time gains in the networks, but is based on empirical analysis. By regressing indicators for standard deviation of travel time on travel times itself and on other relevant indicators such as traffic volumes or speeds, a statistical relationship is derived that can be used for prediction. Examples are found in (Kouwenhoven et al., 2004) and (Peer et al, 2009).

3. While the above methods use network level, aggregate regression parameters to describe travel time variability (or benefits of changes therein) directly, a third category of models use flexible travel time distributions, traffic assignment and Monte Carlo simulation to determine the effects of variations in demand and supply in mutually dependent links and O/D pairs (see Meeuwissen et al., 2004).

For real life cases, from the methods presented above, we chose the probabilistic approach by Meeuwissen (2004) to analyze the benefits of a major network extension program for the Dutch road network. This analysis is presented in the next section. This choice was made since this model can analyze the effects of disturbances that vary from local to network wide disturbances, from disturbances with a small probability to disturbances with a large probability, from supply related to demand related ones and from those with a small effect to disturbances with a large effect. In this way the complete travel time distribution can be analyzed. As a static model is used the computation time stays within acceptable boundaries as well (15 minutes up to several hours on a regular PC). Of course, the fact that a static model is used is a disadvantage as well, because network dynamics are not captured and spill back effect are underestimated. The underestimation of spill back effect is especially a shortcoming for forecasting the effect of large disturbances. Therefore, we use a second method that looks into more detail at these disturbances.

Method 1: Reliability analysis by means of Monte Carlo simulation with a static model

Our model calculates the travel time distribution by means of Monte Carlo simulation. The model predicts the bandwidths of travel times from door to door and on the link level by randomly selecting different demand and supply situations. A statistical analysis has been carried out to get the distribution for the following four situations:

- Demand, generic: influence of seasons.
- Demand, specific: events
- Capacity, generic: weather.
- Capacity, specific: accidents and road maintenance.

Factors and probabilities are determined for these four situations by means of statistical analysis. The factors indicate how much the demand differs from the nominal demand and how much the capacity of the road differs from the capacity under normal circumstances. Furthermore, for different weather conditions there are speed factors as well. The factors are divided in several classes. The probabilities show how often the different classes occur. Below, it is explained how the statistics are determined. The statistical analysis is based on data from before 2004. Of course, an update could be made, however it is likely that these statistics won't change much over time.

The statistics for the influence of seasons are based on large scale surveys that are carried out in the Netherlands (OVG/MON) of 1999, 2000 and 2001 in which people were asked to keep a diary of all the trips that they made within a certain period. Three years were taken to increase the reliability of the data. All trips were selected that were made on weekdays excluding the public holidays in the period 7.00 - 9.00 hour and 16.00 - 18.00 hour for the peak period and in the period 6.00 – 7.00 hour, 9.00 - 16.00 hour and 18.00 - 24.00 hour for the off-peak period. For the peak and off-peak period the total number of trips per day was determined. Twenty classes have been distinguished in such a way that the horizontal distance between the classes (factors number of trips) is equal. The nominal demand is the median of the daily demand. The variations in demand caused by seasonality's are applied to the complete origin-destination matrix.

The statistics for events are based on the top 45 of events in the Netherlands. For these events the number of cars per hour and the probability on the event (related to the number of opening days) are determined. In (Meeuwissen et al, 2004) it is in detail explained how this is done. The number of visitors or cars per event is not uniformly registered for all events. Therefore, for each event different conversions had to be made from yearly or daily number of visitors to number of visitors per hour and from number of visitors to number of cars. Furthermore, the arrival times had to be determined, since the arrival times are not spread uniformly over time. For the events, for which the arrival time distribution was not known, it was assumed that all visitors arrive within a time frame of two hours. Only the events with a probability lower than 40% that occur on weekdays are selected. The other events either occur that often that they are already included in the nominal situation or they occur on weekend days and are therefore not relevant for our weekday analysis. For each event it is known in which region they take place. The origins are spread proportionally with the regular demand to that region.

The statistics for the five different weather conditions (fog, rain + darkness, rain + daylight, dry + darkness, dry + daylight) are based on the weather registration of the Royal Netherlands Meteorological Institute (KNMI), known capacity reduction factors for rain and darkness (Ministry of Transport, Public Works and Water Management - AVV, 1999) and some assumptions that had to be made because of a lack of data. It is for instance assumed that the remaining capacity in case of fog is slightly less than in case of rain and darkness (0.89 versus 0.92). Furthermore, it is assumed that the probability of rain is equally spread over the day. Since we only had data about the motorways, a distinction between road types is not made. Finally, assumptions had to be made about the speed factors which are shown in table 1. The nominal capacity is the capacity under average weather conditions. Therefore, the capacity factor of dry weather during day time is higher than 1. The variations in capacity caused by different weather conditions are applied to all the links in the network at the same time.

The statistics for the incidents are based on different incident registration databases and the number of vehicle kilometers driven per road type. Conversions had to be made from total number of incidents to the number of incidents per road type and number of lanes per road type. In (Meeuwissen et al, 2004) it is in detail explained how this is done. We distinguished four incident types: car Break down, accident that blocks the hard shoulder, accident that blocks one or more lanes and rubbernecking. There is no registration of congestion caused by rubbernecking. Therefore, it is assumed that the chance on rubbernecking is equal to the chance on both accident types (in general car break downs don't cause rubbernecking). Furthermore, it is assumed that the capacity reduction is 50% of the weighted capacity reduction of both accident types. The variations in capacity caused by incidents are separately determined for each link in the network.

The statistics for road works are based on road work registration databases. For 17 different types of road works the capacity factors and the probabilities of occurrence were determined for the peak and off-peak period and for different road types. The variations in capacity caused by road works are separately determined for each link in the network.

Tables I to III present the factors and probabilities for incidents and different weather conditions. Further data can be found in (Meeuwissen et al, 2004).

Table I – Factors and probabilities for different weather conditions

	Capacity factor	Speed factor	Probability Peak	Probability Off-peak
Fog	0.89	0.50	1.81%	1.03%
Rain + darkness	0.92	0.80	1.81%	2.97%
Rain + daylight	0.95	0.85	6.52%	5.42%
Dry + darkness	0.98	0.95	19.52%	32.05%
Dry + daylight	1.02	1.05	70.34%	58.52%

Table II – Capacity factors for different incident types classified by number of lanes.

Lanes	Car Break down	Accident that blocks the hard shoulder	Accident that blocks one or more lanes	Rubbernecking
1	0.95	0.81	0.05	0.83
2	0.95	0.81	0.28	0.85
3	0.99	0.83	0.40	0.87
4	0.99	0.85	0.49	0.89

Table III – Probabilities for different incident types classified by number of lanes.

	Probabilities peak period ($x10^{-6}$)			
Road type	Car Break down	Accident that blocks the hard shoulder	Accident that blocks one or more lanes	Rubbernecking
Motorway	2.87	0.51	0.13	0.64
Main road	11.2	1.98	0.50	2.48
Secondary road	61.9	11.0	2.75	13.8
	Probabilities off-peak ($x10^{-6}$)			
Road type	Car Break down	Accident that blocks the hard shoulder	Accident that blocks one or more lanes	Rubbernecking
Motorway	2.25	0.40	0.10	0.50
Main road	9.20	1.64	0.41	2.05
Secondary road	54.0	9.60	2.40	12.0

Model runs with the national model system (abbreviated in Dutch to LMS), which computes generation, distribution, modal-split, departure time and route choice effects, were the starting point of our study. The resulting traffic demand was used to calculate the 'nominal' road situation with nominal travel times (no disturbances). Thereafter, we calculate the variation to this nominal situation by randomly sampling disturbance from the distributions of weather conditions, road works, incidents, seasonality's and events. This implies that in every iteration the capacity reduction (or increase) of all links (as a result of different weather conditions) or specific links (as a result of road works or incidents) is determined and that also the demand between specific OD-relations (as a result of events) or all OD-relations (as a result of seasonality's) is varied. The outcomes of this Monte Carlo Simulation approach consists of travel times for each Monte Carlo iteration for all OD-pairs and on all links, from which various statistics can be computed. Some statistics, like the standard deviation, are computed automatically.

We use two modes of route choice behavior in case of disturbances. In the first mode, a complete new equilibrium is found which implies that everybody has the opportunity to deviate from the routes that they would use in the case without disturbances and that they have complete information about the disturbances. The second option is that nobody changes routes. This fixed route choice behavior matches with the situation in which nobody had information, route alternatives are not available or nobody wants to make use of those alternatives. Of course, both extremes are not realistic since in practice always a few people change their behavior. However, using the two extremes gives insight in the bandwidths of the results. Furthermore, there is a lack of information about the actual route choice of drivers in case of disturbances, which makes it difficult to calibrate theoretically better route choice models like en-route route choice models.

Method 2: Vulnerability analysis

As was explained above, the first method underestimates the effect of large disruptions. Preferably a dynamic assignment model is used to asses the impact of these disturbances. However, in the evaluation of the policy measures of the "MobiliteitsAanpak" dynamic models could not be used because the size of the network didn't allow us to do that. Therefore, a more simplistic approach with a so called "vulnerability indicator" was developed that can be carried out based on the model runs with the national model system (LMS) that were already available.

The Monte Carlo approach described in the previous section already considers the complete travel time distributions (including the disturbances with a large effect). Fully adding the effects of the large disruptions would result in double counting which should be avoided in CBA's. On the other had, not adding the effects would be an underestimation of the total benefits. Therefore, this second method can be seen as a kind of sensitivity analysis which indicates how large the potential extra benefits could be.

The vulnerability indicator shows to which extent the spare capacity on alternative routes is sufficient as a fall back option for all the vehicles that drive on a certain road which is completely blocked as a result of a disturbance. This indicator is presented in equation 1.

$$\text{VulnerabilityIndicator}_i = \frac{\text{int}_i}{\sum_{j \in J_i} (rescap_j * \alpha^{dist_{i,j}})} = \frac{\text{int}_i}{\sum_{j \in J_i} (rescap_j * e^{\beta * dist_{i,j}})} \qquad (1)$$

In this formula *i* is the link where the disturbance occurs, *j* is a link from the collection *J* of links that form an alternative for link *i*, *int* is the link flow, *restcap* is the spare capacity, α and β are parameters that represent the importance of the distance from alternative routes and $dist_{i,j}$ is the shortest distance over the network between link *i* and link *j*. Identifying the set of all possible alternative links is complex and computationally expensive. Therefore an approximation method is used that finds all roads that run more or less parallel to the road that drivers would choose in the situation in which no disruption occurs. In this approximation method the set *J* is determined by taking a line perpendicular to link *i*. In figure 2 an example of such a line is shown. The links that cross the green line are considered to be an alternative for the blue link if they meet the following requirements:

- The absolute angle between the original link and the alternative link must be smaller than 70 degrees,
- the direction of the original link and the alternative link must the same.

By multiplying the capacity of the alternative link with the parameter alpha with the distance between the two links as exponent, nearby links are considered more important than far away links. *Alpha* must have a value between 0 and 1. We chose to set alpha to 0.8 which implies that links up to about 10 kilometers are considered to be a valid alternative. In areas where people are used to making longer trips, this parameter could be set a bit higher. In an alternative formulation *alpha* is replaced by *exp(beta)*. The higher the score the more vulnerable the link is. Links with a score higher than 1 are considered vulnerable. The presented indicator gives an impression of the vulnerable links in the network solely based on the network structure and can be computed within a short computation time.

Figure 2 – Vulnerability indicator.

This indicator is a simplification of the concept of robustness since it doesn't consider spill back effects explicitly and it also doesn't take into account whether or not the alternative route can actually be reached by the traffic on link *i.*

The indicator can be determined on the network level by taking the weighted average of the indicator for all links based on link flows. The closer the indicator is to 0 the less vulnerable.

BENEFITS ON A PROGRAM LEVEL

In this section we give an example of how the method that is described in the previous section is applied in an evaluation of the network measures that have been announced in the "MobiliteitsAanpak". We describe the evaluation of an extension of the number of lanes of the motorways in the metropolitan area 'the Randstad' to at least 4 lanes in each direction (2x4 lanes concept) were needed (on the most important roads between the cities). The reference network in Figure 3 shows that many of the links in the area marked by the four cities Amsterdam, Rotterdam, The Hague and Utrecht are still 2 or 3 lane roads. The measures are evaluated in two different future socio-economic scenarios: GE and RC. The GE (Global Economy) and RC (Regional communities) scenario are two of the four scenarios which are used in the Netherlands for making long-term forecasts with the highest and lowest traffic growth, respectively. These scenarios describe long-term trends such as the decreasing household size, the ageing population, international migration, economic growth, and increasing personal welfare which all have an impact on mobility. An extensive description of the scenarios can be found in (WLO, 2006). The Dutch National Model System (LMS) was used to compute the effects of the increase in capacity under regular conditions. The national network modeled consists of about 24 thousand links, 18 thousand nodes and 400 zones. In total about 40 thousand lane kilometers are included of which about 15 thousand lane kilometers are motorways.

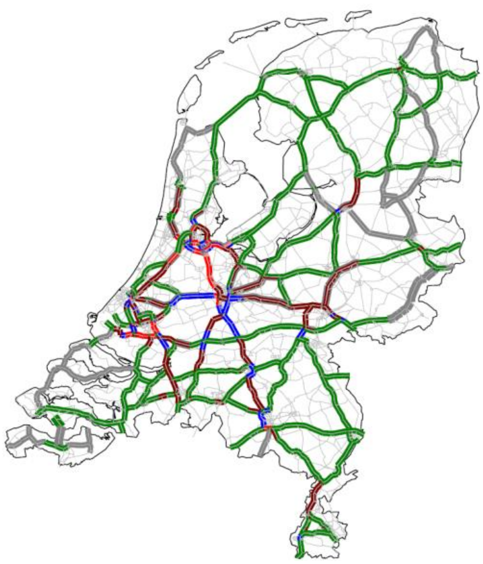

Figure 3 – Reference network 2020 (Source: Ministry of Transport, Public Works and Water Management, 2007). (Number of lanes: gray = 1, green = 2, brown = 3, blue = 4, red = 5)

In Table IV the benefits are summarized. In the valuation we used standard values for the value of time, the value of distance, the reliability ratio and the different indirect and external effects. In Appendix A the numbers that are needed for computing the direct effects are shown. Further details of the calculation can be found in (Snelder et al., 2009).

Table IV – Benefits in EUR millions per year (2007)

	RC scenario	GE scenario
Travel time benefits	172	487
Out-of-pocket costs	10	8
Reliability benefits	142 (±20)	465 (±150)
Indirect effects	50	146
External effect	-11	-20
Total benefits	**362**	**1086**

The measures result in yearly benefits of about 362 million euro per year in the RC scenario up to 1 billion euro per year in the GE scenario. The large differences between the scenarios are caused by the higher value of time in the GE scenario and the fact that more trips are being made in the GE scenario. The measures result in shorter travel times and a more robust road network. From Table IV one can see that the reliability benefits can vary significantly. These variations depend on the level of information that is offered to the traveler (route choice assumptions). Note that optimal network usage in case of incidents reduces the reliability benefits significantly (by a third in the GE scenario and by about 15% in the RC scenario).

The net present value of the benefits is compared with the net present values of the investments. Because of lower growth in the RC scenario, the infrastructure investments will be lower as well in the RC scenario than in the GE scenario. The measures have a benefit-cost ratio of 0.8 in the RC scenario and 2.0 in the GE scenario. An important finding of this analysis was that the reliability benefits are of similar magnitude as the travel time benefits. Not including the reliability benefits in cost-benefit analysis can therefore lead to a serious underestimation of the benefits. These results are based on an integral evaluation of the complete investment packages. It could very well be that some projects are included that score better than others. This is shown in the next section An optimization of the investment package may therefore result in higher benefits.

A sensitivity analysis has been carried out in order to look in more detail at the large disruptions (method 2 from the previous section). The vulnerability indicator indicated that the network was 3% less vulnerable for large disturbances as a result of the measures in the GE scenario. In the RC scenario this was 3.8%. It is difficult to value the indicator since it is a unit less indicator. Nevertheless, an attempt has been made by multiplying the relative change of the indicator as a consequences of the measures that are taken with an estimation of the total yearly costs of vulnerability in 2030: 4,1 billion euro (TNO, 2008b). This results in potential extra benefits of 123 – 156 million euro per year. Of course, the bandwidth of the benefits that are computed in this way is very large.

BENEFITS ON A PROJECT LEVEL

The policy paper describes additional measures that relate specifically to robustness measures. The first is to physically split through traffic from local traffic on the motorways or to split passenger cars from trucks. This can for instance be done by splitting a road which has four lanes in each direction into a road which has two lanes for through traffic and two lanes for local traffic in each direction split by a physical barrier. The second set of robustness measures relates to upgrading the lower level roads by increasing the speeds from 80 km/hour to 100 km/hour or by extending the capacity of the lower level roads (N-wegen).

Both set of measures have not been worked out in detail. This implies that measures are described on a program level, but there is no list of specific projects available yet. As a consequence, LMS model runs weren't available. In order to get an impression of the benefits, four example projects with no official status were defined and evaluated. The locations of the example projects were chosen based on reliability and robustness problems that remained after the implementation of the 2x4 lanes concept (previous section) in 2028.

- Example 1: separating through traffic from local traffic on a large scale. All motorways between The Hague, Amsterdam and Utrecht were by means of example split in such a way that there are two lanes for the through traffic. The remaining lanes (at least two) are for the local and regional traffic. This implies that no additional lanes were needed since the capacity of these motorways is already extended to at least four lanes by the 2x4 lanes concept as described in the previous section. The maximum speed is assumed to be equal on the main road and the parallel road.

- Example 2a: separating through traffic from local traffic on a road stretch of about 9 kilometer on the motorway A4 between the splitting with the A44 and the A5.

- Example 2b: upgrading parts of the parallel road N205 and N207 of the same road stretch of the A4 to 2x2 lanes with a maximum speed of 80 km/uur.

- Example 3: completing the ring road of Eindhoven (A2/A67) by upgrading the N279 between Veghel and Helmond and constructing a new road between Eindhoven and the N279 both with 2x2 lanes with a maximum speed of 80 km/hour.

- Example 4: Upgrading the parallel road of the A1 between Deventer Oost and Twello to a road with 2x2 lanes and upgrading the same road between Twello and Apeldoorn Zuid to 2x1 lanes both with a maximum speed of 80 km/hour.

For the above mentioned examples the Monte Carlo simulations (method 1) are only done for the morning peak and the off-peak period in order to limit the number of model runs that had to be done. It was assumed that difference between the evening peak and the morning peak is equal to the difference between both periods in the 2x4 lanes concept.

For the examples the vulnerability indicator is only computed for the road for which a measure is taken. There is no point in computing the network wide vulnerability effects of a single measure since the impact on the performance of the complete network of the Netherlands is of course very small.

In table V and VI the expected effects of the example projects are shown. These effects are additional to the effects of the 2x4 lanes concept that is presented in the previous section since the 2x4 lanes concept is taken as a reference. Below the tables, the effects are explained in more detail.

Table V – Impact on travel time reliability in the GE scenario in the morning peak

	Change in reliability (variation coef.)		Reliability benefits (mln euro/year)	
	New equilibirum/ complete information	Fixed route choice/ no alternatives/no information	New equilibirum/ complete information	Fixed route choice/ no alternatives/no information
Example 1	+0,0%	+1,0%	79	16
Example 2a	+0.0%	-1.0%	-3	-28
Example 2b	+0.2%	+2.1%	29	115
Example 3	+0.6%	+5.4%	83	184
Example 4	-0.1%	-2.2%	-1	-60

Table VI – Change in vulnerability indicator in the GE scenario in the morning peak

Example 2a (A4)	52%
Example 2b (A4)	48%
Example 3 with city roads considered as an alternative (A2)	2%
Example 3 without city roads considered as an alternative (A2)	11%
Example 4 (A1)	94%

Effects of splitting through traffic from local traffic

Two of the above mentioned examples relate to splitting through traffic from local traffic. In example 1 this is done on a large scale and in example 2a this is done a project level. An analysis of the results shows that in case of complete information the reliability doesn't change in both examples. This is because the network has sufficient spare capacity that can be used as a fall back option in case everybody is completely informed about the disturbance and the availability of the alternative routes. In case of fixed route choice the reliability improves in example 1 with 1% whereas the reliability decreases in example 2a with 1% as well. The fact that the impact of splitting through traffic from local traffic differs per project, indicates that no general rule of thumb can be distracted for the effects of splitting through traffic from local traffic.

The vulnerability indicator indicates that the network gets more robust in example 2a. The vulnerability indicator focuses on large disturbances in which roads are for instance completely closed. In case the road is split into two separate roads one road will maintain its function in case the other one is closed. The capacity of the road that is still open might be lower due to rubbernecking effects. Nevertheless, the fact that one road maintains its functions ensures that the effect of the incident is lower than the case in which all lanes were closed if the road wasn't split into two roads. Besides that, a part of the traffic that would choose the closed road if it hadn't been closed can use the road that is still open if there is spare capacity. However this is only possible for the through traffic, since the local traffic can't use the main road, because than they would miss their off ramps. Creating flexible infrastructures can improve the transferability of traffic and therewith the robustness. For example 1 the vulnerability indicator is not computed because this requires a computation of the indicator on multiple roads. This is possible, but this makes the indicator incomparable with the other examples for which the indicator is computed only for one road stretch (the one between brackets).

Finally, we notice that separating through traffic from local traffic doesn't only have an impact on robustness and reliability. It can also have positive effects on the traffic flow under regular conditions since the through traffic is not slowed done by the local traffic. Furthermore, it can have positive effect on safety and livability as is shown in DHV (2007). This rapport indicates that separating through traffic from local traffic is especially useful in the surrounding of large urban agglomerations where a large part of the traffic is through traffic. The level of success of the measure depends on the total traffic volume, the flow-capacity ratio en the share of through traffic (or the share of trucks). Of course the costs of splitting through traffic from local traffic have to be considered as well on a project level. However, this is not done in this analysis, since the measures are not worked out in enough detail to make an accurate costs estimate.

Effects of upgrading or creating local roads

Example 2b and example 4 focus on upgrading or creating route alternatives. Upgrading the N205 has a slightly positive effect on reliability (0,2% - 2,1%), whereas creating a route alternative for the A1 has a slightly negative reliability effect (0,1% - 2,2%). In example 2b a small part of the traffic shifts from the motorway A4 to the regional roads N205 and N207 which has a positive reliability effect. In example 4 the off ramp Voorst of the A1 is closed. In the reference situation this off-ramp is accessible from the A1 and the A50. After the construction of the parallel road, Voorst can only be accessed through the A50 or the parallel road. Because of this off-ramp closure and the related route choice effects, the A1 is used more intensively, with a slightly negative impact on reliability as a result.

Creating route alternative with extra capacity should spread the traffic better over the network, which makes the network more robust. To a certain extent, the different routes can function as a fall back option for each other. The extent to which a route can function as a fall back option for the other route depends on the spread of the flow under regular conditions and the available spare capacity. In both examples, a route alternative is created with 2 lanes in each direction (a part of the parallel road of the A1 has only 1 lane) whereas the motorways have more lanes. The A4 has 6 lanes in both directions and the A1 has 3 lanes in both directions. The parallel road for the A1 is in that sense a better route alternative than the

N205 for the A4. Table VI shows that the vulnerability of the A1 decreases with 94% and that the vulnerability of the A4 decreases with 48%. In practice this decrease will be small, since local traffic will make use of the roads which is not all included in the model and since traffic generation, distribution and modal split effects are not considered in these examples. This would result in less spare capacity. Furthermore, we notice that upgrading the N205 (example 2b) has a less positive effect on the vulnerability of the A4 than splitting the A4 in a parallel road and a main road, because the N205 is further away from the A4. Finally, the parallel road for the A1 offers an extra cross-river connection which reduces the vulnerability of the bridge near Deventer.

Both examples show that creating route alternatives doesn't have a large effect on the reliability, however, there clearly is a positive effect on the vulnerability in case of large disturbances. Under regular conditions, creating route alternatives can improve the accessibility of living areas and it can improve the traffic circulation. It can have a positive as well as a negative effect on the number of vehicle kilometers travelled. The positive effect is caused by the fact that shorter routes are created and the negative effect is caused by the fact that shorter travel times enable people to travel over longer distances. However, the latter mentioned generation and distribution effects are not considered in these examples.

Effects of completing a ring road

Example 3 shows that completing the outside ring of Eindhoven/N279 (which is also a form of creating route alternatives) improves the reliability of travel times with 0,6% to 5.4% and reduces the vulnerability with 2% (= more robust) in case the roads through the city Eindhoven are considered as an alternative. The vulnerability is reduced with 11% if the roads through Eindhoven are not considered as an alternative. The reliability improves more than in the other examples which is explained by the fact that completing a ring road creates a route alternative for more local traffic. The vulnerability reduces less than in the other examples which is explained by the fact that the N279 is relatively far away from the A2. Furthermore, the vulnerability indicator disregards the fact that for the east-west traffic an alternative is offered as well which also reduces the network vulnerability.

The benefits of the above mentioned projects are shown in the two right most columns in table VI. As is explained, the benefits heavily depend on the availability of route alternatives and the information that is provided. In the case in which information is not available or changing route choice is not possible the benefits can be negative.

DISCUSSION, CONCLUSION AND RECOMMENDATIONS

This paper aimed to give an example of how the reliability benefits of robustness related measures can be computed on a large scale network. First some definitions and indicators were presented. Thereafter, two methods were presented that allow calculating reliability benefits of measures directed at improving network robustness in a way that these can be incorporated in cost-benefits analysis. The first method that we choose is a compromise between theoretical exactness and practical limitations in computation time. We chose to use the Monte Carlo simulation based model by Meeuwissen et al., estimated in 2004 but never applied before in the context of robustness cost-benefit analysis. This choice was made since this model can analyze the effects of disturbances that vary from local to network wide disturbances, from disturbances with a small probability to disturbances with a large probability, from supply related disturbances to demand related disturbances and from disturbances with a small effect to disturbances with a large effect. In this way the complete travel time distribution can be analyzed. Furthermore, since a static model is used to assess network effects the computation time stays within acceptable boundaries as well (15 minutes up to several hours on a regular PC). Of course, the fact that a static model is used is a disadvantage as well, as network dynamics are not captured. Therefore, we introduced a second method that looks into more detail at disturbances with a large impact like road closures.

We applied both methods to compute the reliability benefits of the measures related to creating a robust road network in 2028 as presented in the policy document the “MobiliteitsAanpak”. The modeled network connects 400 zones and includes about 24 thousand links and 18 thousand nodes. The application of the Monte Carlo based evaluation method showed that the gross benefits of extending all important roads to at least 4 lanes by 2028 range between 362 million euro and 1 billion euro per year, with benefit-cost ratios between 0.8 and 2.0. One important outcome of the analyses is that the reliability benefits of the proposed road projects are similar in magnitude as the benefits from reduction of average travel times. This implies that the 25% markup that is currently applied in the Netherlands is likely to be an underestimation.

We also find that the outcomes are overall positive for the complete set of measures, but that effects can be negative in individual cases. In other words, there are specific situations in which the travel times become less reliable for certain travelers, despite a clear gain in average travel time under normal operating conditions. As the projects were not evaluated before with robustness in mind, an important implication of this is that the proposed set of projects in the Dutch road network strategy can be optimized further, bearing in mind that a trade-off between travel time and reliability may lead to different projects. Finally, we showed that splitting through traffic from local traffic, upgrading the secondary road network and completing ring roads, make the network more robust against large disturbances. Of course, the extent to which the robustness improves depends on the amount of spare capacity that is created, the usage of the roads under regular conditions and the distance between the original route and the fall back options.

As far as is known to the authors this is first large scale cost-benefit analysis in the Netherlands in which reliability/robustness benefits have explicitly been computed (not using a rule of thumb). In the world there might be other similar applications, however we are not aware of this. We have shown that the method that we used is actually very well applicable to this size of networks. Nevertheless, theoretical advancements will have to be made in the sense that models have to be developed further in such a way that they can better deal with travelers choice behavior under uncertainty. The route choice behavior could for instance be improved by collecting more information about the route choice in case of disturbances and by including this in the models. Furthermore, the route choice behavior also depends on the reliability of travel times. Therefore, this should also be included in the models. Other choices that are influenced by disturbances (departure time choice, mode choice, activity location) should be considered more explicitly as well. In the future dynamic models might be improved in such a way that they can be used for analyzing the effects of different kinds of disturbances as well. The MIC-module is already a first step in this direction. A lot of model development is already ongoing. However, these models should also be made applicable to large scale networks.

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APPENDIX A: UNITS USED IN COST-BENEFIT ANALYSIS

Table A.1 – Value of time (euro per hour per person).

Purpose	RC 2020	GE 2020	RC 2030	GE 2030
Freight	47.34	52.17	52.80	61.20
Commuting	9.58	10.44	10.80	12.00
Business	33.17	36.17	36.60	42.60
Other	6.61	7.21	7.20	8.40

Table A.2 – Car occupancy rate (persons per vehicle).

Purpose	RC 2020	GE 2020	RC 2030	GE 2030
Commuting	1.117	1.104	1.128	1.099
Business	1.103	1.089	1.095	1.076
Other	1.422	1.390	1.426	1.345

Table A.3 – Out-of-pocket costs (euro per kilometer per vehicle).

Purpose	2020
Freight	0.236
Commuting	0.074
Business	0.074
Other	0.074

Table A.4 – Reliability ratio.

Purpose	Ratio
Freight	1.2
Commuting	0.8
Business	0.8
Other	0.8