Approach to Critical Link Analysis of Robustness for Dynamical Road Networks

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Abstract. This paper presents an approach to determine which links of a dynamic network have the largest impact on network performance in case of link failure. Link failure could be due to any type of incident: a truck that is jackknifed, but also a flooding or any other type of natural disaster.

In earlier studies (Bell, Murray-Tuite),robustness for small scale networks have been studied, including blocked links using bi-level optimization. Contrary to those, we used a real size network and used a simulation based approach. This study adds the dynamics of the simulation and spillback effects of queues are added to the methods used up to now.

We argue that to correctly predict the impacts, it is essential to capture the most important dynamic properties of network traffic flows, such as queue spill back and the propagation of shock waves. As a result, a dynamic approach is proposed. Another innovative feature is that the approach is applicable to real-sized networks that consist of motorways, urban links, and rural roads.

The problem is formulated as a dynamic bi-level optimization problem: the road-users dynamically minimize their individual travel times (lower level), while on the upper level, the critical link that will result in the largest total delay in case of its failure is determined.

Regarding the lower level, two different information scenarios will be considered. In the first scenario, travelers take full advantage of all travel information available. In the second scenario, users are assumed not to have access to information and will hence not adjust their route choice to avoid the link where the incident has occurred.

We found that in the situation in which route choice is not changed, the most delay is encountered if two lanes of a motorway link are blocked. If the route choice is regularly updated, for instance bt providing information to the road users, though, the links that cause the most delay when blocked are urban links close to the destination and close to a motorway link. The traffic for that destination has no alternatives and will just join the queue. The tail of the queue will reach the motorway and the through traffic will face a traffic jam too.

1 Introduction

The reliability and the robustness of traffic networks are important performance indicators, both from the perspective of the traveler (travelers prefer reliable and robust networks, reference) and network operators [1] [2]. Methods to gain insight into impacts on network performance of large accidents, terrorist attacks, flooding, etc., are hence very valuable.

The main research question considered in this contribution is on which type of links the network performance relies. In other words, if there is a incident on a certain link, the service level of the network will reduce. Which are the type of links that reduce the number of arrived vehicles the most when blocked?

We used the number of arrived vehicles as performance measure. Rather than the average or total time spent in the network, where one should correct for the number of vehicles still queuing, this is a more absolute measure for a fixed-time simulation [3].

This is already done in static models for a simple network [4] [5]. There, risk-adverse route choice is studied in a fully analyzable static network of a few links. It analyzes a game between road users and failing links. If links fail too often, users will include the risk in their route choice. This has been further developed by introducing extra costs for a link with high densities [6] [7]; this is still a small test network. We applied these concepts on a real size network with time dependent demand and tried to find typical characteristics of vulnerable parts of a existing road network; general conclusions about reliable network types can be found in [8]. We simulated the flow of a time dependent demand on the whole network and thus taking network dynamics and spillback effects into account.

The symbols used in the article are listed in table 1.

Symbol	Meaning
b	blocked link
L	set of all links in the network
G	the network
G_b	the network with link b blocked
π	path
$\pi^*(G)$	equilibrium paths in network G.
$A(\pi, G)$	number of travelers arrived at their destination at the end of the simulation given route choice π and network G
$A(\pi^*(G), G_b)$	number of travelers arrived at their destination at the end of the simulation if link b is blocked and the route choice is based on a complete network
$A(\pi^*(G_b), G_b)$	number of travelers arrived at their destination at the end of the simulation if link b is blocked and the route choice is based on the actual traffic situation

Table 1. List of used symbols

2 Mathematical formulation of the problem

The problem can be formulated mathematically as a two-level optimization problem. There is a fixed demand of travelers for each origin-destination pair od. At one hand, the travelers aim to change to the route with the shortest travel time. The equilibrium state is such that traveler i had no possibility to change unilaterally change his route and reduce the travel time he perceives at the moment of choice [9]. This optimum is called a Wardrop optimum [10,**?**]. We will refer to this optimum using $\pi^*_{od}(G)$, where G is the network on which the route choice is based. The number of travelers that arrive on their destination within the fixed time frame, using path π given network G is referred to as $A(\pi, G)$.

An effect counteracting the optimization of the travelers is the (partial) closing of one of the links. The network disturbed by the closing (partial) closing of link b is called G_b.

A link is a unreliable element of the network if the number of arrived travelers is much reduced if there is an incident on that link. At this level, the aim is to *minimize* the number of arrived travelers A. So, the aim is to find the link b such that the least travelers arrive in the fixed time frame.

Of course, the optimal route choice is dependent on the network and therefore on the blocked link. Thus, we define a Wardrop optimum of the route choice in case of a network with link b blocked:

$$\pi^*_{od}(G_b) \tag{1}$$

This can be considered as a two-player game: one group of players is the collective of travelers, the destroyer of the network is the other player. In game theory, one speaks of leaders and followers meaning the one who moves first and the one responding on that move, respectively. Here also, we could speak of leaders and followers. Then, two cases can be considered: one in which the travelers lead and the destroyer follows and the other one in which the destroyer leads and the travelers follow.

2.1 Scenario 1: Travelers lead, destroyer follows

In the scenario that the travelers lead, the first move is to be made by the travelers. They find one route choice optimized for the case in which the network is intact. In this scenario, they will stick to the routes $\pi^*(G)$. This scenario describes the situation where neither information is given, nor an extraordinary traffic situation will make the travelers change their route.

Now, the performances of the destroyed network can be calculated. For each blocked link b, we could calculate

$$A(\pi^*(G), G_b). \tag{2}$$

The most critical link b^* can be found by minimizing the number of arrivals,3

$$b^* = \underset{b}{argmin} \left(A \left(\pi^* \left(G \right), G_b \right) \right). \tag{3}$$

2.2 Scenario 2: Destroyer leads, travelers follow

This scenario describes a situation where the people are fully informed about the traffic conditions and delays. They are not informed about the incident, though. That is to say, the vehicles calculate their travel time based on speeds. As long as there are no vehicles queuing yet, they will not foresee any problems in their route choice.

Mathematically, this is represented by letting the first move to the destroyer and letting the travelers respond to this first move. The final function to evaluate is

$$A(\pi^*(G_b), G_b). \tag{4}$$

As the travelers will change their actions, i.e. their routes, on the action of the destroyer, this game is a Stackelberg game. The most critical link b^* in this scenario can be found by optimizing equation 5

$$b = \underset{b}{argmin}\left(A\left(\pi^*\left(G_b\right), G_b\right)\right). \tag{5}$$

3 Model

The simulation model we used, had to be able to simulate spill back-effects well. A substantial part of the discovered delay is namely caused by the spill back effects of a traffic jam. Furthermore, we had to use a dynamic model with different time periods to simulate the morning peak with an acceptable accuracy.

Therefore, we used the macro traffic simulation model DSMART, developed at the TU Delft. It differentiates vehicles with different destinations. The model does not distinguish between user classes, vehicle types nor between road lanes. A traffic jam for vehicles wanting to make a turn will also block the main stream of the traffic. This corresponds to a driving style where drivers wanting to take the exit do not keep the outer lane in a traffic jam.

The stochastic route choice model is done by a probit model. For each link, the travel time is calculated based on the link speeds. At the base travel time is calculated by dividing the length by the speed, an error is added. The expected travel time on which the route choice is based, is randomly drawn from a normal distribution of travel times with the base travel time as mean and with a standard deviation of 10%.

For the case without route choice, the calculation is based on 20 samples from this route choice. Each period, 20 fastest routes from each node to each destination will be determined from this stochastic process. Those routes are considered representative for all travelers. For half of the travelers, the new route choice is based upon these routes; the other half will stick to the routes of the previous period.

In the scenario of adapted route choice, the used model is comparable. Due to computational limitations – now, the route choice has to be recalculated for every simulation – we reduced the number of samples for this scenario from 20 to 8.

The network consists of both motorways and urban links. The urban road network is not very detailed, but the main urban roads are modeled, as well as single origin/destination links representing a quarter/district, see also Fig. 2

4 Simulations

The network we simulated are the roads around Rotterdam, a Dutch city with 600.000 inhabitants (see Fig. 1). Fig. 2 shows the model of this network. As this figure shows, the motorway network is completely modeled. The underlying road network is just partly modeled.

Fig. 1. The map of the Rotterdam area

The simulated time is the morning peak, from 6.30 to 9.30 am. At the start of the simulation, the network is empty. The network consists of 468 transport links, 44 origin links and 44 destination links; the connections are provided by 239 nodes.

As all macroscopic models, DSMART supposes the speed of vehicles constant during a time step. The chosen time step is 15 seconds; for longer times, one cannot assume the vehicle speeds to be constant. Furthermore, serious problems arise if vehicles can travel more then a link length within one time step[references]. On the other hand, further reducing the time step to values of 10, 5 or even 1 second would increase the total calculation time. The simulation time for a scenario with a fixed route choice (in mathematical terms,

Fig. 2. The model of the network

calculate $A(\pi^*(G), G_b)$ or $A(\pi^*(G), G_b)$ with $\pi^*(G)$ precalculated) is a around five minutes on a Pentium 4, 2.8 GHz with 512 MB RAM.

Of course, if the route choice has to be optimized too, calculate $A(\pi^*(G_b), G_b)$ or $A(\pi^*(G_b), G_b)$ takes longer. One of these calculations route choice optimization will take around twenty minutes of calculation time.

These simulation times may seem fair, but remember that calculation of both $A(\pi^*(G), G_b)$ and $A(\pi^*(G_b), G_b)$ are needed for all $b \epsilon L$, so 468 times. All together, it is over a week of calculation time.

5 Results

The types of links that cause the most delay when blocked are different for the both cases studied. In Fig. 3 the number of arrivals for both cases are shown. An asterisk in the figure is the network performance in the case of a blocked link – each asterisk is a different position of the blockage. For each position of the blockage, there are two scenarios possible. In one, the travelers stick to their fixed route and in the other one, they will adjust their route choice. The results, the number of travelers that reached their destination, of both scenarios are plotted on the axes.

The points are located under the diagonal (dashed black line) of the graph. That means that in almost all cases, i.e. for almost all of the blocked links, the number of arrivals is higher if people are allowed to take an other route. Some statistics about these results are that in the case of no rerouting, in average 1.6 x 10^6 travelers arrive, with a standard deviation of 5 x 10^5 travelers, which

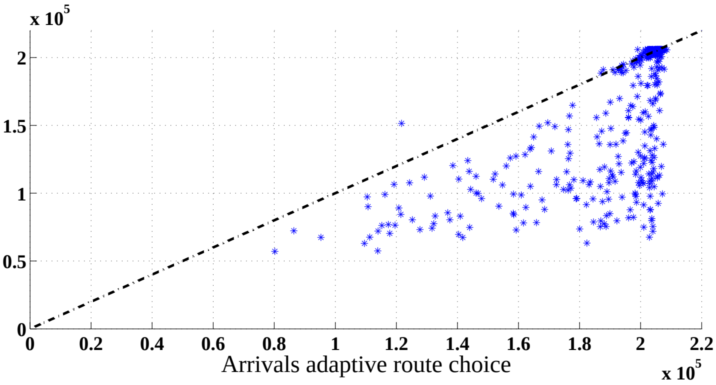

Fig. 3. Comparison of arrivals

equals 30%. In the case of flexible routes, these numbers are 1.9 x 10^6, 3 x 10^5 and 16% respectively.

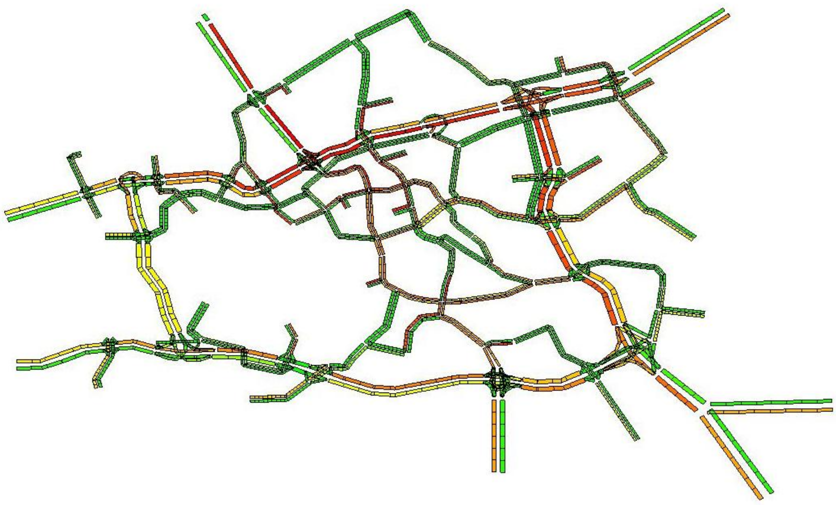

Fig. 4. Loss of arrivals at destination if link is blocked – case without rerouting

In Fig. 4 and Fig. 5 it is indicated how valuable links are. The color is a measure of the travelers not arriving if that particular link is blocked. If a blockage of a certain link is of no influence on the number of arrived travelers, the link is green. If a link is red, it means that the least people arrive if that link is blocked. The scale for the color is the same in both figures. Comparing both figures, one can remark that Fig. 4 is much redder than Fig. 5, meaning that more people arrive. In Fig. 6 the difference of these two is plotted. In case the adaptivity of the route choice does improve the performance of a network (disturbed by the blocking of link b) much, the link (b) is colored green. The

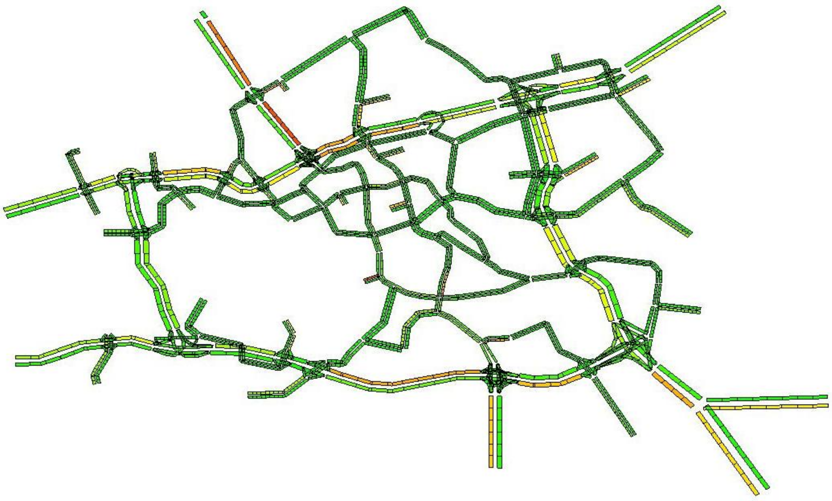

Fig. 5. Loss of arrivals if link is blocked – case with rerouting

redder link b is, the less advantageous the rerouting was for the performance of the network in case of a blockage of link b.

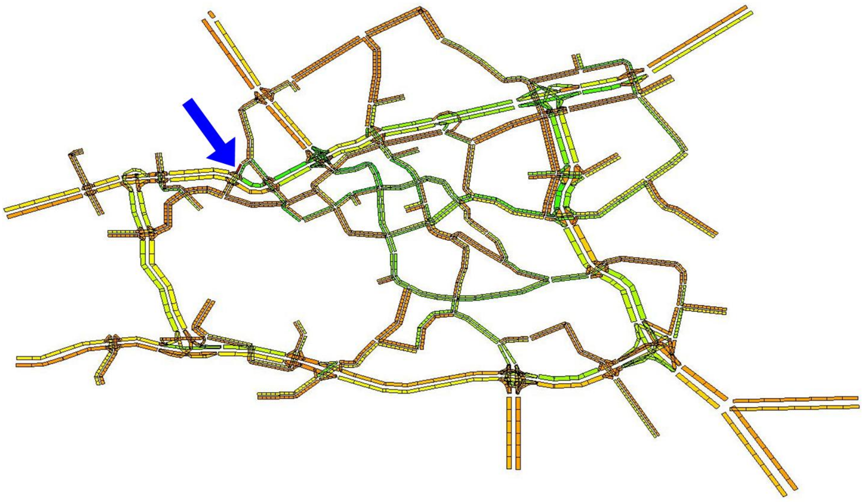

Fig. 6. Difference in arrivals between adaptive route choice and fixed routes

Then, three categories of links can be identified. Firstly, the links that do not harm the flow in either case. These can be found in the upper left corner of the graph. In both scenarios, fixed routes and rerouting, the number of arrivals are high. These are unused links.

The second category that can be found are the links that reduce the number of arrived travelers is both cases, both with rerouting and without rerouting. These are represented by asterisks in the lower left corner When analyzing these points, these links turn out to be motorway links, mostly close to a destination area.

The third area is the most interesting, this is the lower right corner of the graph. At the links represented by the asterisks there, rerouting can improve the network performance a lot. The number of arrived travelers is namely low in the case with fixed route choice and high with a flexible route choice. These links are non-motorway links close to a destination and close to a motorway too.

This can be explained by the fact that there are many alternatives in an urban road network. But, as people take their usual routes, they got stuck. Spillback effects then cause the flow on the motorway to be blocked too.

These spillback effect cause the motorway to be completely blocked. Therefore, the delay for the though traffic could be bigger than in the case of motorway link itself being blocked.

Fig. 6 shows also which link is the one that is above the diagonal in Fig. 3. In one case the network will perform significantly better if the routes are *not* adapted. The link for which that is the case, is indicated with a blue arrow in Fig. 6. This might be a consequence of the location of this link and the busy interchange downstream for the alternative route. If the routes are adapted, the traffic will flow by an alternative route. The best alternative will lead the traffic to an already congested interchange. There, this extra flow can harm the flow of through traffic. Here, the difference between system optimum and user optimum might play a role. It could be better for all if some will not perform their best.

6 Conclusions

We conclude that the motorway links are vulnerable for the performance of a road network, even if the route choice can be adjusted to the faced traffic situation. Furthermore, we conclude that severe congestion can be avoided if travelers are rerouted if there is a blockage of a urban link close close to their destination.

Spillback effects turn out to have a big impact on the occurred congestion. Some urban roads are critical links because of congestion spillback effects to the motorway.

The links for which congestion can be avoided by rerouting are links for which there are parallel alternatives. We therefore conclude that in a network with lots of parallel routes could be regarded as robust with regards to incidents.

The calculations are done in a single lane macroscopic simulation. In regions with good discipline, drivers might queue for an exit at the outer lane, so letting through traffic the possibility to pass. Therefore, a multi lane simulation model with an appropriate modeling of lane change behavior at ramps [12] is required.

For each level of detail, though, calculation time will increase. A way to reduce the total time of computation is to find vulnerable links in an other way than calculating the network performance with all links sequentially blocked. A possible way to search for these links is with an genetic algorithm. This will be a direction for future work.

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