The vulnerability of road networks

Now and in the future

TRAIL Research School, Delft, October 2008

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Contents

Abstract

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Transport networks in major urban areas are becoming more and more vulnerable to unforeseen disturbances in transport networks, like incidents. For the near future, we expect an increasing number of incidents with a large impact due to the overall increase of the traffic load. In this paper the hypothesis is tested that, if no measures are taken, the impact of incidents increases in the future and, therefore, the vulnerability of the road network increases. It is shown that the current network of the area The Hague-Rotterdam in the Netherlands is already vulnerable. If the demand increases, the increase in total travel time is more than linear with the increase in demand in the situation without an incident. The impact of incidents also increases when the level of demand increases. This results in the overall conclusion that it is necessary to make the road network more robust.

Keywords

Vulnerability, robustness, incidents, road network, spare capacity

1 Introduction

Transport networks in major urban areas are becoming more and more vulnerable to unforeseen disturbances in transport networks, like incidents. For the near future, we expect an increasing number of incidents with a large impact due to the overall increase of the traffic load and a growth in the share of trucks on the roads. More importantly, however, it will be more difficult to recover from unforeseen disturbances, as spare capacity in the network is reduced due to

- more spatially concentrated flows around cities because of concentrated spatial development, new land use policies (bundling) and market-led agglomeration forces,
- combined with widening of congestion periods due to pricing measures and a gradual re-organization of household and working schedules.

In Figure 1, the reduction of spare capacity in time-space is shown. When the peak period gets longer and more intensive the spare capacity at each time step *t* reduces. Furthermore, the spare capacity after *t* reduces. The spare capacity after *t* can be used the recover from an incident.

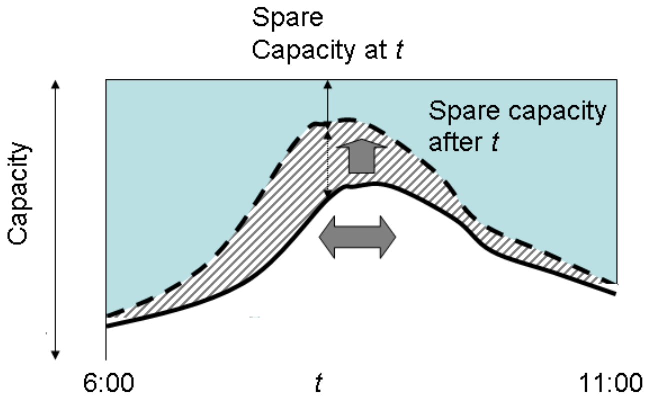


Figure 1: Reduction of spare capacity in time-space

This reduction of spare capacity in time-space leads to increasing risks of sudden drops in network performance, as a result of unforeseen events like incidents. The fact that networks in major urban areas are strongly connected implies both an additional risk (as one link can obstruct another) and an opportunity to mitigate the risk (as spare network capacity can be brought to use). As, during the years, spare capacity becomes reduced, and risks increase, the costs of not investing in robust designs increase and it becomes viable to redesign networks in a way that risks remain within acceptable bounds. The fact that we look at major consequences of unforeseen events, implies that we need to look at network design in a different way than we did before. Instead of a deterministic design approach we now need to move towards probabilistic design, which addresses the risk of collapse explicitly. We are faced with two challenges in this design paradigm change. One is to develop an understanding of the performance risks at hand, both in technical and in economical terms. How large are these risks and how do they change through time? What are the opportunity costs of not investing in network robustness? The second is to identify designs by which these risks can be mitigated. Which measures or policies must be taken to ensure that the spare capacity is increased or optimized over the entire network? This paper deals with a traffic modelling tool that supports the design and evaluation of robust networks. It addresses the question what will happen if incidents occur in networks with increasing traffic volumes.

This paper starts with a chapter in which the vulnerability of the current network is illustrated. In the chapter thereafter a forecast of the vulnerability of future road networks is presented. In the last section the conclusions are presented.

2 Definitions and indicators for vulnerability and robustness

This section presents some definitions and indicators for robustness that are used in literature. At the end of this section the definition and indicators that are used in this paper are presented.

According to Snelder et al. (2003) the robustness of a network and the reliability of travel times have a clear relation. A robust road network is one of the enablers of reliable travel times. The difference between these two concepts is that reliability is a user oriented quality of the transportation system and that robustness is a characteristic of the system itself (Immers et al., 2004). Probability or predictability is a major concern in network reliability studies. The impacts or consequences of disruptions are the focus of vulnerability studies (Husdal, 2004). D’Este and Taylor (2003) note that vulnerability and reliability are two related concepts, but emphasise that network vulnerability relates to network weaknesses and the economic and social consequences of network failure, not so much to the probability of failure.

In comparison with the research into reliability, the research into robustness is less extensive. Robustness and vulnerability have a strong relation, but they are each others opposites. Vulnerability describes the weakness of a network and robustness describes the strength of a network. Berdica (2002) has done leading research into road vulnerability. She defines vulnerability in the following way: “Vulnerability in the road transportation system is a susceptibility to incidents that can result in considerable reduction in road network serviceability.” In this definition the serviceability of a link/route/road network describes the possibility to use that link/route/road network during a given time period. Immers et al. (2004) have also defined robustness and they subdivide robustness into the following four aspects: redundancy, interdependency, flexibility and resilience. The redundancy of a system may be improved by introducing a certain amount of redundancy or spare capacity into the system. With interdependency the following is meant. Congestion at a centrally located link or node may cause a series of cascading failures disrupting traffic on large parts of the networks. The robustness of a network increases if the interdependencies decrease. Resilience is the capability of the transport system to repeatedly recover, preferably within a short time period, from a temporary overload. Finally, flexibility is the extent to which the system is able to carry out more and other functions than it was originally designed for. These four aspects together give a more comprehensive understanding of robustness.

Also others describe the vulnerability of road networks. For example, Taylor and D’Este (2003) relate vulnerability to the degree of accessibility of a given node in the network, where accessibility is expressed as the travel cost needed to access the particular node, comparing optimal and alternative routes or detours. D'Este and Taylor (2001) define vulnerability to be the likelihood of severe adverse consequences if a small number of links (or possibly a single link) is degraded. They distinguish between connectivity vulnerability and access vulnerability. Connectivity vulnerability considers a pair of nodes and the generalised cost of travel between them. If the loss or substantial degradation of one or more network links leads to a substantial increase in the cost, then the connection between those nodes is vulnerable. Access vulnerability considers a single node and the overall quality of access from that node to all other parts of the network. A node is vulnerable if the loss of substantial degradation of a small number of links results in a significant reduction in the accessibility of that node, as measured by a standard index of accessibility. It should be noted that the second definition of vulnerability ignores probability; this vulnerability is really a measure of the consequence of degradation.

In the literature, the following indicators for robustness and vulnerability are used:

- I1: Spare capacity. This is the capacity of a network that is not used under normal circumstances. It is an indicator for the network redundancy.
- I2: The availability and quality of alternative routes. This is also an indicator for the redundancy in a network. It is not easy to measure this indicator. Alternative routes are usually found automatically. Murray-Tuite and Mahmassani (2004) introduced the 'vulnerability index'. This indicator can be computed automatically. The index considers the availability of alternative routes, spare capacity and the travel times on alternative routes. The vulnerability index is an index on the link and OD-level. Besides this indicator they also introduced an indicator on the link level: 'the disruption index'.
- I3: Vehicle loss hours (Tampère et al., 2007) and (Li, in press)
- I4: Total travelled distance (Li, in press)
- I5: Total travel time (Li, in press)
- I6: Total number of arrivals in a period (Li, in press)
- I7: Average speed in the network in a certain period (Li, in press)
- I8: Volume on the network in a certain period (Li, in press)
- I9: Total link length of congested links (Li, in press)
- I10: Total number of vehicles on congested links (Li, in press)
- I11: Number of cases (link closures) in which less than x% of the maximum number of travelers arrives within the simulation time (Knoop et al.,2007).

For most of these indicators the value of the indicators depends on the network size. Therefore, these indicators are meant to compare the situation without disruptions with the situation with disruptions in the same network and not to make comparisons between different networks. The presented list is not a complete list. Besides the indicators in the list, for example, there is a group of indicators that refer to the topology of the network like the degree of nodes and the connectivity of the network.

In this paper we define robustness as the extent to which a network is able to maintain the function where it was originally designed for under all circumstances that deviate from the normal conditions. We define vulnerability as the extent to which a network is susceptible to disruptions like incidents. If the network is made more robust it is less vulnerable. In this paper the vulnerability of the network is determined by simulating an incident at one location, at one time interval and of one type. The vulnerability is measured by comparing the total travel time, the total vehicle kilometers driven and the average network speed in the situation with and without an incident.

3 The vulnerability of the existing road network

In this section the vulnerability of the existing road network is illustrated by an example of an accident that occurred around 7.00h on the 11th of September 2007 at the off-ramp of Voorburg. This location is marked with a star in Figure 2 and Figure 3a. Figure 2 also shows the names of the roads and cities that are used throughout this paper.

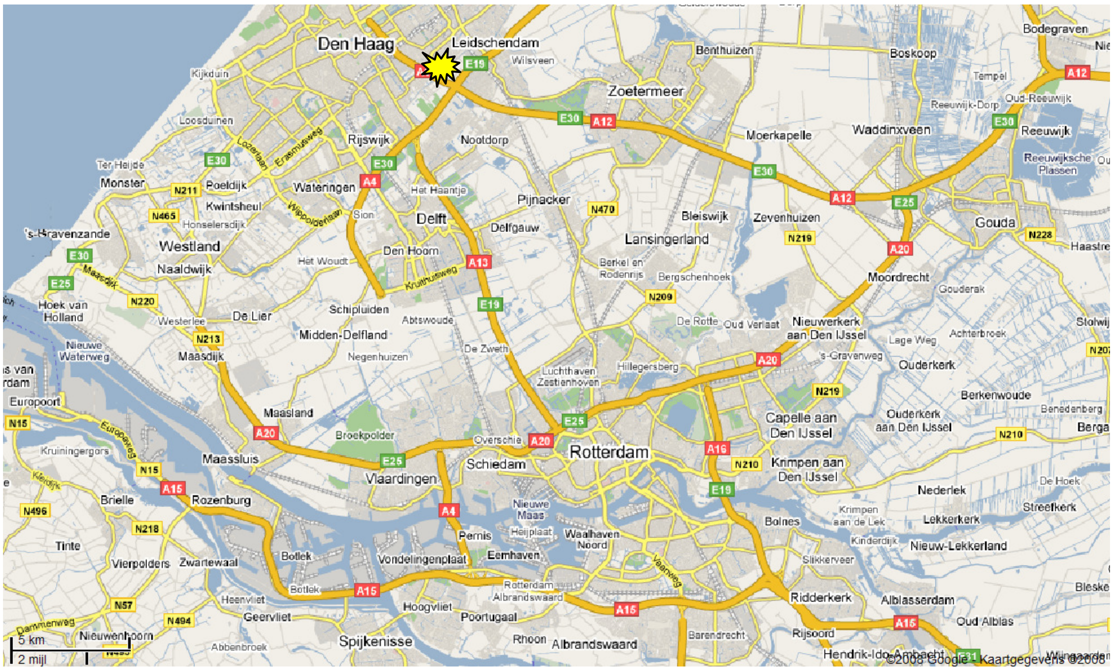
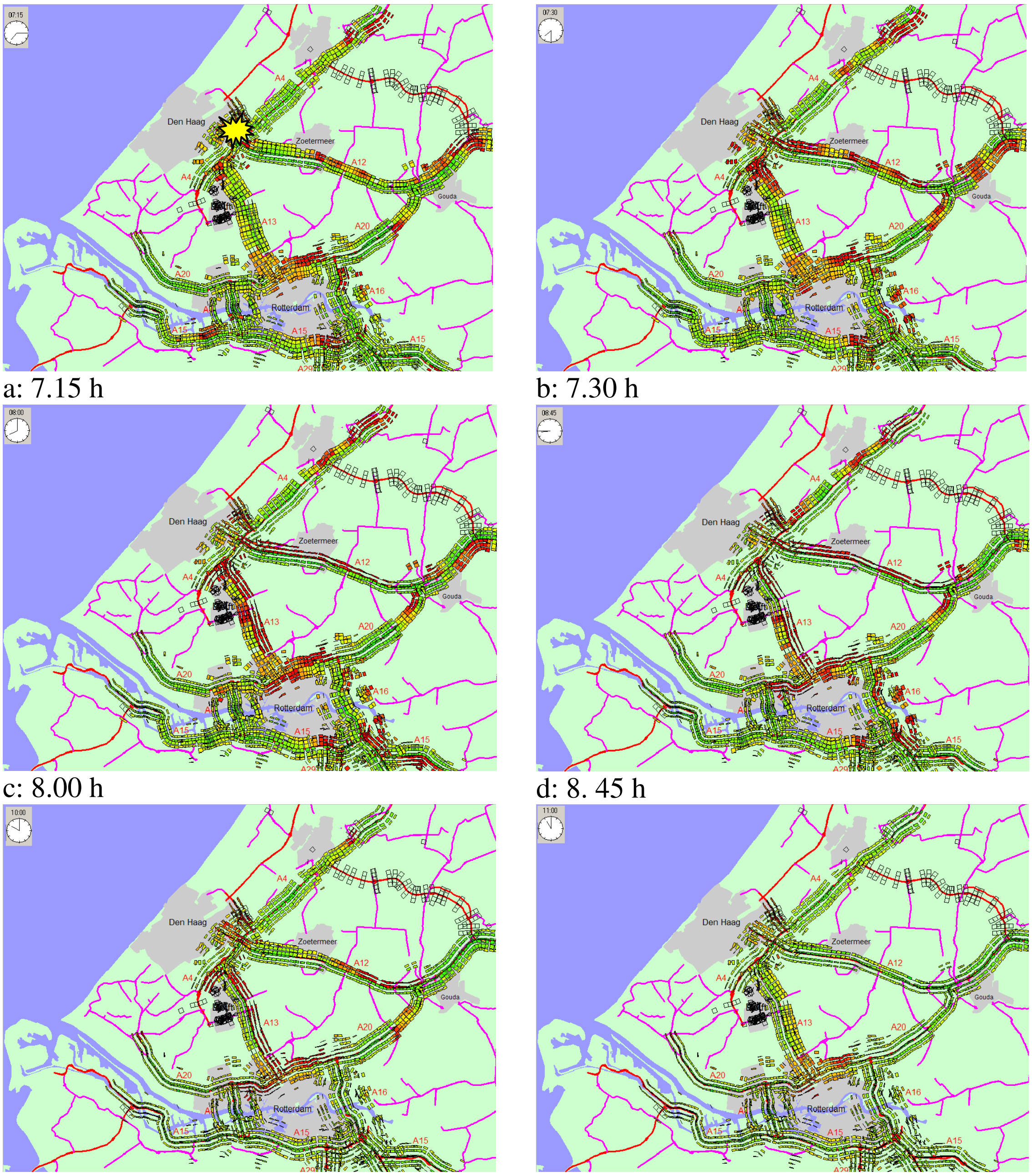


Figure 2: Map of the study area with the names of the roads

Figures 3a to 3f are based on traffic counts. The colour of the links indicates the level of congestion. Green means free-flow and red means severe congestion. The width of the links indicates the flow on the links. When there is no congestion on the motorways the links are green with a large width. When congestion arises the links change from green to red and the width increases slightly and decreases thereafter. When the traffic comes to a stand still the links are red and have a very small width. From Figure 3a, it can be seen that at 7.15 h the congestion spills back over the Prins Clausplein. This is a big intersection of the A12 and the A4. In the period thereafter the congestion spills back over a large part of the A12 and on the A13. At 8.00h the A13 is completely block and the traffic on the A12 has come to a complete stand still up to Gouda (the crossing between the A12 and the A20). At 8.45h the traffic at the A13 also came to a complete stand still. Of course this situation is enforced by the fact that the accident happened just before the start of the regular peak period. In the Netherlands the peak period lasts on average until about 9.00h, but in this case the network as shown in the picture remains completely congested until about 9.50h. Figure 3e shows that congestion starts to solve on the A12 at the head of queue. A short while later also the congestion on the A13 starts to solve and, as can be seen in Figure 3f, at 11.00h the situation is almost back to normal. This implies that the effects of the incidents could be measured until 4 hours after the occurrence of the incident. This example illustrates the vulnerability of the road network around the city of The Hague. If the amount of traffic on the network increases, the impact of incidents will probably increase and, therefore, the network becomes more vulnerable.



a: 7.15 h

b: 7.30 h

c: 8.00 h

d: 8. 45 h

e: 10.00h

f: 11.00h

Figure 3: Congestion that is caused by an incident on the off ramp of Voorburg (source: Regiolab)

4 The vulnerability of road networks in the future

The previous section demonstrated that the existing road network is vulnerable since a small accident on an off-ramp can be the cause of several hours of congestion. It is assumed that in the future the impact of incidents increases and, therefore, the network becomes more vulnerable. In this section this hypothesis is tested with a modelling approach.

4.1 Case and model description

The road network of Rotterdam is used to illustrate the vulnerability of road networks in the future. First the characteristics of the network and of the model Indy that is used for the calculations are presented.

Rotterdam is the second largest city of the Netherlands. It has about 590.000 inhabitants (www.cbs.nl). The city is surrounded by 4 motorways that are called 'Rotterdamse ruit'. The network of Rotterdam that is used in the model is shown in Figure 4. Figure 1 includes the real network of Rotterdam.

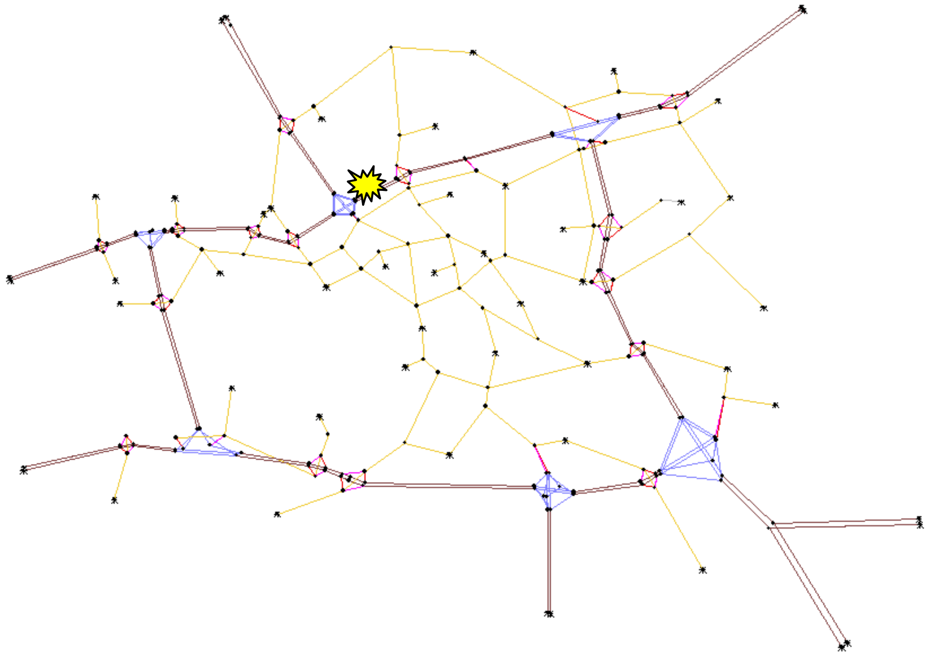


Figure 4: Road network of Rotterdam and surroundings

The network contains 51 zones. In total there are 1890 OD-pairs (not all combinations of zones are used) and 7674 paths were generated. Furthermore, the network contains 239 nodes and 570 directed links of which 468 links are regular links and 102 links are feeder links. In the coming years (2008-2020) several infrastructure projects are planned that have an impact on the traffic situation in and around Rotterdam. In our study we didn't include these network changes, because we wanted to isolate the effect of an increase in the demand. Changes to the network can be considered as one of the measure that can reduce the vulnerability.

The total average OD demand in 2008 per hour is 88141 trips. The total demand period was 24 hours. For each 10 minutes the hourly demand was calculated by multiplying with the factors that are presented in Figure 5. It is likely that in the future the peak periods get longer and more intense. In practice, this will depend on several factors like the increase in traffic volumes and the introduction of policy measures like road pricing. In our model runs, we used two demand patterns as a kind of scenario analysis. The first is called the demand pattern of 2008 and the second is called the future demand pattern. Both patterns are shown in Figure 5.

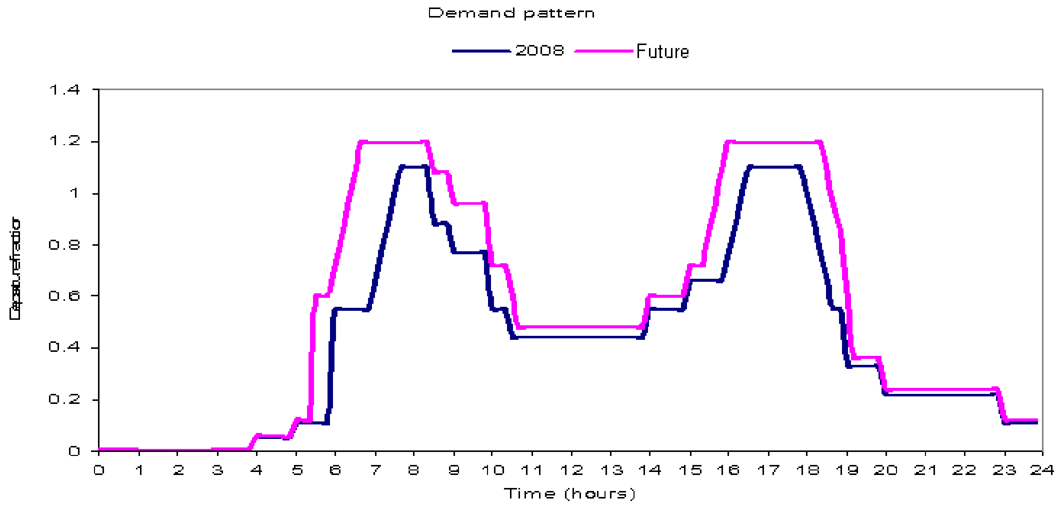


Figure 5: Departure fractions

In order to show the vulnerability of the network an incident is simulated on a location which is usually congested during the peak period and therefore likely to be vulnerable. The link is indicated in Figure 4 with a star. It is an incident on the northern side of the A20 just before the crossing with the A13. The incident occurs at 8.00h and blocks all 3 lanes for 1/2 hour. Thereafter the emergency services remove the vehicles that were involved in the incident. After removing the damaged vehicles, it takes 15 minutes before the capacity is fully recovered.

The model Indy was used for the case study. Indy is a dynamic traffic assignment model. It has a path generation module, route choice module and a network loading module. The link transmission model propagates traffic on network links consistent with the first order kinematic wave theory. A more extensive description of Indy and the link transmission model in Indy can be found in Yperman (2007) and (Bliemer, 2005) and (Bliemer, 2007)

In Indy this incident is simulated by reducing the number of lanes and the capacity. In the first half an hour after the incident the capacity is reduced from 6600 passenger car units (pcu) per hour to 0 pch/hour and the number of lanes is reduced from 3 lanes to 0 lanes. In the 15 minutes thereafter 2 lanes are in use again and the capacity is with 3300 pcu/hour half of the capacity under normal circumstances. In the period thereafter the road functions as normal (capacity 6600 pcu/hour and 3lanes). In Indy there are two options for modelling the route choice behaviour of drivers. The first is to keep the routes fixed. This implies that the drivers choose the route that they would also choose in the equilibrium assignment without an incident. This situation is similar to a situation in which drivers have no information at all about the incident. When they see the incident or the congestion that is caused by the incident they either don't have the opportunity to deviate from their routes or they don't have information about the availability and quality of alternative routes and therefore stick to their original routes. The other modelling extreme of Indy is the situation in which a new equilibrium arises. This situation is similar to the situation in which everybody has complete information about the incident and the alternative routes. Both are not realistic because in practice always some drivers will deviate from their original routes. This can only be modelled by models in which enroute route choice is included. Indy doesn't have this option. On the other hand, if enroute route choice is modelled, it is most likely wrong as well, because of the fact that not much information is available about the route choice behaviour of people during incidents. Hardly any information is available on when people receive the information on the incident and how they will respond to that. Therefore the decision was made to use the two most extreme situations (complete information and no information) to show what might happen during incidents. The truth is somewhere between these bounds.

For this case study a simple calibration procedure was used. This means that it was checked if the congestion locations and moments on which the congestion occurs match the average daily situation on the network of Rotterdam.

A forecast of the vulnerability of the road network of the future was made by doing 54 model runs. In these runs the incident situation, level of demand and the departure pattern was varied.

- There are 3 types of incident situations:
    - Run without an incident
    - Run with the incident and with a fixed route choice
    - Run with the incident and with a new equilibrium
- There are 9 demand levels which are modelled by multiplying the OD-matrix with the following factors: 1.00, 1.05, 1.10, 1.15, 1.20, 1.25, 1.30, 1.35, 1.40.
- There are two demand patterns which are shown in Figure 5.

4.2 Model results

This section presents the results of the model runs. At first the forecast of the total future travel time is presented in Figure 6. In the top left figure the total travel time is shown for the base year (demand pattern 2008). This figure shows that the total travel time first increases slowly as the total demand increases (loading factor). Thereafter, from the loading factor 1.2 onwards, the total travel time increases faster. When the demand increases with 40% the total travel time increases with 68%. This additional increase (68% - 40%) is caused by congestion effects. In the top right figure the same is shown. However, in this figure the total travel time is corrected for the increase in demand (total travel time/loading factor). Therefore, this figure solely shows the effects of extra congestion caused by an increase in demand and by incidents. In these figures, the distance between the lines of the incident situations (with fixed route choice and with an equilibrium route choice) and the situation without an incident indicate the number of vehicle loss hours that are caused by the incident. From the figure it can be seen that in general the distances between the lines increase when the demand increase. This implies that the impact of an incident in heavily used networks is larger than in networks that are used less intensively. In the case of fixed route choice an incident could cause a delay of 5%-10% of the total travel time of 1 day. This is quite a large number given the fact that the duration of the incident was only 45 minutes. In the case of equilibrium route choice during the incident the total travel time only increases with 0%-1%. In practice the increase in travel times will be somewhere in between these values.

For the future demand pattern the same figures are presented at the bottom of Figure 6. These figures show that when the demand pattern changes (the peak period gets longer and more intense), the effects are even larger compared to the situation with the demand pattern of 2008. In this case, when the demand increases with 40%, the total travel time increases with 128%. In absolute numbers the vehicle loss hours in case of an incident are much higher compared to the base year demand pattern. However, the vehicle loss hours expressed relatively to the total travel time without an incident are less remarkable. In the case of fixed route choice this is 4%-8% and in the case with equilibrium route choice -3% to 1%. In the case of equilibrium route choice the total travel time sometimes even reduces when an incident occurs. Theoretically, it is possible that a capacity reduction results in a more efficient usage of the network. This is called the Braess-paradox (Braess, 2005). In Table 1 and Table 2 the results are summarized.

In Figure 7 the total travelled distance is presented in the same way as the total travel time is presented in Figure 6. From these figures it can be seen that the total travelled distance changes more or less linearly with the increase in demand. Furthermore, the incident also doesn't cause large changes in the total vehicle kilometres driven. In the case of fixed route choice the change is of course equal to 0% and in the case of equilibrium route choice the change is less than 1% for both demand patterns.

Table 1: Total travel time demand pattern 2008 corrected for increase in demand

Loading Factor	*Total travel time no incident (hours)*	*Total travel time incident fixed routes (hours)*	*Total travel time incident equilibrium routes (hours)*	*Vehicle loss hours incident fixed routes (hours) (%)*	*Vehicle loss hours incident equilibrium routes (hours) (%)*
1.00	282439	296561	283773	14122 (5%)	1334 (0%)
1.05	282709	299630	284460	16921 (6%)	1752 (1%)
1.10	284825	309537	286954	24712 (8%)	2129 (1%)
1.15	288884	313967	291262	25083 (8%)	2378 (1%)
1.20	294783	319970	296938	25187 (7%)	2155 (1%)
1.25	302627	327988	304239	25361 (8%)	1612 (0%)
1.30	313044	342164	313695	29120 (9%)	650 (0%)
1.35	324058	356825	325282	32767 (10%)	1224 (0%)
1.40	339238	371867	340661	32629 (10%)	1423 (0%)

Table 2: Total travel time future demand pattern corrected for increase in demand

Loading Factor	*Total travel time no incident (hours)*	*Total travel time incident fixed routes (hours)*	*Total travel time incident equilibrium routes (hours)*	*Vehicle loss hours incident fixed routes (hours) (%)*	*Vehicle loss hours incident equilibrium routes (hours) (%)*
1.00	324399	348347	325921	23949 (7%)	1523 (0%)
1.05	325214	353189	327273	27975 (8%)	2059 (1%)
1.10	333861	351873	334812	18012 (5%)	951 (0%)
1.15	347712	368565	349242	20853 (5%)	1530 (0%)
1.20	369565	392441	367447	22876 (5%)	-2118 (0%)
1.25	398636	423494	392851	24858 (5%)	-5785 (-1%)
1.30	437963	463524	424946	25560 (4%)	-13017 (-2%)
1.35	463989	508528	467410	44539 (7%)	3422 (1%)
1.40	527853	566762	506841	38908 (5%)	-21013 (-3%)

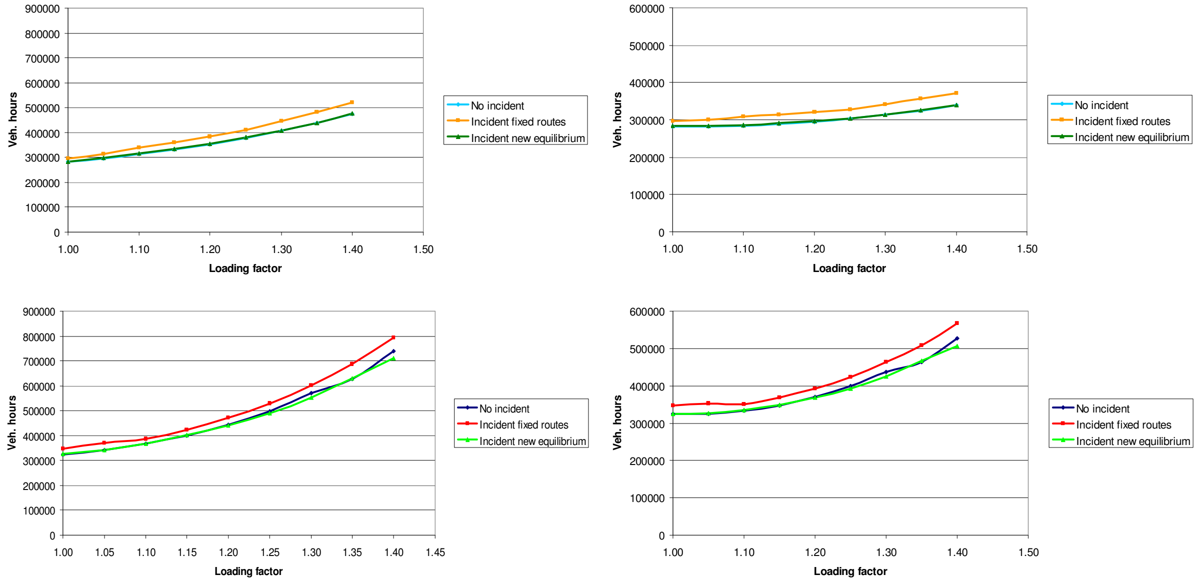


Figure 6: Total uncorrected (left) and corrected (right) travel time in the network with the 2008 (top) and future (bottom) demand pattern

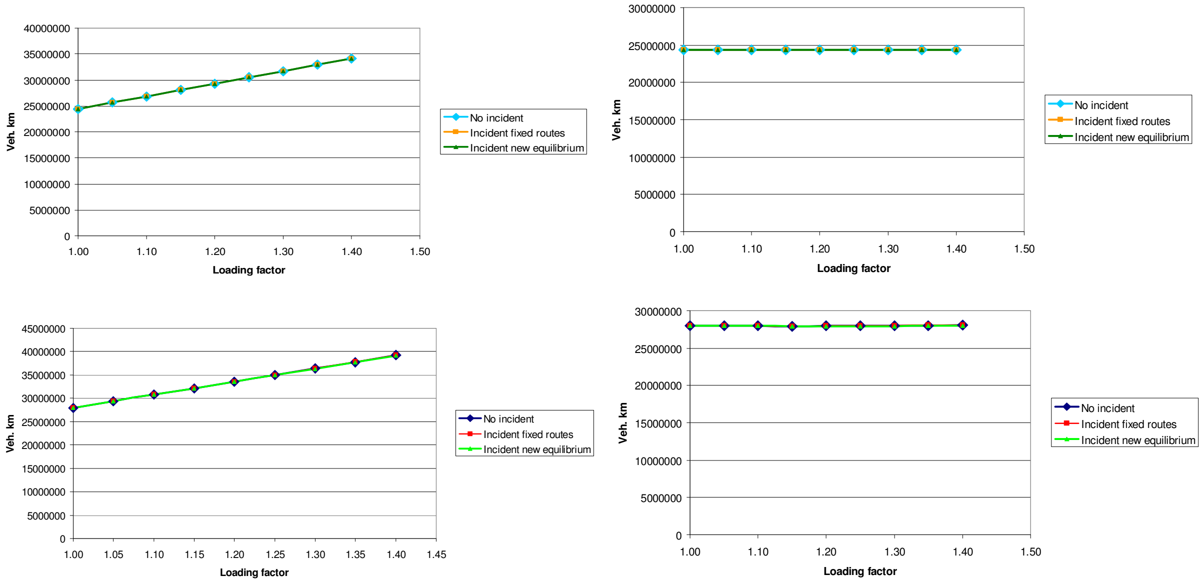


Figure 7: Total uncorrected (left) and corrected (right) vehicle kilometres in the network with the 2008 (top) and future (bottom) demand pattern

In Figure 8 the average speeds in the network are shown. These speeds are computed by dividing the vehicle kilometres by the total travel time. This is done for both demand patterns. From this figure it can be seen that average network speeds decrease when the demand increases. In fact, the speed decreases more than linear with the demand loading factor. When the demand increases more than 20% the network speed decreases rapidly. For example, when the demand increases with 40%, the network speed is decreased from 86 km/h to 72 km/h in the case of the base year demand pattern and from 86 km/h to 53 km/h in the case of the future demand pattern. The incident reduces the average speed even further. For the base year demand pattern it can clearly be seen that the reduction in speed is higher with an increased demand (e.g. loading factor 1.4) compared to the loading factor of 1.0. For the de future demand pattern, this is less obvious. The reduction in speed caused by an incident is for some demand levels less than the reduction in speed for the loading factor 1.0 and sometimes more.

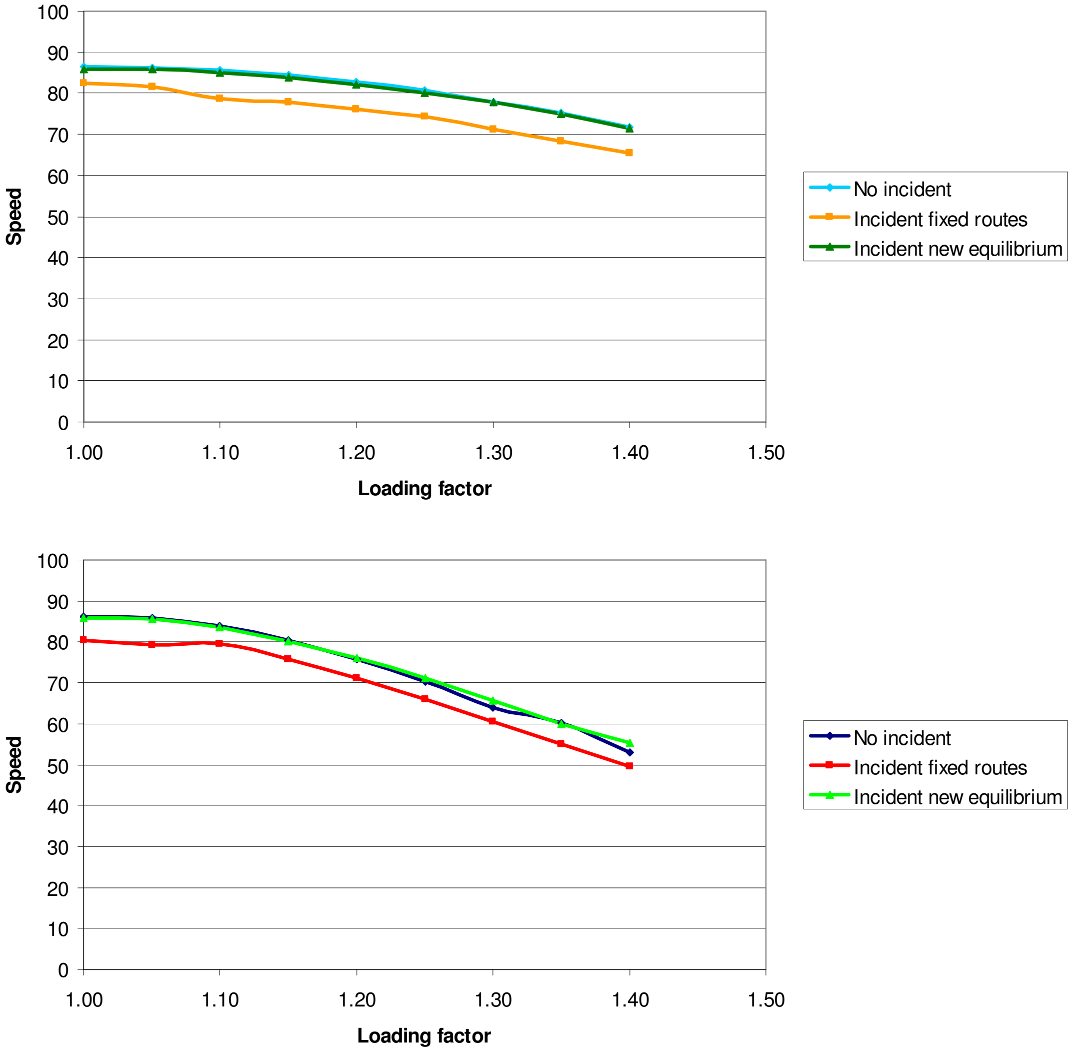


Figure 8: Speeds in the network with the 2008 (top) and future (bottom) demand pattern

5 Conclusions

This paper showed that the existing road network of the Netherlands is already vulnerable. A small incident on an off-ramp caused serious congestion for several hours on a large part of the network. The model runs showed that, if no measures are taken, the network of Rotterdam becomes more vulnerable when the level of demand increases. In the situation where the peak periods get longer and more intensive this phenomenon is even more obvious. This conclusion is based on the fact that when the level of demand increases, the total travel time increases more than linearly. For example, if the demand increases with 40%, the total travel time respectively increases with 68% and 128% in the case of the base year demand pattern and future demand pattern. This implies that the network is not robust for a growth in demand. In the situation when the level of demand is higher and an incident occurs, the impact of the incident is in general also higher. For the base year demand the vehicle loss hours corrected for the growth in demand increase from 14 thousand hours to 32 thousand hours if the demand increases from 0% to 40%. For the future demand pattern the vehicle loss hours increase from 23 thousand to 39 thousand. Both conclusions are based on the situation with fixed route choice. In practice the vehicle loss hours will probably be less since some people change their routes. This implies that the network becomes more vulnerable for incidents when the demand increases. An explanation for this is that there is less spare capacity in time-space and that it is therefore more difficult to recover from the incident.

These conclusions are based on the occurrence of a single incident. In further work, we will try to generalise these conclusions for different types of incidents on different locations. This analysis combined with a more thorough understanding of incident probabilities will enable us to compute the opportunity costs of not investing in network robustness. Once this is known, an optimal investment strategy to improve the robustness of the network will be presented.

Acknowledgements

This research is supported by the Dutch research program Next Generation Infrastructures and by Transumo-ATMA.

References

Berdica K. (2002) An introduction to road vulnerability: what has been done, is done and should be done, *Transport Policy 9*, pp. 117-127.

Bliemer M.C.J. (2005) *INDY 2.0 Model Specifications*, Delft University of Technology.

Bliemer M.C.J. (2007) Dynamic Queuing and Spillback in an Analytical Multiclass Dynamic Network Loading Model, in: *Transportation Research Record: Journal of the Transportation Research Board,* No. 2029, Transportation Research Board of the National Academies, Washington D.C.

Braess D., A. Nagurney and T. Wakolbinger (2005) On a paradox of traffic planning. *Transportation Science*, volume 39, pp. 446-450.

D'Este G.M., M.A.P. Taylor (2003) Network vulnerability: an approach to reliability analysis at the level of national strategic transport networks, in: *The Network Reliability of Transport: Proceedings of the 1st International Symposium on Transportation Network Reliability (INSTR),* Oxford, Pergamon.

Husdal J. (2004) Reliability and Vulnerability versus Cost and Benefits, Molde University College, in: *Proceedings of the second International Symposium on Transportation Network Reliability (INSTR),* Oxford, Pergamon.

Immers L.H., J.E. Stada, I. Yperman (2004) Robustness and Resilience of Transportation networks; problem survey and examples, *Paper presented at NECTAR Cluster Meeting on Reliability of Networks*, Amsterdam.

Knoop V.L., S.P Hoogendoorn and H.J. van Zuylen (2007) Quantification of the impact of spillback modeling in assessing network reliability, *CD-ROM. Transporation Research Board of the National Academies,* Washington, D.C.

Li M. (in press) *Robustness Analysis for Road Networks: A Framework with Combined DTA Models*, TRAIL thesis series, Delft.

Murray-Tuite P.M., H.S. Mahmassani (2004) Methodology for Determining Vulnerable Links in a Transportation Network, in: *Transportation Research Record: Journal of the Transportation Research Board,* No. 1882, Transportation Research Board of the National Academies, Washington D.C., pp 88-96.

Snelder M., L.H. Immers, I. Wilmink (2004) De begrippen betrouwbaarheid en robuustheid nader verklaard, in: *Proceedings of the Colloquium Vervoersplanologisch Speurwerk,* Zeist

Tampère C.M.J., J. Stada, L.H. Immers (2007) Methodology for Identifying Vulnerable Sections in a National Road network, in: *Transportation Research Record: Journal of the Transportation Research Board,* No. 2012, Transportation Research Board of the National Academies, Washington D.C.

Yperman I. (2007) *The Link Transmission Model for Dynamic Network Loading*, Catholic University of Leuven, Leuven.