Architecture for Robust Network Design

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Abstract

The road network in the Netherlands and in many other countries is becoming more and more vulnerable. Small disturbances can cause major disruptions on large parts of the network. The costs of this vulnerability can add up to several billions of Euros in the future. In this paper we present a new network design methodology (architecture) which focuses on improving the robustness and therewith reducing the vulnerability of a road network. The architecture for robust network design consists of the following components:

- a specification of the design standards,
- a functional analysis of the road network,
- a design process, integrating network design and (future) spatial plans
- a test of the quality of the robust road network design.

The architecture can be used to design a robust road network for any area. To demonstrate how the architecture can be deployed we have, in this paper, worked out the various steps in detail for the network of the area The Hague – Rotterdam in the Netherlands for the year 2020. A comparison of the new robust network design with the policy network of 2020 shows that in general the robust network performs better, both in the situation with and without disturbances. The total travel time is 2.3% lower, the total distance travelled is 0.8% lower and the average network speed is 1.6% higher. Furthermore, the average number of vehicle loss hours in the case of accidents is 30% lower. Therefore, it is concluded that the presented architecture for robust network design allows us to improve the robustness of a road network significantly.

1. Introduction

Due to the ever increasing mobility of the population, the Dutch (and Belgian) arterial road network is subject to heavy usage; in many places it is almost fully used during rush hours. This not only causes many daily recurring traffic jams, but also leads to increased vulnerability of the road network. A small accident or heavy rainfall may be all it takes to trigger huge delays affecting large parts of the network in no time. Travel times are thus becoming increasingly unpredictable.
Road users place a high value on increased reliability of travel times. In their opinion, it is even more important than solving the congestion problem. The development of a *robust road network* meets this need. A robust network is much less susceptible to disruptions, thus increases the reliability of travel times.

This contribution shows the importance of a robust road network and describes several general principles for the creation of a robust road network. A vision on a robust arterial structure for the road

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network in the Rotterdam - The Hague urban area has been developed based on these principles. The presentation of the proposed arterial structure should not be seen as a real ‘plan’ in which all of the design issues have been worked out and nailed down, but more as an illustration of how the development of a robust road network might be envisioned.

2. Explanation of the term Robustness

In this paper we define robustness as the extend to which a network is able to maintain the function were it was originally designed for under all circumstances that deviate from the normal conditions. We define vulnerability as the opposite of robustness.

This definition contains two parts:

- *function:* in its most basic form, a road network has the function of making travel from A to B possible. However, for an adequate development and shaping of the road network, we also need to know the *kind* of travel a road or intersection is intended for. The most important functional distinction is that of *travel distance*: a network that must enable long distance travel is quite different from a network for local traffic. But a distinction between passenger traffic and freight traffic may also be helpful, or even a differentiation based on trip purpose. The principles described in what follows are, for that matter, also largely applicable to other modalities; however, in this report, we have limited ourselves to the road network.
- *changing circumstances:* this is about the fluctuations in demand and supply. We have distinguished between the *normal situation* and *abnormal situations*. All ‘normal’ fluctuations in demand and supply are part of the normal situation: the difference in demand between peak and off-peak, or holiday/weekend and business days, but also the influence of, for instance, weather conditions on the quality of the supply: heavy rainfall can reduce the capacity of a road by tens of percentage points. Abnormal situations are things like incidents and calamities: the unforeseen or partial non-availability of a road segment, intersection or even part of the network. But also planned stoppages (for the purpose of major road works) or extreme weather conditions are abnormal.

In thinking about robustness, we have used the aspects formulated by Immers al. (2004a) as a point of departure and added ‘prevention’ and ‘balance’ to the list of aspects:

- *prevention:* the best way to maintain the function of a traffic system is by preventing the occurrence of disturbances. However, in this case prevention refers to preventing that congestion occurs in case of disruptions, instead of preventing the occurrence of disruptions themselves.
- *redundancy*: the robustness of a system can be increased by including spare capacity in the network. This spare capacity is often referred to as redundancy.
- *Interdependency*: the degree to which congestion is limited to the link involved or a small part of the network. In a network where there is interdependency, congestion does not spread like an oil spill over the whole network.
- *resiliency*: resilience refers to the capability of the network to recover over and over again and as quick as possible from temporal disturbances.
- *flexibility*: the robustness of the transport system can partly be measured by the degree to which the system is able to fulfill more and different functions than those for which the system was originally designed. Or, in other words, the ability to adjust is the characteristic that enables the system to grow with the new demands that are made of it.
- *balance in the network:* if the traffic flows and the capacity are distributed over the network in a balanced way, it is easier cope with disturbances. One route can serve as a backup option for the other. In Figure 1, an example is shown of a balanced and unbalanced distribution of lanes over alternative routes. At the situation at the top there are two routes to travel from north to south. The first has four lanes and the other two. If an incident occurs on the route with four lanes, there are only two lanes on the other route left as a backup option minus the capacity that is already used. In the situation in the middle there are two routes with three lanes. This situation is a bit more

balanced. The most balanced situation is the situation in which three routes each have two lanes. If something happens on one route there are four lanes left as a backup option minus the capacity that is already used.

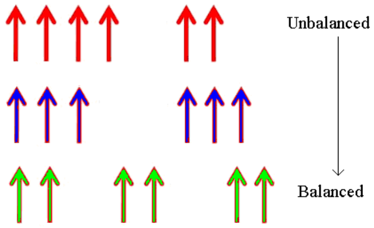


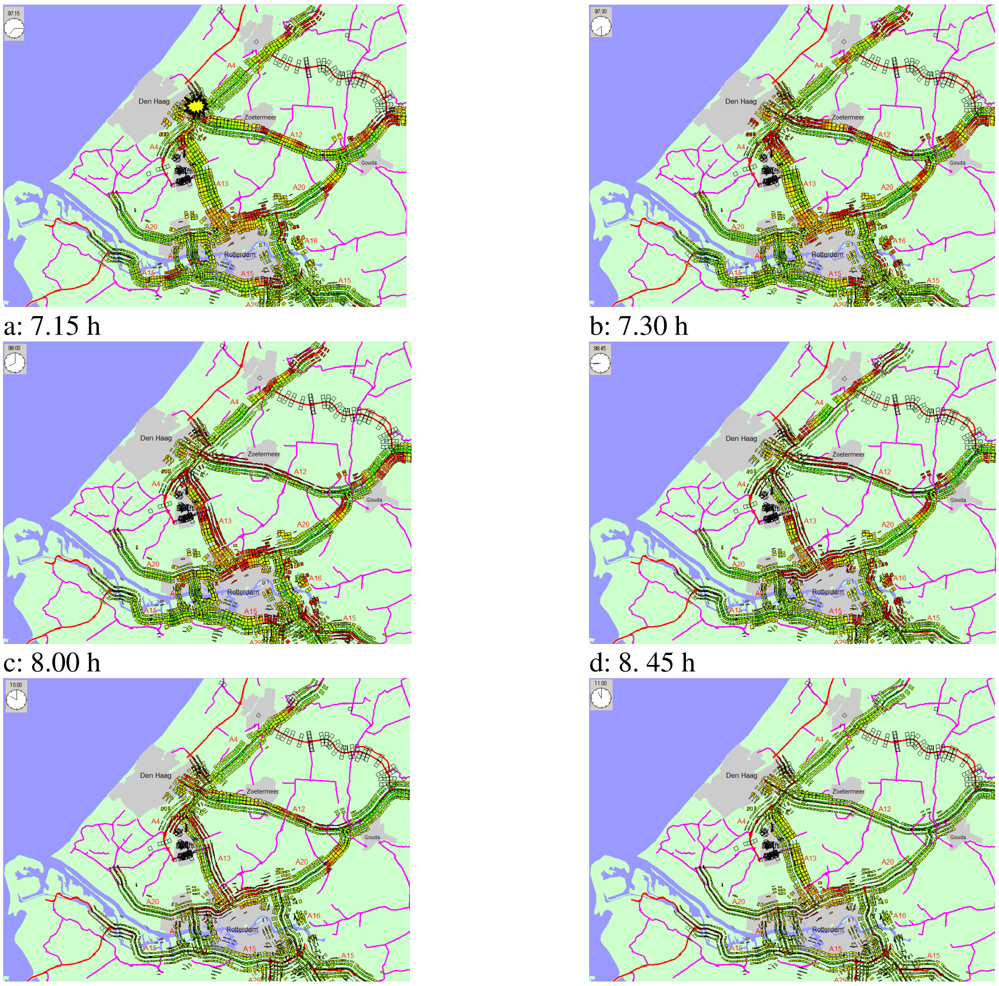
Figure 1: (Un)balanced distribution of lanes.

2. The importance of a robust 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 7.15h 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 four hours after the occurrence of the incident.



a: 7.15 h

b: 7.30 h

c: 8.00 h

d: 8. 45 h

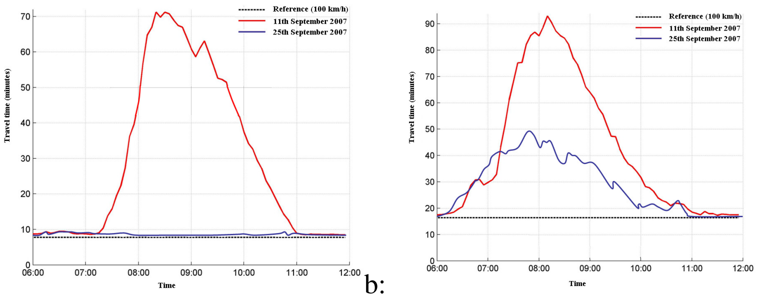
e: 10.00h

f: 11.00h

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

In Figure 4a and Figure4b the travel time that is needed to travel over the complete A13 and the A12 between The Hague and Gouda is shown. The red line is the travel time on the 11th of September. The blue line is the travel time on a regular Tuesday (without incidents) in September in 2007 and the black dotted line is the free-flow travel time with a speed of 100 km/h. These figures show that individual travelers experienced a delay up to one hour on the A13 and up to 40 minutes on the A12.

The total number of extra vehicle loss hours causes by the incident on the A13 and the A12 is about 10 thousand. This number multiplied with an average value of time of 15 euro/hour results in an economic damage of about 156 thousand euro. The real economic damage of this incident on an off ramp is much higher because the extra travel time of taking longer alternative routes is not included in the vehicle loss hours. Furthermore, delays on the local roads, the costs of emergency services, repair costs, medical costs and environmental costs are not yet included.



a: b:

Figure 4: Travel time on the A13 (a) and the A12 (b) on the 11th of September 2007.

This example 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 that, therefore, the network becomes more vulnerable. This hypothesis is tested with a modelling approach. The road network of Rotterdam is used to illustrate the vulnerability of road networks in the future. 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 5. Figure 2 includes the real network of Rotterdam.

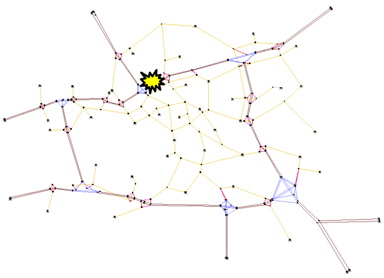


Figure 5: Road network of Rotterdam and surroundings.

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 measures that can reduce the vulnerability.

The total average OD demand in 2008 per hour is 88 thousand 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 6. 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 6.

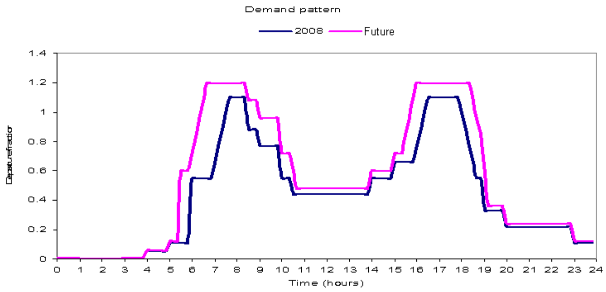


Figure 6: Departure fractions.

The model Indy was used for to calculate the costs of vulnerability of the future network. 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 2007). 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.

With Indy 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 5 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. In order to get an impression of the total costs of vulnerability, the vehicle loss hours for the single incident on the road network of Rotterdam are extrapolated to a yearly average for the Netherlands. The vehicle loss hours are multiplied with an average value of time of 15 euro's per hour and with an average number of 2000 incidents (based on (Meeuwissen et al., 2004)) with a comparable impact that take place on motorways in the peak period in a year. Furthermore, the costs are multiplied with a correction factor for the location. For the situation with fixed route choice, this correction factor is -34.3% and for the situation with equilibrium route choice this factor is -14.2%. This factor is determined by simulating an incident on all the links of the network of Rotterdam for demand with loading factor 1. Based on the chance of an incident on each link (Meeuwissen et al., 2004), the correction factor was determined. This correction factor indicates the difference in vehicle loss hours between the simulated incident on the ring road of Rotterdam and the weighted average number of vehicle loss hours of incidents on all the links of the network.

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.

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.

The resulting costs of vulnerability are shown in Figure 7. From this figure it can be seen that, in the case were nobody change routes, the costs of vulnerability increase from 275 million euro to 900 million euro if the demand increases with 40%. If the future demand pattern occurs the costs vary between the 400 million and 1.2 billion euro. The lines are not constantly increasing. The shocks could be explained by the network structure. At the locations were the costs increase rapidly, extra large parts of the network become congested. The decrease of the costs (from loading factor 1.05 to 1.1) and the negative cost in the case of the future demand pattern seem to be contra-intuitive. A possible explanation for this can be that benefits occur downstream of the incident. Furthermore, it is possible that a capacity reduction results in a more efficient usage of the network. This is called the Braess-paradox (Braess, 2005).

The presented costs are only an indication. The real costs could be lower, because an improved level of information could result in a more optimal route choice in incident situations and network improvements could lead to a lower level of congestion in the situation without an incident. If an incident occurs congestion spreads slower trough the network. The costs could also be higher, because the value of time in unexpected situations is higher than 15 euro's per hour and besides the 2000 incidents with a large impact, also many small incidents occur which add to the costs of vulnerability. Furthermore, delays on the local roads, delays on the roads outside the modeled network, the costs of emergency services, repair costs, medical costs and environmental costs are not yet included. Finally, the number of incidents is likely to increase with the traffic volume and the capacity drop is not considered.

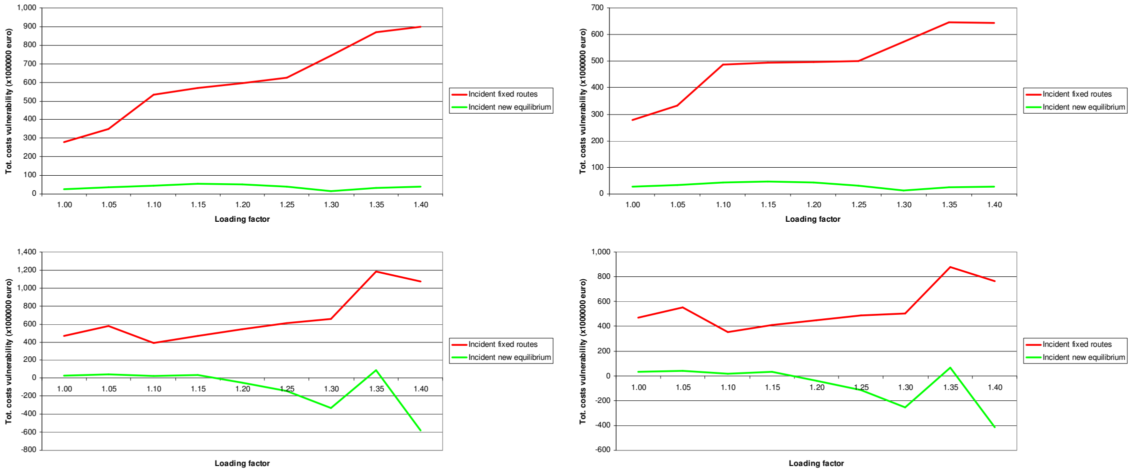


Figure 7: Uncorrected (left) and corrected (right) yearly costs (corrected for the growth in demand) of vulnerability in the network with the 2008 (top) and future (bottom) demand pattern.

3. An infrastructure strategy for a robust road network

The costs of vulnerability give an impression of amount that could be invested in taking measures to improve the robustness of the network and, therewith, reduce the vulnerability of the network. In fact, a small investment could already result in a big decrease in vulnerability.

This section describes several building blocks for an infrastructure strategy for a robust road network. In speaking of an infrastructure strategy, we have distinguished two components:

- the *network configuration*: what principles underpin a robust road network, what connections are necessary for which functions, and what requirements must be established for those connections.
- the *network elements*: which principles should underpin the sizing of the network elements (intersections, road segments, junctions) when viewed from a ‘robustness’ viewpoint?

In developing this further, we have set ourselves several constraints. For instance, the focus is on the infrastructure. This does not change the fact that other measures like, for instance, transportation management, incident management, traffic management and rational road maintenance, form an integral part of a robust road network. In addition to these, there are obviously other modalities within the total concept of mobility (e.g. public transport and bicycles for individuals, and railways and river transport for goods) that play an important role - whether or not in combination with the roads. However, in our vision, we have limited ourselves to the road network, although we will discuss connections with public transport in passing.

Below four general principles for a robust road network are presented: 1) A healty balance between demand and supply; 2) Integrating flexibility and options into the network; 3) Designs for both flow and buffering; 4) Form follows function.

A healthy balance between demand and supply

A robust road network must be able to stand a good deal: if part of the road capacity fails for whatever reason, the network must be able to compensate for this to some degree. A healthy balance between demand and supply should therefore be the starting point in the normal situation. The occurrence of a limited amount of congestion (localized and temporary) is acceptable under these circumstances: the largest peaks in demand are thus spread out over a somewhat longer period of time so that the expensive infrastructure need not be sized according to the ‘peak within the peak’.

But what is a ‘healthy balance’? The principle we have used is that the direct and indirect costs of the creation of extra capacity on the road must be balanced with the benefits for consumers and producers in that less time is lost through incidents (see Meeuwissen A., 2002, and Yperman et al, 2003). Access optimization is not the only important thing in this consideration - the consequences for quality of life and space utilization are also important.

At the same time, we want to prevent this extra capacity from generating increased mobility, thus causing the extra space on the road to 'evaporate' within a few years. This mechanism contradicts with the principles of a robust road network, since it also needs to continue to function well in the long term. The core of the solution is careful selection of the design speed of the infrastructure. Continuous traffic flow is more important for traffic that remains within urban areas and travels relatively short distances, than a high design speed is. For long distance traffic the requirements are different: this kind of traffic should be enabled to bypass urban centers without significant loss of speed.

Integrating flexibility and options into the network

A robust road network offers multiple ways of getting from A to B. This results in a leveling off of peaks, because road users on a certain route have the option of taking another route during flow utilization, be it one of somewhat lower quality, or one that is a little longer. These alternative routes may also make use of other modes of transport - public transport, for instance. We do not consider different forms of transportation to be in competition with each other, but see them as an increase in options for the transport consumer.

In addition to freedom of choice, these alternative routes also offer fallback options in case a road segment or intersection becomes (entirely or partially) unavailable, whether for foreseen or unforeseen reasons. Moreover, extra flexibility that is only used during abnormal situations can be built into the network at strategic locations. Examples of this include closable crossovers or connecting roads that are normally not used, but also extra capacity that is only utilized in abnormal situations, e.g. road shoulders suitable for driving on. Traffic flow over the alternative route is handled well by providing information to road users and through dynamic traffic management.

Designs for both flow and buffering

Since we anticipate a certain amount of congestion in a robust road network, we must not only consider the flow function, but also – far more than has been done so far – integrate the *buffering function* of road segments into the design of roads, intersections and junctions. Every road segment can accommodate a certain number of vehicles: the ‘natural’ buffer capacity. Wherever the natural buffer capacity is insufficient, we can intentionally offer extra buffer capacity. These buffers prevent congestion spillback to other routes; they also regulate the traffic, so that certain roads, like through roads or the urban road network, for instance, remain as congestion-free as possible (see figure 8).

As indicated in figure 8, it can be useful to apply buffers at the following locations:

1. Prevent congestion on the long distance network by creating traffic regulation buffers at access ramps, but also spillback buffers at exit ramps in the long distance network;
2. Prevent congestion on the urban road network by creating traffic regulation buffers at the urban area ‘access points’ (and spillback buffers at the ‘exits’, if needed); this includes keeping urban ring roads as congestion-free as possible;
3. Add spillback buffers upstream from bottlenecks *within* the metropolitan network, if needed.

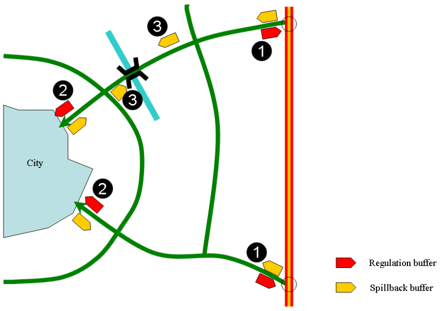


Figure 8: Example of buffers in the metropolitan network.

Form follows function

The highway network was originally designed for long distance traffic: design speed 120 km/h, broad lanes, weak curves and spacious intersections. However, we are noticing that highways to a considerable extent are being used for short trips, simply because the highway is often the only route available. Thus, the two traffic types, using the same routes, tend to get in each other's way. The form is thus not tailored to the function, leading to an inefficient usage of traffic space.

In a robust road network, form follows function: we have made a physical distinction between long distance and short distance road networks, so that we can focus the network characteristics (mesh size and design speed) on their function. This makes the total network more efficient (e.g. in terms of space utilization), especially in urban areas with heavy traffic, and ensures that the different functions are not in conflict with each other.

The above presented aspects and design principles of robustness lead to the following set of concrete measures that could be applied to improve the robustness of a road network. This list is not intended to be complete. The effectiveness of the measures will depend on context in which they will be applied and the synergy that could be obtained from applying several measures at the same time:

- Creating backup options in the public transport.
- Separating through traffic and local traffic, for instance by splitting motorways in two roadways: a main roadway for trough traffic with only a few entrance and exit points and a parallel road for local traffic with many on and off ramps.
- Creating equivalent route alternatives by downgrading motorways that are mainly used for local traffic, by upgrading local roads and by adding new roads for missing links in possible alternative routes.
- The restructuring of intersections and junctions so that they fit within the new structure.
- Introducing buffers to prevent spill back to (other) motorways and to cities and to regulate the in flow to motorways.
- Introducing flexibility in the network for example by tidal flows and contra flows.
- Improving the information that is given to drivers.
- Improving the incident management strategies.

The effectiveness of some of these measures has been shown in literature. In (Snelder et al., 2008) the importance of alternative routes is shown. In (Immers et al., 2004b) it is shown that upgrading the secondary network, thereby considering it to be an independent subsystem and not seeing it solely as a feeder system to the motorway network could improve the robustness of a road network because it reduces the interdependencies. In (Schrijver et al., 2008) it is shown that in the regular situation buffers can potentially reduce the total travel time with a maximum of 12%.

4. Example for the area Rotterdam – The Hague in the Netherlands

Based on the principles and measures, we have drawn up a robust arterial structure for the road network in the Rotterdam - The Hague urban area. This should not be seen as a ‘plan’ in which all design choices have been worked out in detail, but as an illustration of a vision on the development of a robust road network.

Functional analysis for the Rotterdam - The Hague urban area

'Form follows function'; the first step in this development is thus a ‘functional analysis’: an analysis of the current and future use of the network in the Rotterdam - The Hague urban area, in which a distinction is made between the different functions. In doing so, a distinction is made between:

- metropolitan traffic, remaining within the Rotterdam - The Hague urban area,
- incoming and outgoing traffic, exiting or accessing this area, and
- through traffic, exiting or accessing a location outside of the area, without passing through the area.

The following table gives the distribution of the total traffic over these three categories.

Table 1: Traffic in the Rotterdam - The Hague urban area (as % of the total number of kilometers driven in the area).

Metropolitan traffic	44%
Incoming and outgoing traffic	45%
Through traffic	11%

Most of the traffic on the main routes in this area stays within the Rotterdam - The Hague urban area (‘metropolitan traffic’). This traffic uses many different types of roads, each having its own speed regime, capacity, intersections and access forms. The differences between all these road types are not (any longer) functional: the road user (and transporter) simply chooses the fastest route at random. In the example below (figure 9), which gives possible routes between Rotterdam-Alexander and Leiden, it is easy to see that choosing the highway often leads to a huge detour, while there are hardly any alternatives for staying off the highway and taking a more direct route.

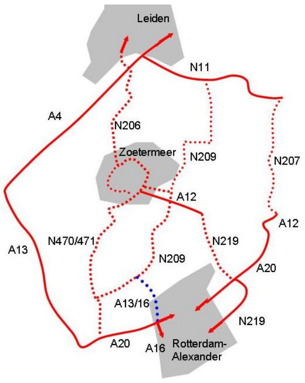


Figure 9: Routes between Rotterdam-Alexander and Leiden.

There are a limited number of highway routes available for metropolitan trips through the region (A12, A13, A15, A20), with few or no alternatives. This makes the network structure very vulnerable. Because the mesh of highways has remained relatively rudimentary in comparison with the ever expanding and thinning urban area, it is understandable that it has become very tempting for travelers to take 'shortcuts'.

There are two important through traffic flows in the Rotterdam - The Hague urban area: the north-south route that runs from Amsterdam to Belgium, and the traffic flow to and from Rotterdam harbor, which runs mainly along the east-west axis to and from Germany. Both flows of through traffic use the same roads as the metropolitan traffic, which leads to relatively low speeds, unreliable travel times, and chaotic traffic. This is especially the case on the routes passing Rotterdam and The Hague. Moreover, no real alternatives are available for several crucial road segments – for instance, the A4 between Ypenburg and the Leidschendam intersection, or the A15 to the west of the Benelux tunnel.

Towards a new road network structure

The functional analysis may be best summarized as follows: the problem is not so much the congestion of highways, but much more the fact that the metropolitan traffic almost exclusively depends upon a few highway routes and must share these routes with through traffic. Therefore, we must look for the core solution in the *adaptation of the structure* of the whole road network in the Rotterdam - The Hague urban area, and in a way more compatible with the nature of mobility in the area. The main components of this new structure are:

- a separate, robust and balanced network of ‘metropolitan arterial roads’ (80 km/h), specifically targeted at metropolitan traffic that remains within the Rotterdam - The Hague area. This ‘metropolitan arterial network’ consists of regional traffic flow roads that are a hybrid between highways and the underlying road network;
- a limited number of congestion-free arterial routes specifically targeted at through traffic (120 km/h). The through traffic would be physically separated from the metropolitan traffic (it would be ‘unbraided’, as it were). There would be only a limited number of locations where traffic can access or exit the through routes.

This new structure does not require large-scale asphalting: the overall amount of extra asphalt required for the *Robust Road Network Vision* is roughly the same as for the *MIRT*[6], but the total traffic space is divided differently, i.e. a larger part of it is reserved for metropolitan arterial roads than is currently the case. Some existing highways may even be ‘metropolitanized’: converted into metropolitan arterial roads. Since this type of road is more space-efficient (narrower lanes, simpler intersections and junctions), the same amount of asphalt covers more lane kilometers.

Example Rotterdam - Delft section

We will now illustrate this approach using the Rotterdam - Delft section as an example. Theoretically, a lane can process 2200 cars per hour. In order to be able to process the traffic demand expected in 2020, an average of seven lanes will be needed per direction. This figure includes the limited extra growth in demand due to the improved network; however, this growth will be slowed down as a result of price policy.

But we need to build extra capacity into a robust network. We believe this can be done by assuming a ‘robust capacity’ of 1900 cars per lane per hour in our calculations - a figure at which the additional investment costs for more lanes are roughly in balance with the reduction of time loss through incidents (Immers et al, 2004b). This leads to a requirement for one extra lane in the Rotterdam - Delft section (see figure 10).

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[6] MIRT, in Dutch, is an acronym for the Dutch Ministry of Transport, Public Works and Water Management's *Multi-Year Programme for Infrastructure, Spatial Planning and Transport.*

Figure 10: Rotterdam-Delft: number of lanes needed in 2020.

According to the *MIRT*, a total capacity of 6 lanes has been planned for 2020 for this section (see figure 11): the current A13 (3 lanes) and N471 (1 lane), plus the A4 Midden-Delfland which is yet to be built (2 lanes). This means that, based on the theoretical capacity, we are short of one lane in the MIRT, and based on the 'robust capacity' we are even two lanes short. Moreover, the distribution of the lanes over road types does not match the traffic demand: five highway lanes are being provided, while only two such lanes are needed for through traffic - it would suffice to size the others as metropolitan arterial roads.

Figure 11: Rotterdam-Delft: lane provision in 2020 (MIRT).

In the *Robust Road Network Vision*, we offer a robust capacity of six lanes for metropolitan traffic that is equally distributed across the three 80 km/h routes, the 'N4', the 'N13' and the N471. Due to the equal distribution of the capacity, a reasonable processing of traffic is still possible, should an incident on one of the three routes lead to stoppages there. This means that the N471 needs to be expanded to 2 x 2 lanes, but that the A13 can have one lane less in each direction, while the remaining 2 x 2 lanes could also be a little narrower. The space gained could be used for the realization of a South tangent-like public transport lane beside the N13 (OV), leading to a more robust public transport network in this corridor (see figure 12).

In addition to these six lanes (in total) for metropolitan traffic, we still need two lanes per direction for through traffic. We have chosen to locate these next to the A4, since that complies best with current policy. It means that the A4/N4 would get a total of four lanes in each direction – two for metropolitan traffic (80 km/h) and two for through traffic (120 km/h). That is two more than the number projected in the current plans.

Figure 12: Rotterdam-Delft: lane provision in 2020 (Robust Road Network Vision).

Details for the Rotterdam - The Hague urban area: Metropolitan arterial network
The metropolitan arterial network will have a 80 km/h speed limit and has a finer mesh than the current highway network: the mesh size is around 5 km. These routes have comparable capacities

(usually 2 x 2 lanes). Wherever it makes sense, this network can be combined with the public transport lanes.

Metropolitan arterial road intersections can be a mix between (turbo) roundabout(s), fly-over(s) and/or traffic lights, depending on the situation. However, it is undesirable to have roundabouts in the main traffic flow at locations where local roads connect to this metropolitan arterial network. It is preferable to use simple fly-over solutions, or, if need be, traffic lights with a 'green wave'. The chance of congestion on the metropolitan arterial network will be lower than it is now because of the design-level inclusion of extra network capacity. If a traffic jam occurs, the intentional inclusion of buffer areas in the road design ensures that little or no spillback to other routes will take place any more. Figure 13 shows the metropolitan arterial network connections.

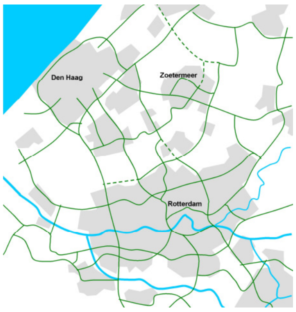

Figure 13: Metropolitan arterial network.

Details for the Rotterdam - The Hague urban area: Through traffic routes

Two primary backbone routes have been planned for through traffic: a north-south one and an east-west one. The processing of the traffic on these through routes will be physically separated from the metropolitan traffic. The access to the through route will be very limited - roughly one access ramp in every 10 km - whereas currently there is one every 2 km or less in urban areas. The through routes have two lanes in each direction, a design speed of 120 km/h and no congestion in the normal situation. This is also achieved by offering buffer areas at the through route access and exit ramps. The through routes should *bypass* urban centers as much as possible (they should be tangential).

In addition to these primary through routes, several secondary arterial routes have been planned that offer additional access and exit routes for traffic to and from the urban area. These routes will also function as a backup for through traffic. If further backup is needed, it can be offered through the metropolitan network, which will be supported by traffic management when used for through traffic.

The A15 is the primary east-west route. In principle, two solutions are conceivable for the primary north-south route (see figure 14):

1. Primary north-south route using all of the A4 (including sections that are currently still missing);
2. Primary north-south route using the A16, that will be joined to the A4 heading for Leiden using the new section of road north of the Terbregseplein.

The figures show the possible alternative routes using dotted and dashed lines.

The extended A16 option offers benefits from a network structure viewpoint: the through route avoids the urban area, and what's more, there is space for a fully adequate alternative route that does not interfere with the primary route (by way of A44-N14-A4). However, creating a new A16-A4 link is expected to be a huge operation that would take a long time to realize. Thus the variant that fits better with current policy was chosen after all: a through route using all of the A4.

This implies that a solution needs to be found for the secondary (alternative) route. Coming from the south, it would be the A16, and from the north it would be the A44. These two main access roads will be joined together using several metropolitan arterial network routes that need to be made suitable for through traffic in case of calamities.

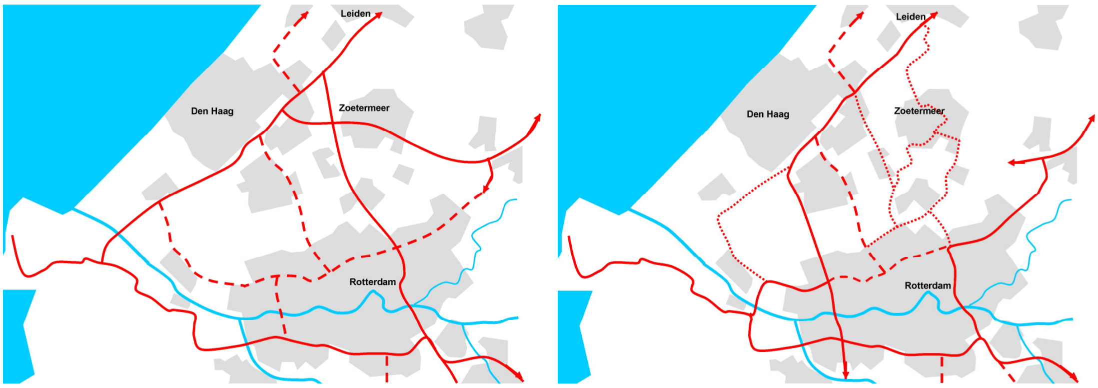

Figure 14: Principal options for through routes (Left: extended A16; right extend A4)

Connection to public transport

Good connections with public transport are an integral part of a robust road network. They increase the options for travel from A to B – rather than merely reducing traffic congestion. Figure 15 below gives an example of how these connections could be implemented for incoming and outgoing travel, i.e. inbound and outbound travel in the Rotterdam - The Hague urban area. There are connection points at the area boundary that are easy to reach from the through routes and that offer the option of switching to high-speed, high-frequency public transport that has adequate capacity and goes to the main destination areas.

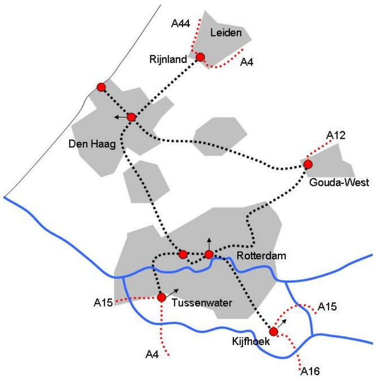

Figure 15: Public transport connections for ingoing and outgoing travel.

Overview

The map (figure 16) shows the details of the robust network; both metropolitan arterial roads and through roads are included.

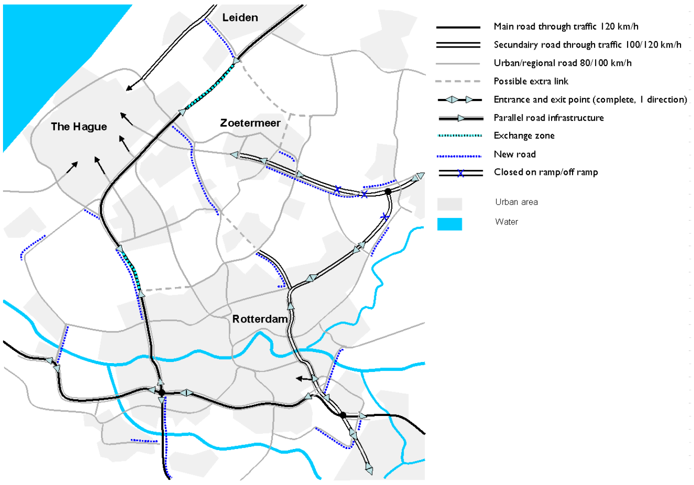

Figure 16: Robust Road Network Vision: overview map.

Modeling

The robust road network was compared to current policy for 2020 using the Indy model that includes both price policy and all *MIRT* projects. The results show that the robust road network not only reduces the average travel time in the regular rush hour by 2.3% but also reduces the distance travelled by 0.8% through the elimination of detours. However, the robust network is especially better equipped for handling incidents – which is what it was designed for: additional travel time due to incidents is almost 30% lower.

Comparison to MIRT

Figure 17 gives insight into the ways in which the *Robust Road Network Vision* suggests the planned investments in the MIRT should be changed. Sometimes, the robust road network uses less traffic space than the *MIRT* (indicated in black) and sometimes it actually calls for more traffic space (indicated in gray). In these cases, it's not just about road segments, but also about the restructuring of intersections.

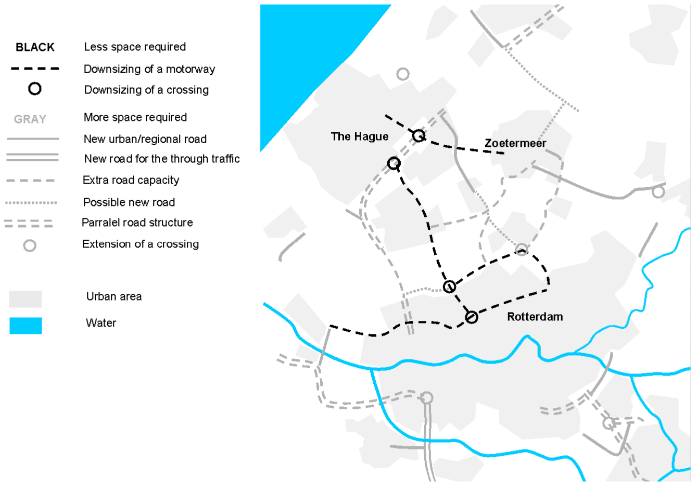

Figure 17: Comparison Robust Road Network Vision to MIRT.

Network element sketches
A robust infrastructure strategy does not only consist of a vision for the network configuration, but also includes the sizing of the elements in the network: intersections, road segments and junctions. What these elements could look like in the new structure has been further developed in sketches for several locations in the network structure, for instance the new configuration of the Prins Clausplein (figure 18).

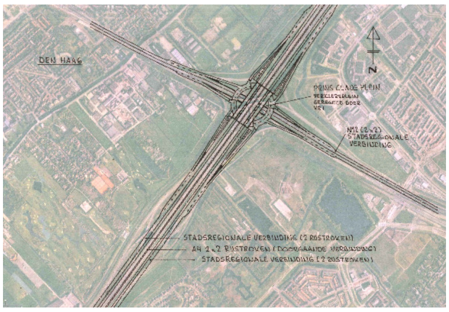

Figure 18: The Prins Clausplein (sketch by Grontmij).

An intersection of two metropolitan roads (the ‘N12’ and the ‘N4’) is planned at the current location of the Prins Clausplein. The traffic going straight ahead will use a fly-over, and the exiting traffic will make use of a traffic light controlled roundabout. The traffic lanes for through traffic (A4) would fit between the metropolitan through traffic lanes of the N4. The A4 lanes do not have access or exit ramps here.

The Kleinpolderplein (figure 19) will also become an intersection of two main metropolitan routes (N13 and N20). The traffic going straight on will use an interchange, and the exiting traffic flows (that will be much smaller than in the current situation) will make use of a traffic light controlled roundabout.

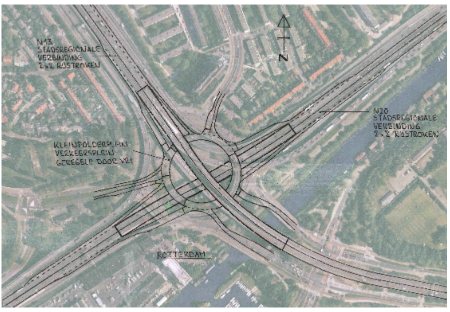

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Figure 19: The Kleinpolderplein (sketch by Grontmij).

5. Conclusion

The road network of the Netherlands is vulnerable. In fact the costs of vulnerability could add up to several billions of Euros in the future if no measures are taken. This shows that it is necessary to improve the robustness of the road network. Therefore, a vision on a robust road network for the area Rotterdam-The Hague has been developed. The *Robust Road Network Vision* resulted from first carrying out a functional analysis. This analysis showed that most of the traffic on the main routes in the Rotterdam - The Hague urban area (‘metropolitan traffic’) does not leave the area. This traffic uses many different types of roads, each with its own speed limits, capacities, intersections and access and exit types. The differences between all these road types are, however, no longer functional: the road users simply choose the fastest route, using a random combination of road types. There are a limited number of highway routes available for metropolitan trips through the region (A12, A13, A15, A20), with few or no alternatives. This makes the network structure very vulnerable. Because the mesh of highways has remained relatively rudimentary in comparison with the ever expanding and thinning urban area, it is understandably tempting for road users to make use of 'shortcuts'.

There are two important through traffic flows through the Rotterdam - The Hague urban area: the north-south route that runs from Amsterdam towards Belgium, and the traffic flow to and from Rotterdam harbor, which runs mainly along the east-west axis to and from Germany. Both flows of through traffic use the same roads as the metropolitan traffic, which leads to relatively low speeds, unreliable travel times, and chaotic traffic. This is especially the case on the routes passing Rotterdam and The Hague. Moreover, no real alternatives are available for several crucial road segments, for instance, the A4 between Ypenburg and the Leidschendam intersection, or the A15 to the west of the Benelux tunnel.

The road network can be made more robust by:

- making a physical distinction between road network functions (interregional traffic, metropolitan traffic and urban traffic),
- connecting the different functional networks well,
- offering a wider range of options for getting from A to B,
- taking the flow and buffering function of road networks into consideration when sizing road segments, intersections and junctions,
- making the infrastructure flexible,
- separating though traffic from local traffic.

The results of the functional analysis combined with the building blocks of a robust network have led to a vision for a robust road network. This network is represented in figure 16. A comparison between the robust network and the current policy for 2020 that included price policy, growth of latent demand and all *MIRT* projects has been carried out. The modeling analyses show that the robust network reduces disruption of traffic flows due to incidents by almost 30% relative to the reference network. What's more, it is possible to reduce potential travel times by 12%.

In the normal situation, the robust network ensures a limited reduction in both number of kilometers travelled (0.8%) and total travel time (2.3%). Finally, we expect the robust network to have a positive effect on the environment and traffic safety because in total less kilometers are travelled. Moreover, the metropolitan traffic is separated from the through traffic, thus making it possible to organize roads according to their functions.
Lower speed limits for metropolitan traffic will reduce damage to the environment and will lead to safer traffic processing.

Acknowledgements

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