# DEVELOPMENT OF MEASURES FOR THE INSTANTANEOUS OPERATING CONDITIONS OF A NETWORK

**C. Makoriwa[a], F. Brandt[b], E. van Berkum[a]**
[a]Dept. of Civil Eng., Twente Univ., PO Box 217, 7500 AE, Enschede, The Netherlands
[b]Goudappel Coffeng, Snipperlingsdijk 4, 7417 BJ, Deventer, The Netherlands
c.makoriwa@ctw.utwente.nl, e.c.vanBerkum@ctw.utwente.nl, fbrandt@goudappel.nl

**Abstract**

The project developed a suite of measures to determine the instantaneous operating condition of a network. These measures are intended to be used by network managers to facilitate decision-making. The measures developed take cognizance of the network topology, instantaneous travel demand and ability of some users to reroute trips. A key constraint imposed on the project is that no measure developed should require any additional equipment for data collection beyond what currently exists on roadways – namely loop detectors. It was realized that to effectively describe the situation on a road network requires more than a single measure. A series of four measures were then developed. This paper presents one of these measures. Link breakdown is defined as a stochastic event whose outcome is related to the volume of traffic on a link. Further, the current travel demand is used to determine the short term probability of failure of the network based. These probabilities are then used to assemble an ensemble of the probable network states in the immediate near future. For each element in the ensemble, the probability of failure of each link is then obtained using a macro-simulation progamme - MaDAM. The results are collated to determine the short term risk potential for every link on the network that takes cognizance of the flow on every link on the network and current demand. It is intended to implementation the measures on a large scale real world network be attempted to verify their suitability for scaling. Further, it is intended to determine the suitability of these measures for on-time strategic network management decisions.

Keywords: Network management; Network performance measurement
Topic Area: E2 Performance Measurement

## 1. Introduction

With the increasing demand on road transportation infrastructure, provision of an adequate level of service for the users of infrastructure is becoming increasingly difficult. This is aggravated by the increasing constraints under which road agencies have to operate. Until the mid 20th century, one could always increase the road network to meet increased demand, with little heed to issues such as land take, environmental degradation, pollution or noise. Today, increased awareness of the detrimental effects of these maladies makes it very difficult to increase the physical size of road networks without meeting tremendous resistance.

Road agencies have available only three options in their quest to maintain an acceptable level of service; namely

- increase the physical size of the road infrastructure, through construction of additional roadway or lanes
- increase the throughput of existing facilities without constructing additional infrastructure i.e. maximize the utilization of existing infrastructure

- implement policies that limit the demand for travel, especially non-crucial travel and particularly at peak hours

Since the first option is facing increased resistance, and the third option requires the intervention of political forces i.e. it is often beyond the powers of the road agencies to initiate measures that with limit travel demand, the second option is becoming increasingly attractive.

The rational being that the agencies have most freedom acting in this domain. Their actions do not involve additional construction efforts with the associated capital outlay requirements and also do not require legislative action to implement. Infact, one dares say that a significant part of Intelligent Transport Systems (ITS) initiatives lie in this domain, where agencies are adopting technologies that will improve the performance of the infrastructure with minimal changes to legislation or infrastructure size. We note that the use of performance in the previous sentence refers to several facets of network performance such as safety, throughput, security etc.

System information plays a crucial role in management. In the management of traffic flows on road networks, performance information is useful for;

- development of alternative strategies
- setting feasible performance targets and determining the performance envelop of the system
- evaluate effectiveness of traffic stratagem
- evaluate efficiency of interventions and stratagem applied
- learning or understanding the traffic behaviour and performance of the system under various operating conditions & external stimuli

It is important to realize that the information this research is concerned with is detailed information used for the development of dynamic traffic management strategies. The type of information that changes every second and is useful to monitor. This research however is not concerned with long term average measures that are useful for policy formulation or annual evaluations. Policy formulation requires long term aggregated measures such as person-km/year, total delay. Such information, though very useful is too coarse for use in dynamic traffic management.

Current dynamic network management systems simply indicate the prevailing traffic load level on individual links. No attempt is made to correlate the flow on various links to the travel demand patterns i.e. the spatial distribution of trip origins and destinations and hence decipher the available alternate capacity for flows on individual links. Restated as; if we have flow *(q)* on a link *(x)*, the current systems do not provide information on the general susceptibility of the network for the current level of travel demand in case the flow on link *(x)* is disrupted nor vice-versa (effect on *(x)*, when flow on other links are disrupted). This paper presents the development of a technique that correlates the performance of links on a network with all other relevant links depending on the current traffic demand.

## 2. Probabilistic link failure

For a given link *(x)* the Highway Capacity Manual (HCM) defines failure as the event: flow *(q)* exceeds the capacity of the link i.e. ($q_x > C_x$). We however choose to adopt a stochastic approach to breakdown and hence the primary difference with the HCM, is that we define the breakdown as a stochastic event which can occur at any flow rate. This is not a new concept and is in line with the recent work of researchers like Lo and Tung (Lo and Tung 2001, Evans et al 2001, Lorenz & Elifteriadou 2001) where the researchers do not use a prescribed deterministic value for breakdown. It is also superior to the current HCM method of defining capacity as a prescribed fixed value because, observations do not support failure occurring at a certain flow but over the entire spectrum of observed flows with a tendency to occur around some mean value. This mean value is expected to be in the neighbourhood of the capacity as described in the HCM.

Since, the flow at any instant can be determined including at breakdown, i.e. when $q_x \geq C_x$, we are forced to conclude that the stochastic element in the relationship must be the link capacity $C_x$.

## 2.1 A closer look at link breakdown

Following from the above, where we have defined link capacity as a random variable, we now want to compute the probability that we have breakdown i.e.:

$$P(\,flow \geq Capacity) \qquad \text{...........} \; (1)$$

or, restated using our notation as,

$$P(q_x \geq C_x) \qquad \text{...........} \; (2)$$

The probability stated above is effectively the cumulative distribution function of $C_x$, which we can write as,

$$F_{C_x}(q_x) = P\{C_x \leq q_x\} \qquad \text{...........} \; (3)$$

And if we know the PDF of $C_x$, we can compute $F_{C_x}$ as,

$$F_{C_x}(q_x) = \int_{-\infty}^{q_x} f(C_x)\,d(C_x) \qquad \text{...........} \; (4)$$

We now have the probability of failure (the flow exceeds capacity), as a function of flow. A deterministic approach to breakdown assumes that breakdown does not occur until the flow of traffic reaches a certain predetermined value – the *"capacity"* of the roadway. A stochastic approach allows for failure to occur for any volume of traffic. However, as the volume increase, so does the probability of failure. This formulation is closer allied to observations. From observations, the probability of breakdown increases with flow, however, it is still possible to have breakdown at very low flows e.g. accident induced breakdown, collisions, spills, adverse weather etc. Further investigation of the HCM and the definitions and descriptions associated with breakdown such as level of service allow easy reconciliation between these two apparently divergent views on breakdown. At high flow rates, e.g. those associated with level of service D, E etc, the behaviour of traffic is such that flow stability is very low and hence the chances of failure are very high. Hence adoption of a stochastic definition to breakdown is not expected to entirely disrupt the integrity of the HCM.

An advantage of using a stochastic approach to failure is that it allows one to gracefully handle the observed differences in the mean value of breakdown even when exogenous factors such as weather, driver skills etc. are the cause. A simple shift in the distribution function allows handling of such factors.

## 2.2 Brief comment on earlier work

In an earlier work by the authors [Makoriwa et al 2003] a step function was used that enabled reconciliation between the stochastic approach to breakdown and the observed data. In that work, a normal function was used to describe the distribution of ($C_x$). However, since the data used in that work was historic data, it was necessary to ensure that when failure had occurred, the method did show that failure had occurred, hence a step function that included a stochastic approach was used to evaluate the risk of failure in combination with speed to actually determine when failure had occurred was developed. This was formulated as:

$$P(breakdown)_x = \begin{cases} F_{C_x}(q_x) = \int_{-\infty}^{q_x} f(C_x)\,d(C_x), & u > u_{breakdown} \\ 1, & u \leq u_{breakdown} \end{cases} \qquad \text{..........} \; (5)$$

### 2.3 Development of link failure

We assign a simple triangular distribution function to define link capacity.

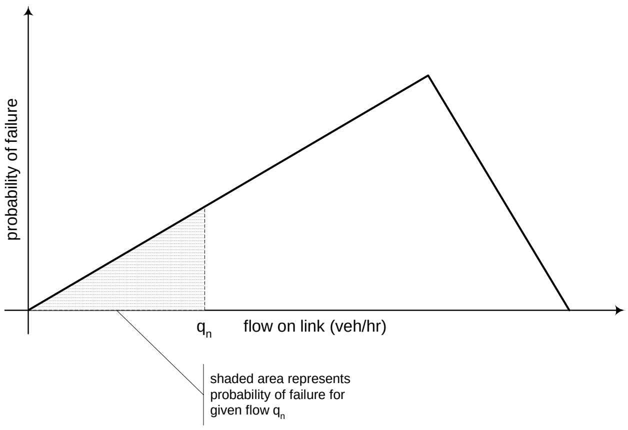



Figure 1: Distribution used for link failure

This is selected for computational ease and demonstration purposes only. One would have to select an appropriate distribution. The technique developed would however remain the same.

### 2.4 From link to network

A link often forms part of a lager collection of links which together form a network. A traffic network manager generally attempts to minimize the possibility of breakdown on individual roadway sections. This is done by taking measures that reduce the possibility of failure e.g. reduction of speed in certain circumstances or influences that disrupt the integrity of the flow etc. Further, a network manager has to anticipate not only breakdown on roadway sections, but also the effects of this breakdown at a network level i.e. the side-effects of breakdown occurring on a link, at a network level. The following are key elements one has to monitor and evaluate to effectively manage a traffic network in the short run:

- current travel demand
- network topography and link features
- response of the users to changes on the network

The travel demand i.e. the location of the orgins and destinations in addition to the number of trips is required to determine the loading in space and time on the various links on the network.

The network topography and the link features are required to determine how the users will assign themselves to the network. The link features contribute to the cost of travel on the link. This is useful for both the initial assignment and to compute rerouting options. There are of course other elements that contribute such as user's knowledge of the network and the income of the users, but we choose to ignore those at this point.

Knowledge of the response of the users to the changes on the network is fundamental to management because the entire network can be viewed as a system which the manager is trying to control. Hence, before control measures are applied, we must be at least know the changes to expect and the approximate magnitude of these changes i.e. the system response.

The challenge is to provide the network manager not just with a picture of the current situation on the network and a picture of the immediate expected future but the probability of future breakdowns and the consequences of these breakdown events on the operation of the network. The current situation is easily measured using loop detectors, cameras etc. The future situation on the network may be predicted from historical assignment data or by simulation using data from current traffic.

Further, it is acknowledged that for network management, simple assignment data traffic onto a network fails to capture the current complex interaction between various vehicle streams. This interaction between vehicle streams is a fundamental element of dynamic network management because it often leads to breakdown.

Simulations are best at capturing this complex interaction between individual road users as well as between streams of road users. For this reason a simulation model is used in this work to accurately predict the behaviour of the users.

At this point, having decided that a traffic simulator is the ideal tool to use, we are confronted with the choice between a microscopic simulator and a macroscopic simulator. General fundamental differences in the two are that microscopic models describe stochastic behaviour while macroscopic models describe deterministic behaviour (Gut 1991). A macroscopic model is selected and applied for the following reasons:

- speed of execution. Macroscopic models are generally faster than microscopic models, and speed is of essence in dynamic traffic management.
- suitability. This work deals with entire links and junctions and the effects of increased demand. Hence for network management, the level of resolution provided by macroscopic models suffices for the task. Though a higher resolution model would yield additional information, it would not aid network management at higher level.
- relevance. The stochastic nature of breakdown is not easily captured by a microscopic model, in spite of microscopic models being better at simulating the stochastic nature of traffic. Further, for this work the notion of probability on a link being a function of flow already estimates the detrimental elements of the random behaviour of road users within a link.

### 2.4.1 Current network management systems

On most traffic monitoring systems with a graphical output, the road network is represented by a series of lines/curves to indicate the alignment of the roadway. The current traffic flow situation on the roadway is coded either using a colour scheme or by varying the width of the lines/curves that represent the roads. Sometimes a combination of both is used as shown in the figure below. This form of representation is very powerful for conveying the current status of the network to the operators. This is the most commonly used format for presenting information to the traffic managers.

However, the weakness of such systems is that the traffic operators or managers are not presented with the broad consequences of failure on a single link at a network level. In reality, network traffic managers do have significant experience working on a particular network and are thus able to tell from past experience what the effects of failure in a certain link will do to the entire network, given a certain travel demand. Since, most (often all), their actions are based on their knowledge of the specific network they are managing, they are often unable to forecast the effects of an event (or series of events), they have never encountered. Further, as with any system managed using heuristics, one is never sure how close to the optimum the system is operating. Often the operators are simply satisficing, i.e. operating the system at a predetermined level deemed satisfactory, but certainly not optimizing. This is because optimization requires knowledge of the entire possible solution space to identify the optimum before one can even begin to try to move the network towards the optimum. Further, since management of a network requires rapid response to the changes in the operating condition of the network the operators often do not have sufficient time to determine the consequences of situations they have never encountered nor to time to compare the effects of their actions against possible alternatives actions.

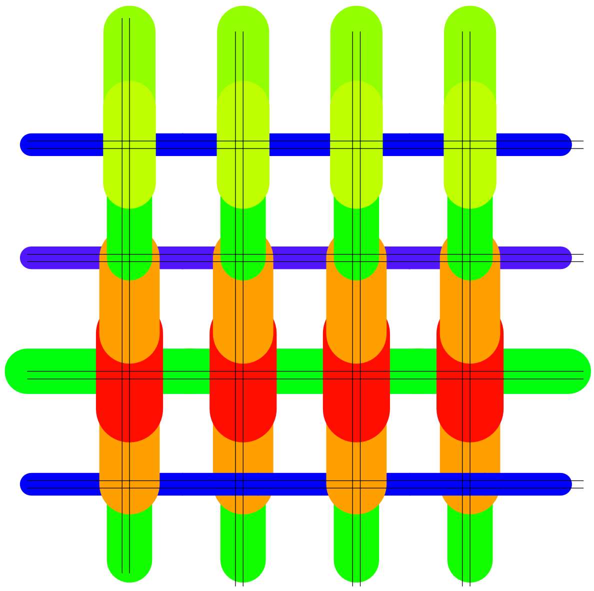


Figure 2: typical image of current network monitoring applications

When a traffic operator looks at the maps of the current network condition as shown in Figure 2 above, they have to deduce from the figures the following information:

- the risk level associated with failure on every link This they deduce from the volume of traffic on links that have not yet failed.
- the possible effects on the network in the event that the most probable failures occur. This they deduce from the current demand, network topography, and user reaction in situations similar to the current situation.

A requisite to accurately and rapidly execute the above two mentioned steps is an excellent intrinsic knowledge of the network as well as the expected responses of the network users. It is the reason why an experienced traffic operator is not guaranteed to function well when moved to a new location at the first instant. And, until he/she acquires a lot of local experience, they never perform as well as before.

The objective of this work is to develop a procedure that will evaluate the short-term risk potential that the current situation on each link poses to the integrity of network for the projected short-term flow and present this to the traffic operators, thus eliminating the mental computation currently required of the operators and reducing dependence on heuristics.

### 2.5 Procedure

In this section, the procedure developed to compute the probability of breakdown occurring on a link and the possible effects of breakdown is explained. The system works by first computing the probability of failure on each link based on the current traffic situation. This allows one to generate an ensemble of possible network configurations at some infinitely short time in the future i.e. with links either failed or not failed at time $t_0 + \delta t$, $(\delta t \to 0)$. Since the performance of any network in the immediate future is a function of the performance in the recent past, one can use these possible network configurations to determine possible operating conditions of the network in the short-run $t_1$, where $t_1 = t_0 + \Delta t$ and $\Delta t \ll \delta t$. Using the predetermined possibilities for each configuration one can collate all possible operating conditions at $t_1$ into a single diagram that depicts the probability of failure on each link at $t_1$. Further, for each link, the computed probability of failure will be a combination of the probability of failure due to traffic at $t_0$ on the link itself and the probability of failure due to diverted traffic as a result of failure on other links on the network. We explain the process in detail below.

1. At an instant ($t_0$), the probability of failure $P(N_{t_0})$ of each individual link ($n$) is computed from the current flow ($q_{n_{t_1}}$) on the link at this instant used an appropriate distribution function (e.g. distribution in figure 1).
2. these results may be used to generate a schematic map similar to that shown in figure 2, replacing the speeds with probability of failure. This would indicate the instantaneous probability of failure for each link though it would fundamentally not differ much from the speed maps currently used.
3. one then generates a matrix which consists of an ensemble of all possible unique network states ($S$) with different link conditions with respect to breakdown for all links on the network. Typically this would be a space containing all possible outcomes i.e. all possible combinations of the conditions of the links. For the Nguyen network [Lo and Tung 2001] a portion of one such a matrix is illustrated below. *Note that we adopt the convention that 1=failure has occurred and 0=failure has not occurred.*

Table 1: possible network states for Nguyen network

| **Situation No. /Link No.** | **Status of link at time ($t_0$)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | | | | **…** | **18** | **19** |
| $s_1$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $s_2$ | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| … | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $s_{(n)}$ (note $n = 2^{n_{links}}$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

4. each of the events ($s_n$), is a possible state of the network at time $(t_0 + \delta t)$. This can be restated as, $S$ is the set that contains all possible states of the network at time $t_0 + \delta t$, where $S = \left\{ s_1, s_2, ..., s_{(n)} \right\}$ and $n = 2^{n_{links}}$ where $n_{links}$ = total number of links on network.
5. the probability of each of the events $s_n$, occurring is then computed. This would be the product of the possibilities of the state of each individual links. We illustrate this computation for some of events in Table 2.
6. a computer simulation is then run for each of the network situations ($s$). i.e. a simulation is run with the network configured as shown in each row of Table 2 above with the current travel demand; i.e. we run a simulation on a network on which the links that are marked 1 have been removed – this done to reflect breakdown on those links. The result of this step is assignments for the network for all possible link breakdown configurations.
7. from the results of the previous step, the predetermined distribution, is used to compute the possibility of failure on each of the functioning links for each configuration ($s_n$) at time $t_1$. The results of this exercise are the probability of failure on each of the links at time $t_1$ for each configuration given the fact that some of the links have already failed at

$t_0$ i.e. the links that were marked 1 at $t_0$. Restating, *the result of this step is the probability of failure of various links at time* $t_1$ *given some predetermined network configuration.*

8. finally, we collate the results into a single future possible network status by using probability computations for independent events. This result is then presented to the operators as the future possible network state given the current conditions.

Table 2: probabilities associated with possible network situations at time $t_2$

| **Situation No. /Link No.** | **Status of link at time ($t_1$)** | | | | | | **Probability of event $s_n$ occurring, $P(s_n)$** |
|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **…** | **18** | **19** | |
| $s_1$<br>Probability | 0<br>$P_{1_0}$ | 0<br>$P_{2_0}$ | 0<br>$P_{3_0}$ | | 0<br>$P_{18_0}$ | 0<br>$P_{19_0}$ | $(P_{1_0} \times P_{2_0} \dots P_{19_0})$ |
| …<br>Probability | 1<br>$P_{1_1}$ | 1<br>$P_{2_1}$ | 0<br>$P_{3_0}$ | | 0<br>$P_{18_0}$ | 0<br>$P_{19_0}$ | $(P_{1_1} \times P_{2_1} \dots P_{19_0})$ |
| $s_n$<br>Probability | 0<br>$P_{1_0}$ | 0<br>$P_{2_0}$ | 0<br>$P_{3_0}$ | | 0<br>$P_{18_0}$ | 1<br>$P_{19_0}$ | $(P_{1_0} \times P_{2_0} \dots P_{19_1})$ |

Each individual result $P(s_n)$, can be defined as; “*the probability that the network configuration at some infinitely short time after ($t_0$) is ($s_n$).*”

## 3. Simple example

We illustrate using a simple 3 link network. Assume this is part of a larger road network. This network has a current travel demand at time ($t_0$) which is used to compute the probability of failure of the network at ($t_0 + \delta t$). The table contains all possible configurations of the network links. We adopt the following nomenclature:

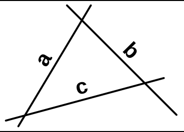
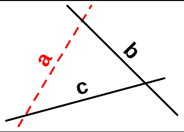
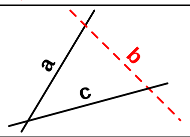
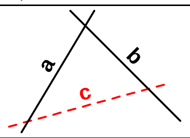
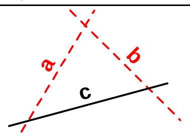
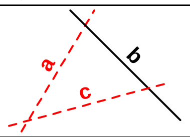
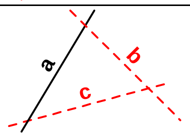
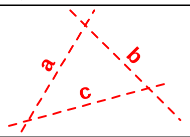
| | |
|---|---|
| $t_0$, $t_1$ | time. Note $t_0$ precedes $t_1$ |
| $P(A)$ | probability of failure of link e.g. $a$ |
| $P(\neg A)$ | probability that link a has ***not*** failed |

A simulation model is then run for each of the network configurations with the current demand for some time ($t_1 - t_0$). Based on the traffic volumes on the links at $t_1$ we compute the probability of failure of the links at $t_1$. The table contains an example of the computation for link b for each possible network configuration. The sum of this column would give the probability of failure of link b at time $t_1$.

## 4 Discussions and conclusion

To reduce the number of computations required, it is possible to apply an approximation to compute a composite possible state of the network at time $t_1$. This is done by determining a value of for which network configurations which have a probability less than this are not considered. This would not disrupt the integrity of the computations if well chosen. Network configurations that would have very low possibilities of occurring generally would consist of several failures on links with very low traffic. In reality, failure on such links do not have a significant impact on network performance, because the volume of traffic due to rerouting after such a rare event is not expected to be significant enough to disrupt the network performance.

Table 3: computation example for a 3-link network

| config. of possible network ensemble at $(t_0 + \delta t)$ | | probability of ensemble occuring based on traffic observed at $(t_0)$ | probability of failure on link b at $(t_1)$ given situation $(S_n)$ at $(t_0 + \delta t)$ |
|---|---|---|---|
| $S_1$ |  | $P(\neg A) \times P(\neg B) \times P(\neg C)$ | $P(S_1) \times P(B_{t_1})$ |
| $S_2$ |  | $P(A) \times P(\neg B) \times P(\neg C)$ | $P(S_2) \times P(B_{t_1})$ |
| $S_3$ |  | $P(\neg A) \times P(B) \times P(\neg C)$ | $P(S_3)$ |
| $S_4$ |  | $P(\neg A) \times P(\neg B) \times P(C)$ | $P(S_4) \times P(B_{t_1})$ |
| $S_5$ |  | $P(A) \times P(B) \times P(\neg C)$ | $P(S_5)$ |
| $S_6$ |  | $P(A) \times P(\neg B) \times P(C)$ | $P(S_6) \times P(B_{t_1})$ |
| $S_7$ |  | $P(\neg A) \times P(B) \times P(C)$ | $P(S_7)$ |
| $S_8$ |  | $P(A) \times P(B) \times P(C)$ | $P(S_8)$ |
| | | | $\Sigma$\{to obtain total P(failure$_B$)\} |

The duration of the simulation $(t_1 - t_0)$ should be adjusted to fit the lengths of the links. Generally as $(t_1 - t_0) \rightarrow 0$, it is expected that the accuracy of the predictions would increase. However, this would increase the computational burden. A suitable simulation time difference would have to take cognizance of the rate of change of demand, and susceptibility of the network to breakdown in addition to the link lengths.

For implementation of this problem on a real traffic network, one would require a very efficient macroscopic simulator. Initial work with MaDAM (Goudappel Coffeng 2003) indicate that it is suitable (fast and accurate enough) for such a task.

The volume of traffic at the end of the simulation (i.e. at $t_1$), is used to compute the probability of failure in the future. It is assumed that the flow rate does not change dramatically for each link for the duration of the simulation. If the rate of flow changes dramatically, in addition to reducing the simulation time, it may be beneficial to use the maximum flow rate during the simulation to estimate the probability of failure at $(t_1)$.

This formulation of estimation of future network operating condition is a P-problem class. The size of the solution space is bound by $(2^{n_{links}})$, which means that the number of possible network states increase exponentially with the number of links in the network. The possibilities to execute such an algorithm efficiently are; to use neural networks that would generate partial solution sets containing the most crucial solutions or develop parallel algorithms that would reduce computation time. The neural network would make a particularly good preprocessor because neural networks are very strong at pattern recognition. One would thus be able to eliminate network configurations that have a very small possibility of occurring while developing the ensemble of possible configurations.

Heuristics and knowledge based systems will continue to play a vital role in network management. The computational burden of network management calculations as well as the lack of simple well defined objective functions for network performance stand in the way of extensive use of optimization in network management. However, methods that that allow the improvement of heuristic/knowledge based techniques will probably see a wider acceptance in the near future. This technique for example, expands the "*what-if*" horizon of the traffic operators and thus directly expands their knowledge horizon. Further, since it is possible to eliminate/ignore options that have very low possibilities of occurring, it can be made to selectively expand the horizon of the operators – only in the direction that matters and thus avoid information overload – another serious problem operators face.

In spite of the apparent daunting computation requirements, if one compares the cost of computation equipment to the cost of infrastructure, it is still very reasonable. At current prices, a good CPU costs about 1000$, and to set up a massive parallel computing process is no significant compared to the average cost/km of motorway or urban arterials.

This technique is especially powerful for use in urban areas or highly interconnected networks where the interrelation between links and failure on links would be too difficult to track based on past experience.

## References


Evans, J., Elefteriadou, L., and Gautam, N., 1999. Probability of breakdown at freeway merges using Markov chains. Transportation Research Part B 35, 237-254.

Goudappel Coffeng, 2003. Manual for MaDAM – Macroscopic Dynamic Assignment Model. Goudappel Coffeng, Deventer Netherlands.

Gut, A., 1991. An Intermediate Course in Probability. Springer-Verlag isbn 0-387-94507-5.

Hall, F., 1999. Traffic Stream Characteristics. chapter in - A Monogram of Traffic Flow Theory, Transportation Research Board pp 2.1-2.36.

Lo, H. K., and Tung, Y. K., 2001. Network design for improving trip time reliability. Transportation Research Board Annual Meeting.

Lorenz, M., and Elifteriadou, L., 2001. Defining Freeway Capacity as a Function of Breakdown Probability. Transportation Research Board Annual Meeting.

Makoriwa, Brandt and van Berkum, 2003. Measuring the operating condition of a road network. 10th ITS Congress Spain.