The Effect of Network Layout on the Reliability of Travel Time

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Synopsis

Much of the current research in network reliability is concerned with techniques to assess the degree of reliability of a given network. Our paper, on the other hand, is aimed at minimising the consequences of varying network loads and (large) incidents by an adequate *design* of the network. Some of the ongoing research on network reliability is based on a simulation of incidents in a network. By examining the consequences of failures of different links in a network one may detect which links are of primary importance in securing the reliability of the network. This in turn may provide guidance when deciding to upgrade certain network links. Our work takes a similar approach, but focuses on network layout.

In the first sections of our paper we introduce the following important aspects of robustness: redundancy, interdependency, resilience and flexibility. The meaning of these terms as well as their relevance for the robustness of networks is explained.

In the second part we present the results of a series of exploratory simulation exercises. We study three alternative networks starting from a reference network that is loosely inspired on the road network east of Brussels. The performance of the reference network is examined under varying network loads and accident conditions. Then two alternatives to the reference network are introduced. In the first alternative the backbone function of the motorway is emphasised by concentrating more flow capacity onto the motorway. In the second alternative flow capacity is more evenly distributed among motorway and regional roads. Our results clearly indicate that the performance of the second alternative is best under all prevailing conditions.

The Effect of Network Layout on the Reliability of Travel Time

There is a growing awareness that in the past insufficient consideration has been given to the robustness and associated reliability of road networks. It is only during the last decade that considerable research interest has started to emerge for this important aspect of the transportation system. There may be some confusion around the concepts of robustness and reliability. We consider the reliability of travel time to be a user-oriented quality of the transportation system. Robustness, on the other hand, is a characteristic of the system itself. Offering a high degree of reliability to the user often requires a robust system, especially when dealing with overloaded network links.

Different approaches are used in the state-of-the-art research into traffic network reliability. Classifying the literature according to the principal way of approaching the subject, the following subjects can be distinguished (Clark en Watling, 2005):

Reliability of travel times has attracted most interest of researchers. It is defined as the probability that a journey can be completed within a predefined time frame. The principal research method is model analysis through Monte Carlo simulation (Bell en Iida, 1997; Yang et al., 2000; Inouye, 2003; Chen et al., 2003). Other researchers like Bell et al. (1999) and Du & Nicholson (1997) apply sensitivity analyses to a stochastic equilibrium assignment. Similar approaches were reported by Lo & Tung (2000) and Clark & Watling (2005).

In *connectivity* research, one tries to quantify the probability that nodes in the network remain connected, i.e. the probability that certain destinations can no longer be reached. In this type of research, techniques of mathematical graph theory are used (Bell & Iida, 1997; Wakabayashi, 2000).

Other researchers stress the importance of *capacity reliability*, i.e. the probability that a network, or certain components like links and nodes in a network, can accommodate a given level of traffic demand. Just as for travel time reliability, the principal research method is Monte Carlo simulation (Yang et al., 2000; Chen et al., 2002).

Yet an alternative point of view is the impact of *behaviour in unreliable conditions*. Here one examines how travellers account for variability of travel times when making route choice or departure time decisions. The impact of these individual choices on overall network conditions is quantified using traditional traffic assignment techniques, with a cost factor for the unpredictability of travel times introduced into the discrete choice models (Lo & Tung, 2000).

Finally some research has been devoted to *vulnerability* analysis: the objective is to identify the potential *weak* links or nodes, defined as those components having the largest impact on network performance (e.g. travel times) in case of failure. Berdica (2001, 2002) examined the impact on network performance of a limited set of input variables, like demand fluctuations and incidents. Cassir & Bell (2000) applied game theory, with an ‘evil entity’ trying to find the network links having largest impact on travel time distributions. Husdal (2004) points out that vulnerability analysis should be an integral part of project evaluation in road development projects.

The work that we report in this paper has some relation to the last line of research mentioned above. In our research we focus on minimising the consequences of varying network loads and (large) incidents by an adequate *design* of the network.

Some of the ongoing research on network reliability is based on a simulation of incidents in a network. By examining the consequences of failures of different links in a network one may detect which links are of primary importance in securing the reliability of the network. This in turn may provide guidance when deciding to upgrade certain network links. Our work takes the similar approach of simulation, but focuses on network layout.

In the first sections of our paper we survey a number of important aspects of reliability and network robustness; in the second part we present the results of a series of simulation exercises. We compare the performance of three alternative network layouts and show the important effect of a correctly partitioned hierarchical highway system on network reliability.

FACTORS AFFECTING NETWORK RELIABILITY

Figure 1 schematically shows the important factors affecting the reliability of travel time. Travel time and degree of uncertainty depend on traffic disruptions brought about by changes in traffic demand and supply. It are network robustness, which we will discuss in the next section, and the behaviour of drivers and network operators that determine how serious the consequences will be of these changes in traffic demand and supply. Assuming, for example, a blockage caused by an incident, the use of alternative routes depends on timely information issued by network operators and the willingness of drivers to deviate from their chosen routes.

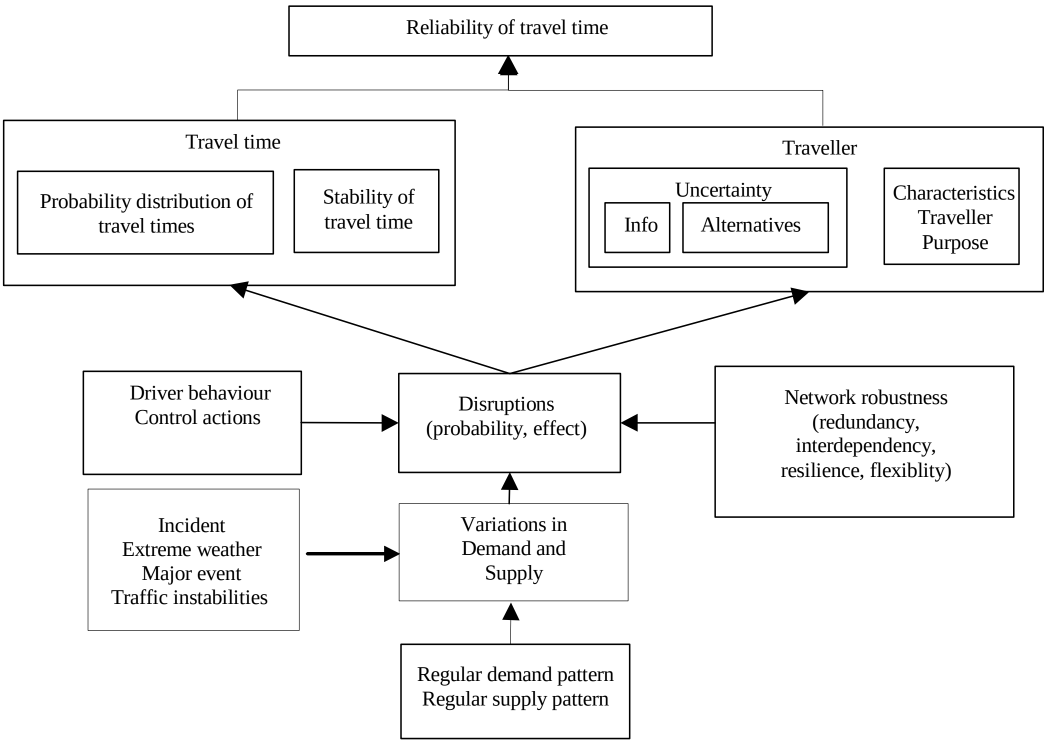


Figure 1 Factors influencing the reliability of travel time

The variations in the demand and supply pattern may be grouped along several dimensions. An important subdivision is the distinction between expected and unexpected situations. These, in their turn, may be subdivided in frequently occurring circumstances and exceptional events. Table 1 shows examples of the different possibilities. As the examples in the table show overloading is sometimes caused by variations in demand (rush hour traffic, public events) but more often it involves a change in the supply of road capacity (normal and extreme weather conditions, incidents ranging from minor accidents to catastrophic events, road works ranging from the routine to major overhauls).

Table 1 Causes of variation in demand and supply.

	Everyday occurrences	Exceptional conditions
Expected situations	Rush hour Bad weather Minor road works	Public events Major road works
Unexpected situations	Minor accidents	Calamities Extreme weather conditions

NETWORK ROBUSTNESS

Robustness is defined as the degree to which a system is capable of functioning according to its design specifications in the case of serious disruptions. Taking a number of corrective measures may enhance the robustness of the transportation system. These measures include the introduction of a certain *redundancy* or spare capacity into the system and *minimising* the *interdependency* of system components to prevent a local disturbance from propagating through the entire system. In our opinion the related notions of *resilience* and *flexibility* also have a bearing on the robustness of a system.

Redundancy

The robustness of a system may be improved by introducing a certain amount of redundancy or spare capacity into the system. Redundancy means the existence of more than one means to accomplish a given function. There are two types of redundancy: active and passive redundancy. In the case of active redundancy both main system and spare system operate together in normal conditions but each system is capable of handling the complete task on its own in case of failure of the other. Passive redundancy means that the backup system is activated only upon failure of the main system.

On the road network insufficient spare capacity may lead to degradation in the quality of service. This could potentially have grave consequences in situations necessitating a rapid evacuation of the population. On a smaller scale even relatively minor incidents may cause sizeable congestion on the road network that not only causes delays but also may interfere with the emergency services reaching the incident location. Incidental situations such as major road works, extreme weather conditions and large-scale public events also require some redundancy in road capacity.

Minimising interdependency

The location of a link or a node is important in the sense that in certain cases congestion and associated unreliability are confined to the concerned link or a small part of the network. In other cases congestion at a centrally located link or node may cause a series of cascading failures disrupting traffic on large parts of the network. These cascading failures are enhanced by the presence of all types of interdependencies between system components (Alderson, 2002). Possible options to minimise interdependency in infrastructure networks are:

- Maintaining a hierarchy of essentially independent, but well-connected functional road subsystems.
- Reducing the vulnerability of main network nodes for example by limiting the number of branches at an intersection and optimising the distance between nodes.

Resilience and flexibility

Organic, biological systems are characterised by a high degree of robustness, which they achieve mainly by possessing substantial redundancy and sometimes by a spreading of functionality throughout the organism. Also, organic systems turn out to be resistant against adverse environmental conditions because they are capable of rapidly recovering from temporary strain and because they are able to gradually adjust to changing conditions in the long term. It is interesting to apply these notions to the transportation system.

Resilience is the capability of the transport system to repeatedly recover, preferably within a short time period, from a temporary overload. The resilience of the transportation system is enhanced by the availability of fast professional emergency services.
Flexibility is the property enabling a system to evolve with new requirements. As an example we could mention the flexible layout of network components enabling the network to adjust capacity according to demand or the ability of using the existing motorway network for road trains or double-stack containers.

NETWORK STRUCTURE AND TRAVEL TIME RELIABILITY

By means of simulation we examined what type of road network structure is most capable of adjusting in a flexible way to fluctuations in demand and supply. We briefly present the main conclusions of that research.

In principle one can distinguish two broad types of network structure:

- A backbone network with a number of subsidiary road networks
- A hierarchy of essentially independent functional road subsystems.

In a backbone network each subsidiary network functions as a feeder system to the next higher system. This type of network structure provides for some robustness because of the generic nature of the backbone network, but it also results in certain vulnerability because a single blockage of an important node or link may disrupt the entire functioning of the system.

In the second type of network each subsystem can act as a backup system to the next higher level, in the case of an emergency. This type of network is aimed at a separation of functions. A malfunction of one of the subsystems causes no disturbances in any of the other subsystems. For example, regional traffic cannot cause congestion on long-distance national roads. Additional advantages, besides robustness, of a hierarchical structure are that not each system has to be constructed to the highest design standards and that the infrastructure is geared to the user's requirements.

In order to be able to assess the impacts of the network structure on travel time variability we designed the following setting:

Variations in the structure of the network are represented by three alternative networks (see Figure 2)

- Reference network (A): The reference network is loosely inspired by the road network east of Brussels, covering an area stretching to about 20 kilometres from the capital. It is characterised by a main motorway heading to Brussels and connecting to the beltway around the city, indicated by node 2 in Figure 2. A system of subsidiary roads, mainly feeding onto the motorway, provides for access to and from the region.

- Motorway-plus network (M+): By concentrating more flow capacity on the motorways, as compared to the reference network, we obtain the M+ network. In this network the backbone function of the motorway is emphasised. The predominant function of the underlying network is to provide access to the motorway.

- Regional-plus network (R+): This network tends to the hierarchy of independent road subsystems as described above. Flow capacity in this network is more evenly distributed among motorways and regional roads. In this way many regional, short-distance, trips can be accommodated by the regional network, thus relieving the motorway links.

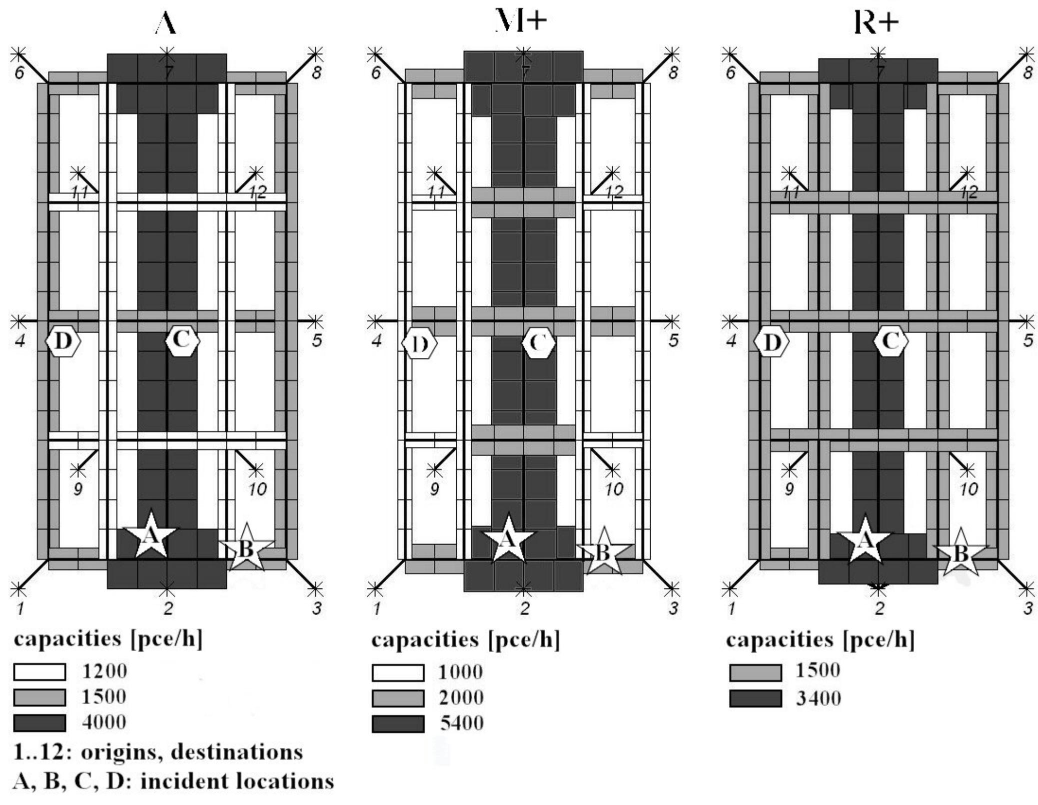


Figure 2 Alternative road networks considered in simulation

The flows in the network are predominantly ‘vertical’, either directed downwards towards the beltway in the morning, or upwards away from the beltway in the evening. The networks are comparable in that total vertical capacity across a horizontal screenline is the same for all three network layouts. In addition total network capacity (calculated as capacity times length summed over all links) and thus costs are roughly the same for each of the three networks.

We applied two different origin-destination matrices to this network. In the first load pattern, which we will call the morning commute MC, all flow is directed from eleven origin nodes to the only destination node 2 in Figure 2, representing access to the beltway (commuter traffic, strong orientation towards zone 2). In the second load pattern the traffic flow is in the reverse direction, representing the evening commute EC. In this second OD pattern the origins are located at nodes 1, 2, 3, 9 and 10. Restricting the origin flow exclusively to node 2 would cause a bottleneck at that node and prevent most of the traffic from entering the network in the first place.

Variations in demand and supply are modelled in the following way:

- The traffic load will be increased in 8 consecutive steps starting with free flow conditions (base load) and ending with serious congestion in the network (8 times the base load). At a traffic load factor of about 4 times the base load the networks start to show some signs of overloading at certain locations. The OD-tables (in vehicles/hour) for the base load in step 1 are given in Table 2 and 3.

Table 2 OD table for the morning commute MC; base load in step 1

		From											
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
To	*2*	125	0	125	200	200	100	300	100	50	50	75	75

Table 3 OD table for the evening commute EC; base load in step 1

		To											
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
From	*1*	0	0	0	30	30	15	50	15	0	0	10	10
	2	0	0	0	100	100	50	150	50	50	50	45	45
	3	0	0	0	30	30	15	50	15	0	0	10	10
	9	0	0	0	20	20	10	25	10	0	0	5	5
	10	0	0	0	20	20	10	25	10	0	0	5	5

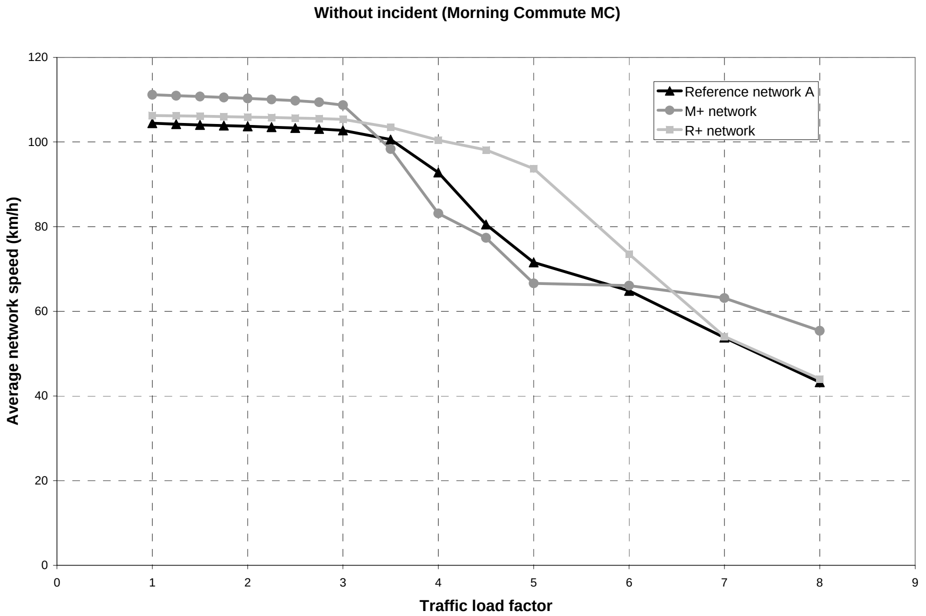
- Local variations in supply are modelled assuming an incident on one (heavily loaded) link being either a motorway link or a regional road link. The incident locations for the morning commute MC are indicated by the stars marked A and B in Figure 2, while the incident locations for the evening commute EC are indicated by the hexagons C and D in the same figure. We assume that an incident reduces link capacity on the motorway to 1000 vehicles/hour and on the regional road to 400 vehicles/hour.

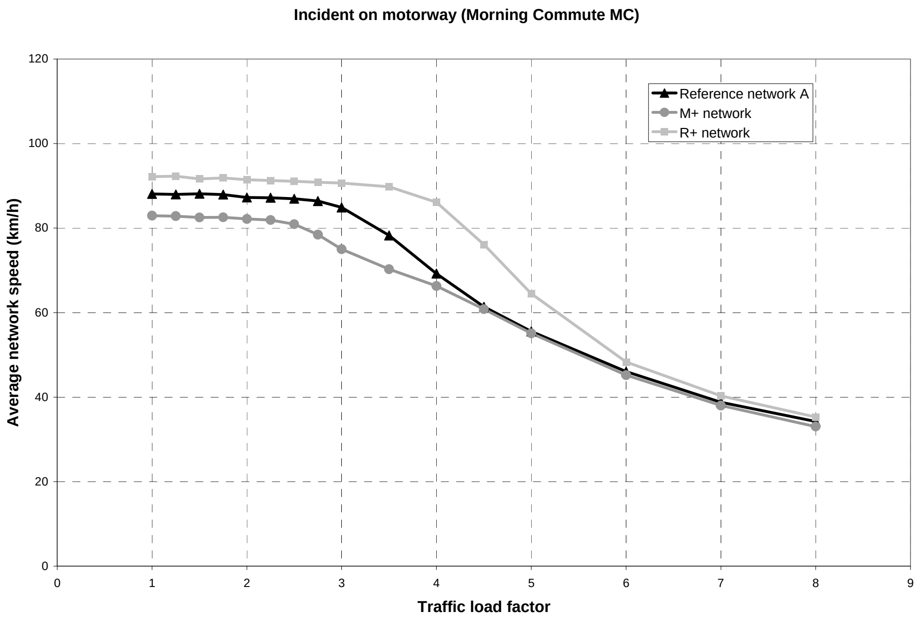
  Because of the incident some drivers will change their routes and others will not, depending on their familiarity with alternative routes and the traffic information they receive (Abdel-Aty, 1998). For lack of further information, in our preliminary investigations we decided on the following assumption. We assume that 50% of all travellers persevere in their once chosen route as if no incident had happened, for the other 50% of travellers we assume that they are susceptible to the changes in travel time due to the incident. They divert to other routes thus avoiding the incident.

Traffic was loaded on each of the three networks using a *dynamic traffic loading algorithm* (Omnitrans, 2005). As an indicator for the performance of the networks in terms of traffic time sensitivity we computed the average network speed, defined as the total distance covered by all travellers on the network divided by the total travel time spent by all travellers on the network. Figure 3 shows how the average network speed develops under changing load conditions under the morning commute (MC) load pattern. Figure 4 shows the same for the evening commute (EC) load pattern.

Although there is some difference between the morning commute load pattern (MC) and the evening commute load pattern (EC) the following general observations can be made:
- The M+ network performs slightly better than the other networks under normal conditions (normal flows, no incidents)
- High traffic loads provoke a serious deterioration of the network quality for the M+ network. The reference network A and in particular the R+ network are less sensitive to a serious increase in demand.

- Incidents on the motorway have a serious impact on network performance even when we are dealing with low-demand conditions. The impact of an incident on the regional network is limited as long as demand is low, but as soon as total demand increases the impact of an incident on the regional network becomes significant.
- The M+ network is more sensitive to incidents and changes in demand than the reference network and the R+ network. The performance of the R+ network is the best under all prevailing conditions





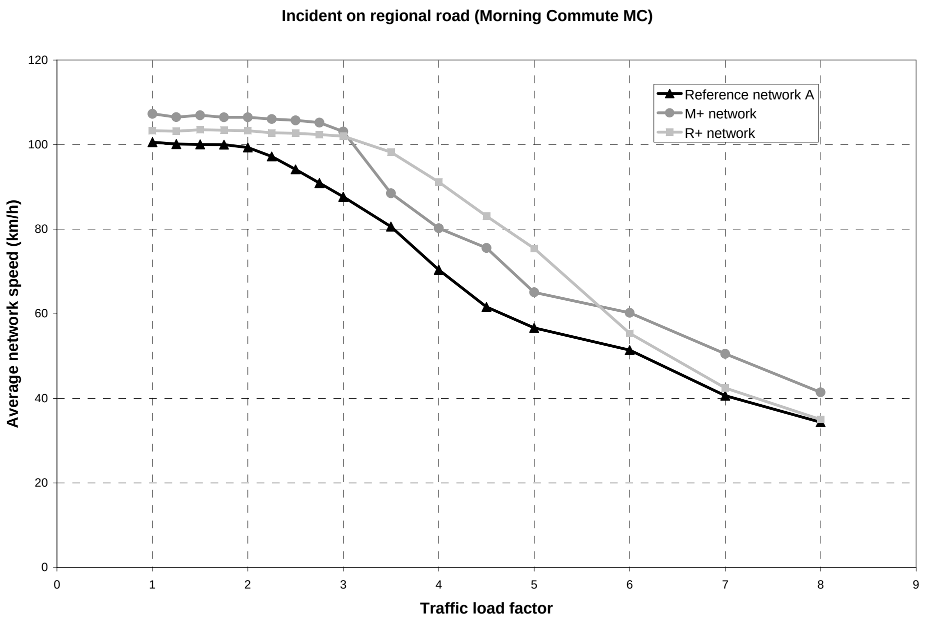
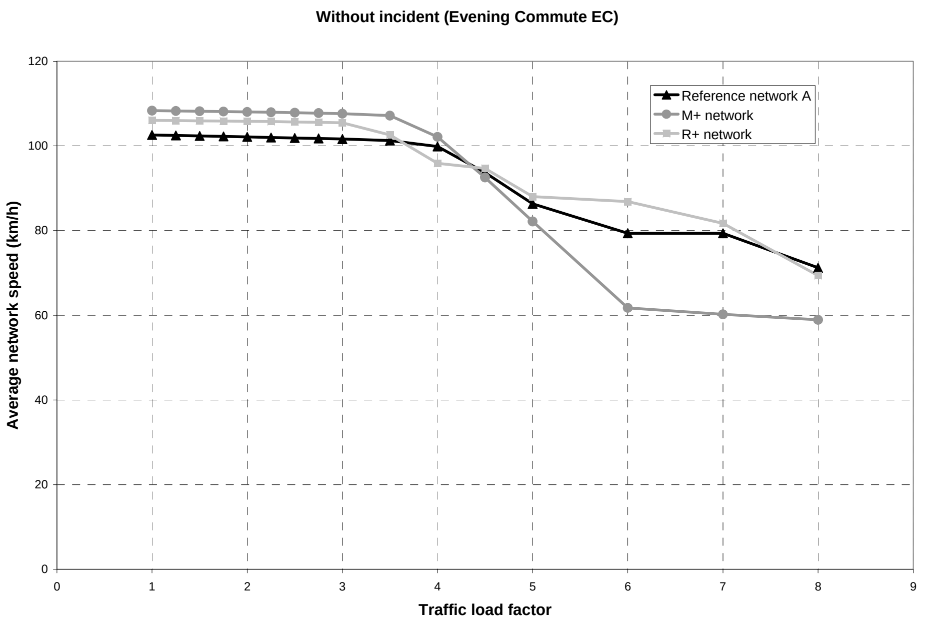
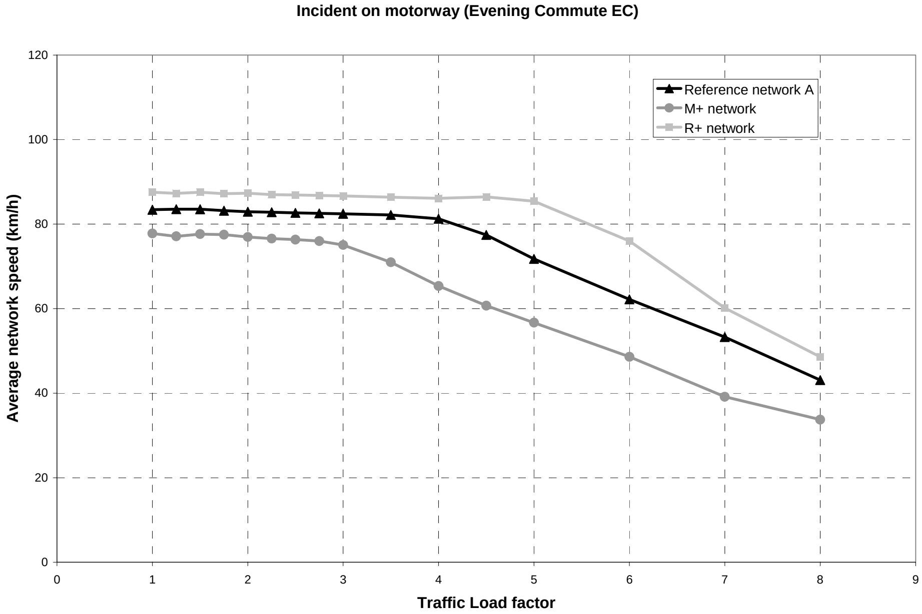


Figure 3 Performance curves for the Morning Commute (MC) load pattern





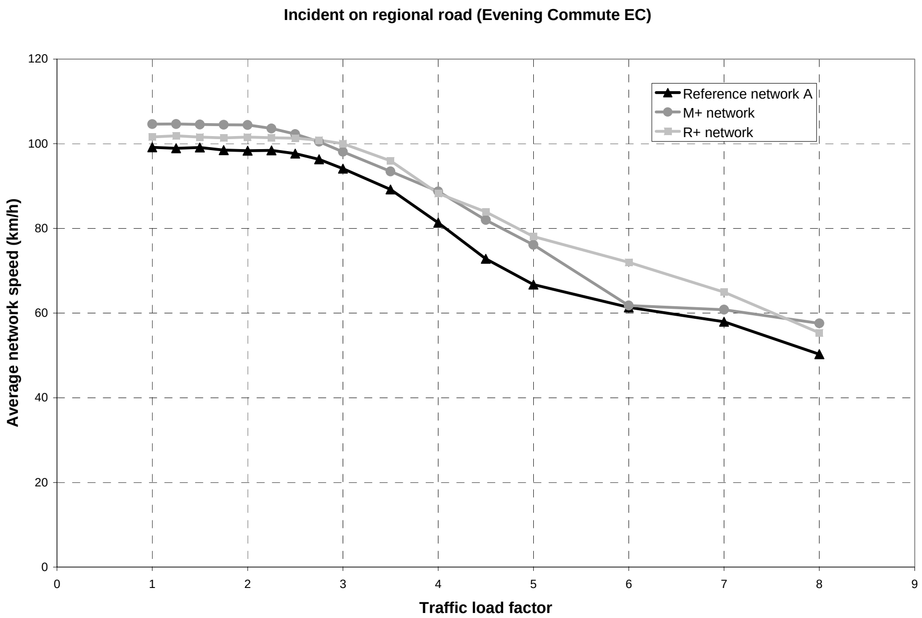
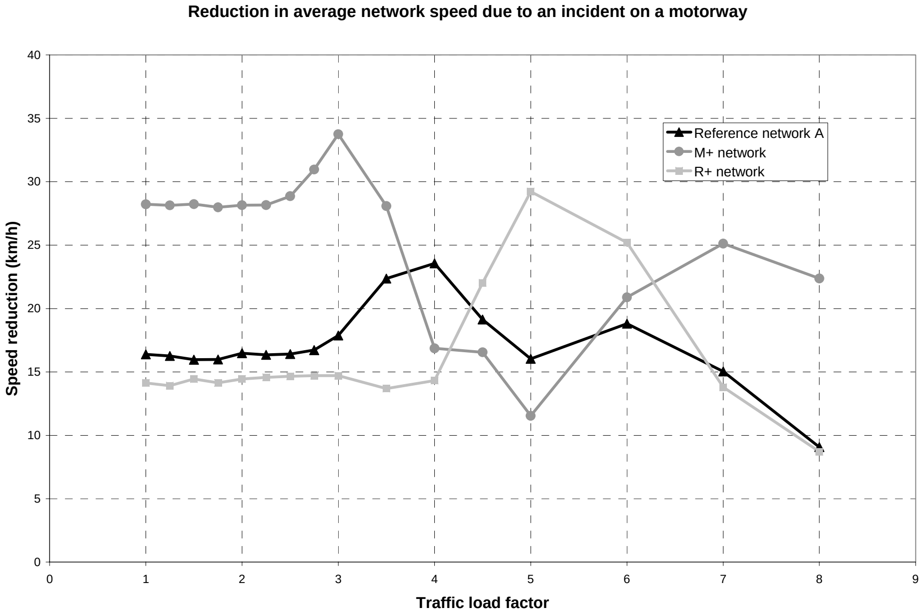


Figure 4 Performance curves for the Evening Commute (EC) load pattern

Because of the similarity of the flow patterns for both the morning commute and evening commute load pattern we continued our analysis for only one of the load patterns: viz. the morning commute (MC) pattern.

Figure 5 shows the reduction in average network speed due to an incident on the motorway (upper panel) and on a regional road (lower panel). When there is an incident on the motorway, there is a serious decline in network speed on the M+ network, even under moderate traffic load conditions. In contrast, an incident on the motorway has less serious repercussions for the reference network and in particular for the R+ network. The reductions in network speed are smaller and occur at higher loads in the latter networks

When dealing with an incident on a regional road, again the R+ network performs better under moderate traffic load conditions. At higher traffic loads the reductions in speed increase in the R+ network, which is predominantly caused by the superior performance of the R+ network under incident free conditions. Notice that the changes in average network speed are significantly smaller if an incident happens on a regional road.



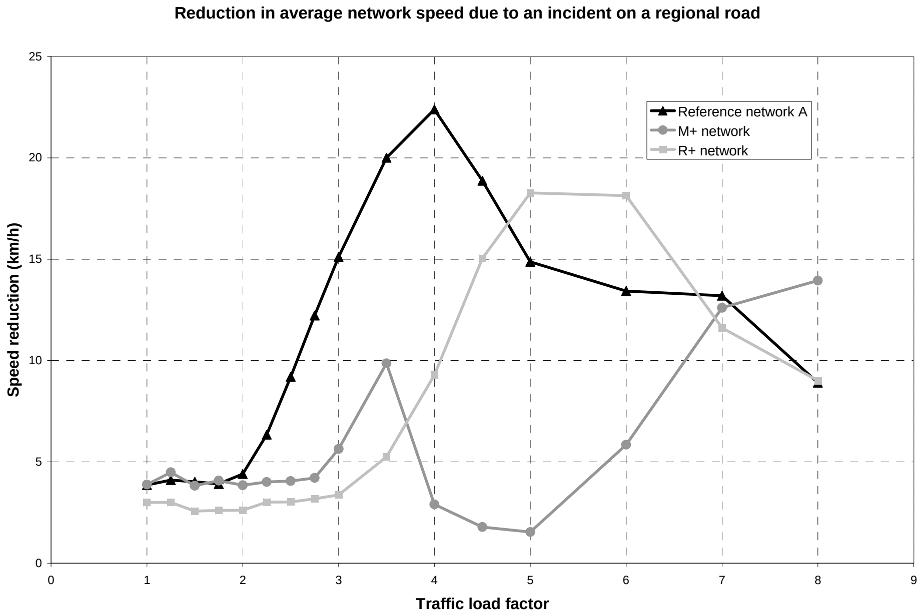


Figure 5 Reduction in average network speeds due to an incident

Summarising we conclude that the performance of the R+ network is superior under various conditions. Especially the stability of network performance at increasing network loads is an interesting characteristic. This characteristic is often referred to as the property of *'graceful degradation'*. It makes the R+ network structure the most appropriate when dealing with heavily loaded network conditions.

The sensitivity of network structure to increases in network load is clearly demonstrated in Figure 6, which shows the gradients to the average network speed curves, given earlier in Figure 3. The M+ network shows the highest gradient and this occurs already under moderate traffic load conditions. The R+ network is quite insensitive to increases in demand (up to load factor 3) and the gradient is quite moderate.

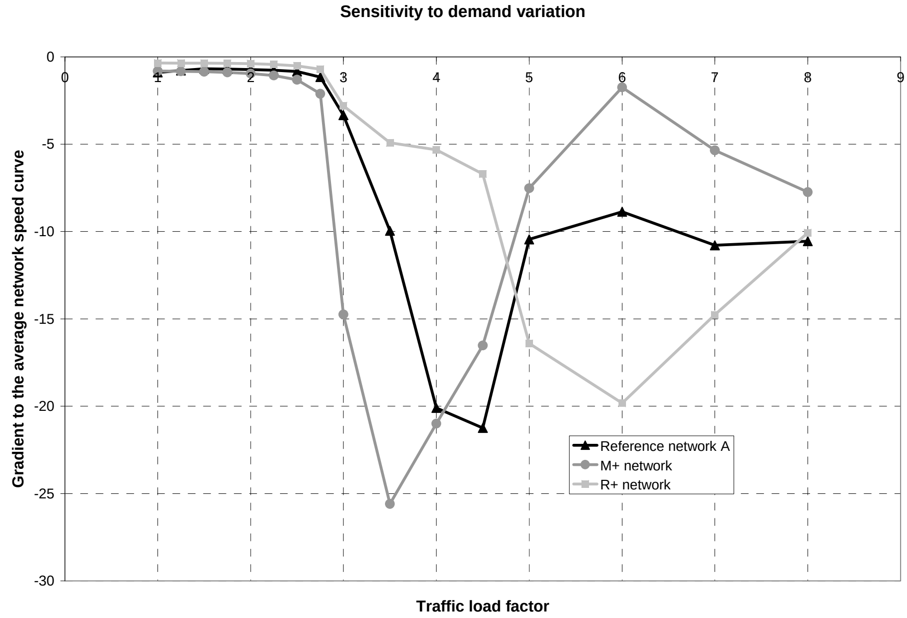


Figure 6   Sensitivity to demand variation of the various networks

Interpretation of the simulation results and policy implications

The above results indicate that, when dealing with growing demand, the R+ network has two interesting properties:

- it exhibits the characteristic of 'graceful degradation',
- it is less sensitive to incidents than other considered network structures.

We believe that the above characteristics are highly relevant for present-day traffic conditions. Three major issues can be mentioned:

- During the last decades investment in additional network capacity has not kept pace with growth in traffic demand. As a consequence relatively little capacity is available to cater for increasing traffic flows. This leads to heavily loaded networks during peak periods and, as people change their behaviour to avoid congestion, the length of these peak periods is still increasing.
- To mitigate the impact of increasing traffic loads on network performance, various dynamic traffic management measures are being implemented. These measures may have a positive impact on traffic flow conditions in that higher traffic volumes can be accommodated, without higher congestion levels. The opportunities to apply dynamic traffic management measures however strongly depend on network structure, such as the availability of alternative routes, etc.
- The higher traffic loads make the network more susceptible to small variations in demand or supply. In countries like the USA, Germany and the Netherlands 40 to 50 % of congestion is caused by incidents and other unexpected occurrences, with an accompanying serious impact on the reliability of travel times.

CONCLUSIONS

- Network robustness plays a vital role in providing travel time reliability to travellers. The robustness of networks depends on several factors: redundancy, network structure which influences interdependency of network components, resilience and flexibility

- A hierarchical network structure encompassing independent mutually connected road subsystems may considerably improve the robustness of a transport system if compared to a backbone network with a number of subsidiary networks.

Further work

The analysis presented in this paper has only been explorative in nature and is meant to open directions for further research.

- In order to be able to describe the traffic performance correctly we should be able to incorporate spill-back effects and (if possible) hysteresis effects (capacity drop). This means that we actually need a very sophisticated traffic assignment model that allows us to model traffic performance of the network very accurately.

- A robustness check of a network would imply quite a bit of variation in demand and supply, thus representing real world conditions. Therefore, in the next step of our analysis stochastic characteristics of demand and supply will be dealt with using Monte Carlo techniques.

- As indicated in the first part of the paper, various factors determine the robustness of a network for fluctuations in demand and supply. Further analysis therefore will focus on calculating the contribution (impact) of a series of network characteristics e.g.: network topology (grid structure, radial structure, etc.), hierarchy in the network, interconnectivity of various networks, node density, etc. Furthermore the robustness of the network will be described using a series of assessment criteria e.g. travel time distribution, median of travel time, average network speed, etc.

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