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A proposal for a new design load concept for highway infrastructures

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Abstract

This paper proposes a design load concept that treats capacity and traffic flow as random variables. This contrasts with the n^{th} -hourly-volume concept (e. g. 30th hourly volume), which neglects the highest traffic volumes, which produce a disproportionate share of the social or generalised costs of any facility. It will be shown that the traffic flow is normally distributed within time windows, but varies in the standard deviation depending on the volume to capacity ratio. A new definition of capacity is given and estimated for an example. The method estimates the probabilities of traffic flow being larger than the capacity for any given scenario. This reserve capacity is linked to breakdown probabilities, queue lengths and therefore generalised costs of facility use. These results could easily be integrated into a cost-benefit analysis, which systematically focuses on the most expensive situations.

Keywords

Design concept, highway infrastructure, random variables, breakdown probability, reserve capacity, generalised costs

Preferred citation style

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1. Motivation

Highway design is commonly based on the idea, that a particular percentile (e. g. 99.7%) of annual distribution of hourly volumes, defines the economically relevant load. The question, if a design providing for a fixed percentile of the hourly volumes of a year is economic, has never been answered in detail. This paper provides initial ideas of how one might be able to address this issue and obtain a new, consistent design concept for road infrastructures. While the paper will focus on motorways, it aims to be general and applicable to any type of road facility.

Central to any design concept is the conceptual separation of traffic load and facility capacity. Existing approaches often do not explicitly keep these two effects apart. Generally speaking, the capacity has been identified as the maximum expected traffic flow that can be achieved repeatedly (HCM, 2000). In this context the single capacity gives no information about the frequency or probability that the flow can reach the expected value under a sufficient demand.

A modern design concept has to take this into account and be includable into a cost-benefit framework to assess the alternatives to improve an infrastructure in a proper way. It is therefore desirable to use a method that links the estimated demand with the resulting generalised costs for a given infrastructure design.

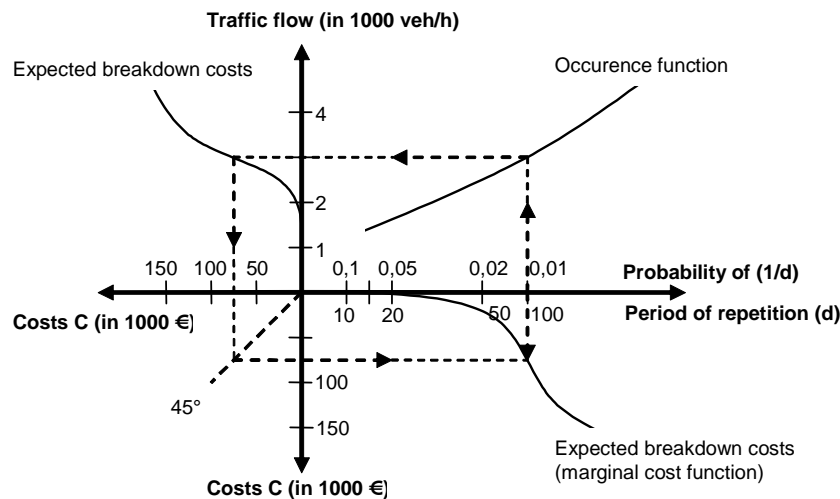
2. Adopting the idea of a scenario (load configuration)

It is known that the hours with the highest traffic volumes produce the largest contributions to the total generalised costs of a facility (Brilon and Zurlinden, 2003). The scenario concept proposed below is adapted from hydraulic engineering where the costs of a certain breakdown event (e. g. flooding due to high volumes) are estimated and valued (DVWK, 1989). By combining the period of repetition with the expected costs that a breakdown (queuing) will produce at a certain flow, one can define a marginal cost function which is needed for a cost-benefit analysis (see Figure 1).

In this context a scenario is an event that will result in increased generalised costs, and usually these events are relatively easy to identify from an engineering perspective. An example of a

scenario with the duration of one hour is a certain traffic volume during the peak hours of a common weekday that is expected to occur e. g. 200 times a year. It could be assumed that this scenario-group has a considerable share in the total generalised costs. Another scenario could be a lower traffic volume that prevails 500 times a year for one hour, resulting in lower generalised costs for the single event but having a higher frequency. A benefit of the scenario concept emerges from the increasing accuracy of a cost-benefit analysis with the preciseness and level of disaggregation of the defined scenarios. For application purposes not all possible scenarios have to be regarded for a cost-benefit analysis. With respect to transport engineering, the scenario concept focuses on hours with high frequencies of repetition and high traffic volumes, for which the costs start to grow non-linearly and which have substantial spatial spill-over effects. Boundaries are defined in this context to restrict the minimum and maximum traffic flows considered, as traffic flows below the lower limit produce (nearly) no congestion costs and the upper limit excludes extremely rare events. The boundaries have to be properly defined that the excluded scenarios, have a negligible influence on the total costs. Externalities and safety costs are in the first instance assumed to vary directly with the volume, but defined scenarios can also cover these effects.

Figure 1 General design of a cost function based on the occurrence function and the breakdown function (numbers are illustrations)



Source: adapted from DVWK (1989)

Generally speaking, the total yearly costs of the facility must be known. That means, for each event the resulting costs need to be provided. As the hourly volume distribution is known, the frequency of each demand level is known and can be described by an occurrence function that

maps the number of occurrences per year to traffic flows. In Figure 1 the occurrence function (1st quadrant) is embedded into a nomogram of the cost function of an infrastructure element. In this graph a breakdown describes a major increase in travel time, so the function of the breakdown costs (2nd quadrant) returns the expected generalised marginal costs for a given flow. These costs base on the willingness to pay for a reduction in travel time (see e. g. Axhausen *et al.*, 2004) and for a reduction in the variation of travel time, having a share in the total generalised costs (Chen *et al.*, 2003). Combining the occurrence function and the function of breakdown costs leads to the marginal cost function (4th quadrant). It serves as the basis for a cost-benefit analysis as it maps the probability of occurrence to the resulting costs of the scenarios considered. With the risk of a scenario being the product of the probability of occurrence and the generalised costs of the event the expected yearly marginal costs are computed by integrating (or summing up in the discrete case) over the risk of all regarded scenarios.

The next sections discuss the elements of the design concept. First new results on breakdown probabilities are presented to support the idea of capacity as a random variable, which is matched to the idea that long intervals of a flow can be thought of a set of shorter intervals with the mean of the long intervals but a predictable standard deviation and distribution. These two concepts are combined through the idea of a reserve capacity, which is then used to estimate the capacity distribution. The reserve capacity is the basis of an initial cost estimate associated with a particular load situation (scenario). Finally the design concept is summarised and future work is outlined in the final section.

3. Capacity as breakdown probability

Traditionally one assumes that a breakdown occurs when the flow regime changes from the upper branch (undersaturated flow) to the lower one (oversaturated flow) of the fundamental diagram (HCM, 2000). Alternatively, one could define a breakdown as an event, when the flow is deteriorating by a defined speed reduction; say 15 km/h before and after the event. The probabilities of such capacity violations have been shown recently to grow with traffic flow (e. g. van Toorenburg, 1986, Minderhoud *et al.*, 1996, Okamura *et al.*, 2000, Matt and Elefteriadou, 2001, or Brilon and Zurlinden, 2003). Capacity defined through capacity violations and mainly perceived through speed reduction has therefore not a fixed value, but is better described as random variable with a certain set of moments (mean, variance, skew etc.)

There are different methods to calculate the breakdown probability for a given traffic volume on a highway. A breakdown is usually indicated by a speed drop and the probability of the event is associated with the traffic volume before it occurs. In the literature one can find two general approaches: Okamura *et al.* (2000) and Matt and Elefteriadou (2001) analyse the breakdown probability for classes of traffic volumes whereas van Toorenborg (1986), Minderhoud *et al.* (1996) and Brilon and Zurlinden (2003) use the product limit method (PLM) to estimate the survival times of flow regimes. Exemplarily, the methods described by Matt and Elefteriadou (2001) and the one of Brilon and Zurlinden (2003) and an alternative method are to be compared in the following.

Matt and Elefteriadou (2001) have identified the breakdown probabilities for Highway 401 in Toronto. They define that a breakdown has occurred when the mean speed of all lanes drops for five minutes below a critical speed (70 km/h) that they employ to separate free flow from congested traffic. The traffic flow during the 1-minute interval before such a breakdown corresponds to the maximum traffic flow that can be handled at the moment under the given conditions.

In contrast to Matt and Elefteriadou (2001) Brilon and Zurlinden (2003) apply the product limit method (PLM) to identify the breakdown probabilities (speed drop below 90 km/h) of motorways in Germany. This method is based on the theoretical concept of a hazard data analysis where the lifetimes are substituted by traffic flow (regimes). On the one hand, this method provides steadily increasing breakdown functions, but on the other hand, it is not completely clear whether this method can be applied here, since traffic flow is not characterised by a continuous increase during an episode in the free-flow traffic flow regime.

When estimating the probability distribution of breakdowns due to traffic volume from counting data, it is important that the counting station be located at the bottleneck of an infrastructure element. Doing this, one avoids measuring effects due to upstream or downstream congestion. The counting data for the following analysis was provided by the Swiss Federal Roads Authority (ASTRA). The site Gunzgen in Switzerland between Bern and Zurich is located at the motorway A1 (east-west) where the motorway A2 (north-south) merges this road for nearly ten kilometres. About five kilometres before and after this counting station the traffic flow splits onto two motorways (A1 and A2) each of them with two lanes for both directions, whereas at the counter location both streams have to share only two lanes per direction.

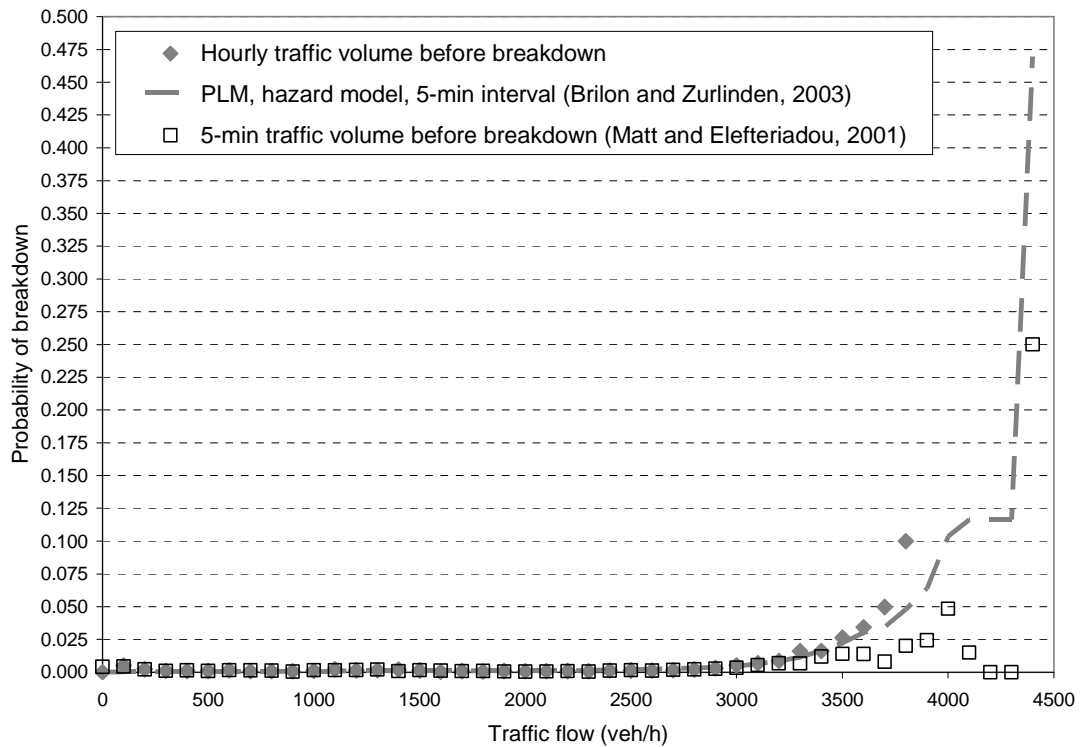
In this paper all calculations are based on 5-minute intervals to enable a comparison of the results of the different methods. The breakdown probability of the presented alternative

method is calculated by defining capacity to be the 60-minute traffic flow before a breakdown occurs (speed drop below 80 km/h in a following 5-minute interval). This method is compared with the methods of Matt and Elefteriadou (2001) and of Brilon and Zurlinden (2003) using 5-minute intervals and 80 km/h as breakdown speed (see Figure 2). The traffic flows were grouped into classes of a width of 100 veh/h with theoretical means of 0, 100, 200, ... veh/h (i. e. classes of -50 to 50, 51 to 150, 151 to 250, ... veh/h). The breakdown probability is calculated by dividing the number of intervals marked as “before breakdown” by the total number of intervals in this class.

Figure 2 shows that the methods of Brilon and Zurlinden (2003) and the alternative method (hourly traffic volume before a breakdown) serve as a good basis to estimate the distribution function of the breakdown probability at the site Gunzgen. In contrast, the results of Matt and Elefteriadou’s (2001) method might produce difficulties when fitting a function, as the probabilities fluctuate strongly at very high traffic volumes at this counting station. As a matter of fact, the scheme of Matt and Elefteriadou (2001), as applied to this example, would underestimate the breakdown probabilities, since the measured traffic volume directly preceding the breakdown may itself be lower than the higher traffic volume before which was the initial reason for the breakdown.

The breakdown probabilities using the hourly traffic volumes are higher than the corresponding probabilities of the other methods, as the traffic flow before a breakdown is averaged over one hour (twelve 5-minute intervals before breakdown). If there was another breakdown within this hour the traffic volumes during the breakdown were not regarded. The advantage of this method is the combination of the high precision of 5-minute intervals and hourly volumes which are often a basis for assessment.

Figure 2 Comparison of different methods to estimate breakdown probabilities at the site Gunzgen (Switzerland)



Data: Counter Gunzgen (Switzerland), highway A1 between Bern and Zurich; 245,000 intervals between April 2002 and May 2005 for each direction; traffic flow in veh/h based on 5-minute intervals

Having no further information, it should be mentioned that the breakdown probabilities alone do not allow conclusions about the capacity of a given road type, as the traffic flow properties also affect the probability of a breakdown. The traffic flow during an interval is never constant but follows a distribution. Depending on the shape of the distribution, the breakdown probability will change, i. e. traffic flow with a low mean but a high variance can have the same breakdown probability as a flow with a higher mean but a small variance.

4. Within-class traffic flow variance

The traffic flow measured for example over a 60-minute interval summarises flows, which when measured for shorter intervals will vary around the 60-minute average. If one could show that there is a consistent relationship between 60-min flows and the variance of, say, the 5 min intervals of that hour, then it become possible to predict the number of breakdown during that interval better. To test this idea, the traffic flows and speeds measured for 219 days at 19 automatic counting stations on ten Swiss motorways (“Autobahn”) were analysed (Swiss Federal Roads Authority, ASTRA, 2003).

The raw count data was aggregated into intervals of five minutes q_5 . Based on these flows, the corresponding 60-minute means q_{60} were calculated. The traffic flow $q_{60,A,t}$ of one direction of a road A at the time t is given by:

$$q_{60,A,t} = \frac{1}{12} \sum_{i=-6}^5 q_{5,A,t+i \cdot 5 \text{ min}} , \text{ if all } q_{5,A,t+i \cdot 5 \text{ min}} \text{ are defined and contain valid data.}$$

For each hourly traffic flow $q_{60,A,t}$ twelve 5-minute intervals $q_{5,A,t}$ were identified. To get comparable values from different road types with different number of lanes, the flow to capacity ratios r are calculated with the capacity C_A (from VSS, 1999) for each position A of a counting station on a certain road and direction. With an assumed average percentage of heavy vehicles of $\leq 5\%$ C_A becomes for a motorway (“Autobahn”) with two lanes per direction 3600 veh/h per direction and 5500 veh/h for three lanes per direction:

$$r_{60,A,t} = \frac{q_{60,A,t}}{C_A} \text{ and } r_{5,A,t} = \frac{q_{5,A,t}}{C_A} .$$

The volume to capacity ratios r_{60} are assigned into n groups G defined by ratio intervals:

$$G_i = \left\{ r_{60,A,t} \mid \frac{i-1}{n} \leq r_{60,A,t} < \frac{i}{n} \right\} .$$

As volume-to-capacity ratios higher than 1.0 can be measured due to traffic volumes being higher than the norm capacities, it is likely that more than n groups will be built. In addition, a few groups might be empty, especially those with very low ratios, due to a lack of observations.

Within a group G_i of J_i elements the mean of the ratios r_{60,G_i} are calculated:

$$r_{60,G_i} = \frac{1}{J_i} \sum_{j=1}^{J_i} r_{60,A,t} \quad \text{with } r_{60,A,t} \in G_i \quad \text{and } J_i = \|G_i\| .$$

Knowing the 5-minute ratios which build the 60-minute mean ratios, the standard deviation for each group can be estimated as follows:

$$sd(r_{5,G_i}) = \frac{1}{J_i} \left[\sum_{j=1}^{J_i} r_{5,A,t}^2 - \frac{1}{J_i} \left(\sum_{j=1}^{J_i} r_{5,A,t} \right)^2 \right] \quad \text{with } r_{5,A,t} \in G_i \quad \text{and } J_i = \|G_i\| ;$$

where $r_{5,G_i} = \frac{1}{J_i} \sum_{j=1}^{J_i} r_{5,A,t} \approx \frac{1}{J_i} \sum_{j=1}^{J_i} r_{60,A,t} = r_{60,G_i}$ is a good approximation, as for large J_i
 $r_{5,G_i} = r_{60,G_i} \left(\lim_{J_i \rightarrow \infty} (r_{5,G_i}) = r_{60,G_i} \right) .$

In the following, it will be demonstrated that the 5-minute ratios are normally distributed within their corresponding 60-minute ratios. Given a mean ratio r_{60} , an interval $r_{60} \pm \Delta r$ is created to obtain multiple measurements of r_{60} within this interval. For three sample intervals the assumption of normally distributed r_5 within their interval $r_{60} \pm \Delta r$ is demonstrated by example:

- a) $r_{60} \pm \Delta r \left(= \frac{q_{60} \pm \Delta q_{60}}{C} \right)$ between 20% and 25%,
- b) $r_{60} \pm \Delta r$ between 45% and 50% and
- c) $r_{60} \pm \Delta r$ between 95% and 100%.

These three intervals include enough measurements to permit significant results, and the means of the 60-minute ratios differ very little (less than 3%) from the means calculated by the 5-minute ratios indicating that the measurements are valid. The statistics are shown in Table 1. The Shapiro-Wilk test has significant values that indicate a normally distributed variable, where α indicates the error probability of this test (Shapiro and Wilk, 1965).

Table 1 Test of normally distributed 5-minute volume to capacity ratios r_5

Interval of r_{60}	Count of means (r_{60} and r_5)	Mean r_{60}	Mean r_5	Standard deviation of r_5	Shapiro-Wilk test sign. $\alpha=(1-p)$
a) 0.20-0.25	827	0.226	0.220	0.033	0.001
b) 0.45-0.50	3421	0.476	0.473	0.050	0.000
c) 0.95-1.00	1101	0.974	0.990	0.081	0.000

Figure 3 shows 5-minute volume to capacity ratios of the three examples a, b and c as bar charts and normal plots. In the Q-Q-Plot (normal plot), the theoretical distribution of a normally distributed variable is indicated by the line, whereas the dots represent the expected position on an ideal normal distribution versus the observed value. It can be seen that the measurements match the theoretical expected values very well.

The graphs strongly support the hypothesis that the r_5 -ratios are normally distributed within their 60-minute means. With these results, a mapping is possible from an expected mean traffic flow during one hour coming from a forecast or count data to the coefficient of variation for this traffic flow. Figure 4 shows a graph of this relationship. It is obvious that the coefficient of variation ($sd(q_5)/q_{60}$) decreases with increasing volume-to-capacity ratios. The reason for this is the limited freedom of choosing the desired gap and speed with higher traffic volumes. The graph also gives a systematic alternative for the definition of boundaries of the qualities of service levels A to F.

The analysis of this Swiss data set has shown that the 5-minute traffic volumes within an hourly traffic flow can be described by a normal distribution and that the standard deviation of this distribution varies predictable with the hourly volume to capacity ratio.

Figure 3 Normally distributed 5-minute volume to capacity ratios ($r_5=q_5/C$):
Bar chart and normal-plot for three r_{60} intervals

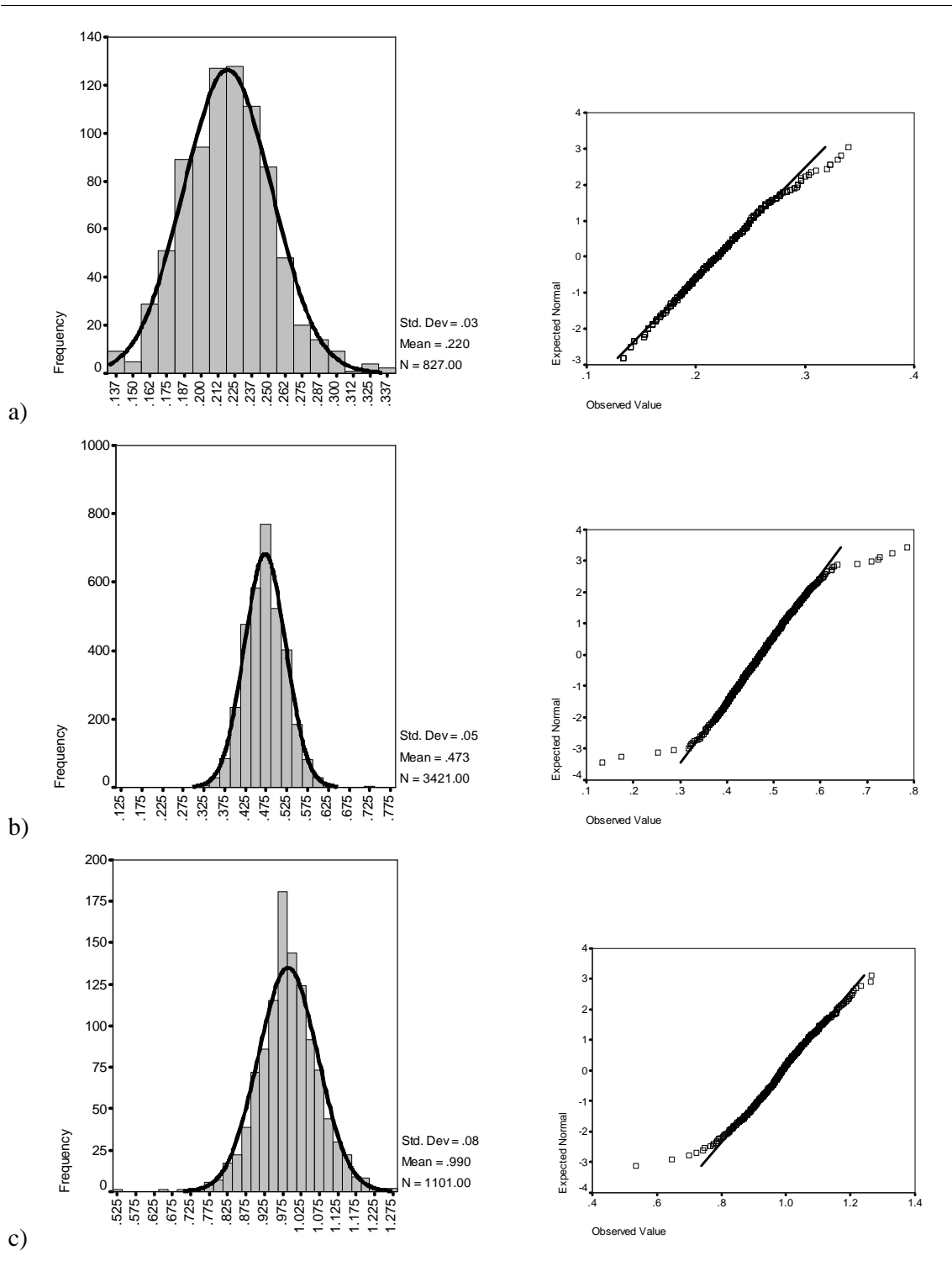
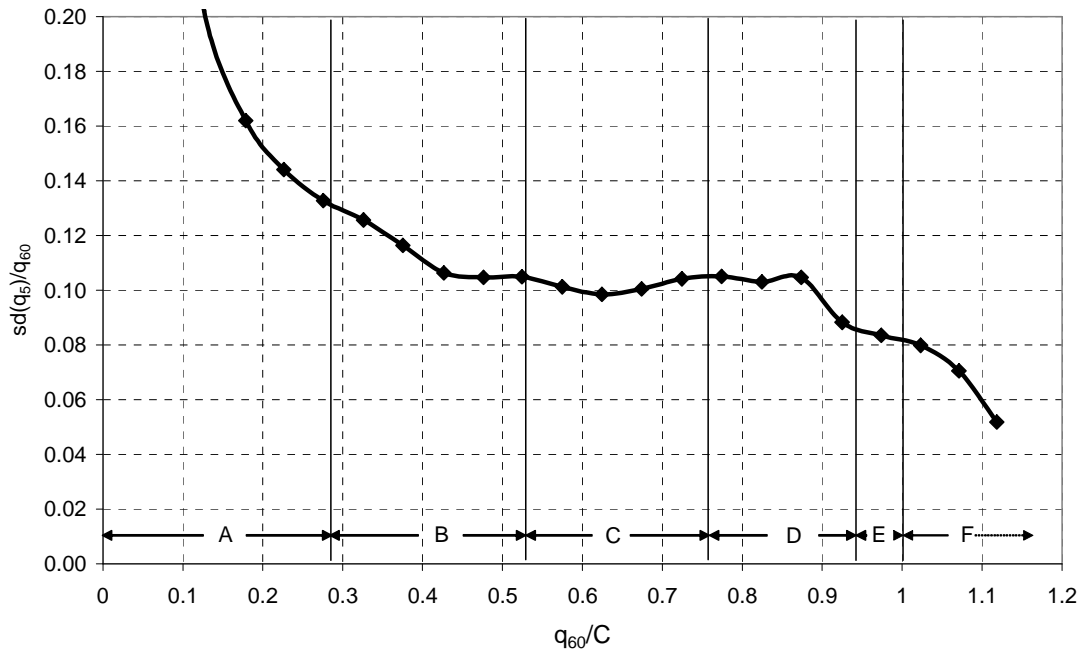


Figure 4 Coefficient of variation ($sd(q_5)/q_{60}$) of 5-minute intervals vs. hourly flow to capacity ratio (q_{60}/C)

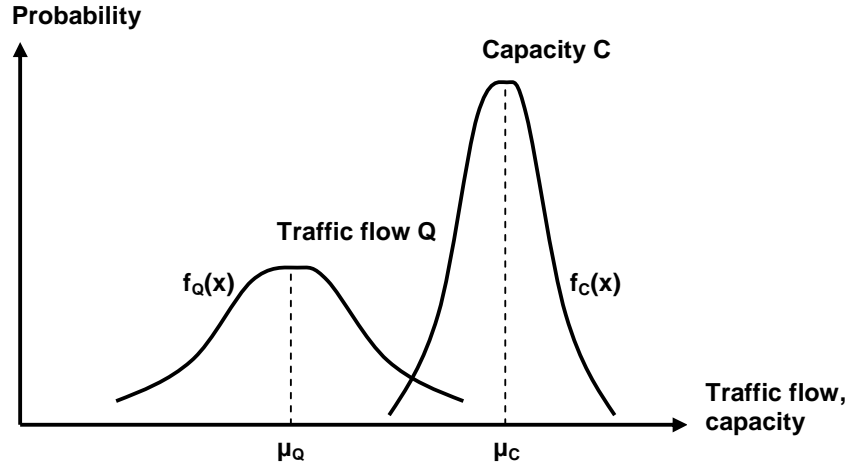


$sd(q_5)/q_{60}$ coefficient of variation of hourly volumes
 q_{60}/C normalised by capacity given by VSS (1999)
 A to F quality of service by VSS (1999)

5. Reserve capacity of a road section

In the following, the random variable of the capacity of an infrastructure element will be denoted as C with the probability density function $f_C(x)$ and the traffic flow as random variable Q with probability density function $f_Q(x)$ (see Figure 5).

Figure 5 Traffic flow (demand) and capacity as random variables



An infrastructure element fails to work properly (i. e. a breakdown occurs) if the traffic flow q exceeds the current capacity c (q and c denote realisations of the random variables Q and C). With the probability density function of the random variable C the probability P_f of C being smaller than an actual q can be written as:

$$P_f = P(C \leq q) = F_C(q) = \int_{-\infty}^q f_C(x) dx .$$

If q itself is not known, but the distribution of Q is, then the probability that Q exceeds C becomes:

$$P_f = P(C \leq Q) = P(C - Q \leq 0) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_C(x) f_Q(x) dx^2 = \int_{-\infty}^{\infty} F_C(x) f_Q(x) dx = \int_{-\infty}^{\infty} f_{P_f}(x) dx .$$

Here, the capacity C and the traffic flow Q are defined such that both variables are statistically independent. In the structural reliability theory this case is called the fundamental case (Gulvanessian *et al.*, 2002). The integral for two probability density functions f_C and f_Q of any shape cannot be solved in general, but assuming that C and Q are normally distributed, an analytical solution can be found.

If the reserve capacity (safety margin) is defined as:

$$M = C - Q$$

the breakdown probability P_f becomes:

$$P_f = P(C - Q \leq 0) = P(M \leq 0).$$

If C and Q are normally distributed then also M is normally distributed with the mean μ_M and standard deviation σ_M as follows:

$$\mu_M = \mu_C - \mu_Q \quad \text{and} \quad \sigma_M = \sqrt{\sigma_C^2 + \sigma_Q^2} \quad (\text{if statistically independent}).$$

With the cumulative probability density function of the normal distribution $\Phi = N(0, 1)$:

$$\Phi_x(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^x \exp\left(-\frac{1}{2}x^2\right) dx$$

P_f can be written als:

$$P_f = \Phi\left(\frac{0 - \mu_M}{\sigma_M}\right) = \Phi(-\beta)$$

with the reliability index (coefficient of variation) $\beta = \mu_M / \sigma_M$.

6. Estimation of capacity

As shown above, one can estimate the breakdown probability on the basis of the distribution of the prevailing traffic flow and the distribution of the capacity. The parameters of the distribution of the capacity will be computed using a model of the traffic flow and the breakdown probability.

The breakdown probabilities for a given mean traffic flow μ_Q of Figure 2 using the 60-minute traffic volumes before a breakdown of at least 5 minutes are denoted as a_{μ_Q} . The standard deviation of the mean hourly traffic volume $\sigma_Q(\mu_Q)$ is given by the function shown in Figure 4 and the analytical breakdown probability $P_f = \Phi(-\beta)$ which is dependent on μ_M and σ_M where the two parameters are dependent on μ_Q , σ_Q , μ_C and σ_C . Since the traffic flow parameters (μ_Q , σ_Q) are given only μ_C and σ_C remain as unknown values. The analytical breakdown probability b_{μ_Q} of the traffic volume μ_Q can be written as:

$$P_f = b_{\mu_Q}(\mu_C, \sigma_C) = \Phi \left(- \frac{\mu_C - \mu_Q}{\sqrt{\sigma_C^2 + \sigma_Q(\mu_Q)^2}} \right)$$

The parameters μ_C and σ_C are estimated by minimizing the sum of squares of the residuals $\delta_{\mu_Q} = b_{\mu_Q} - a_{\mu_Q}$:

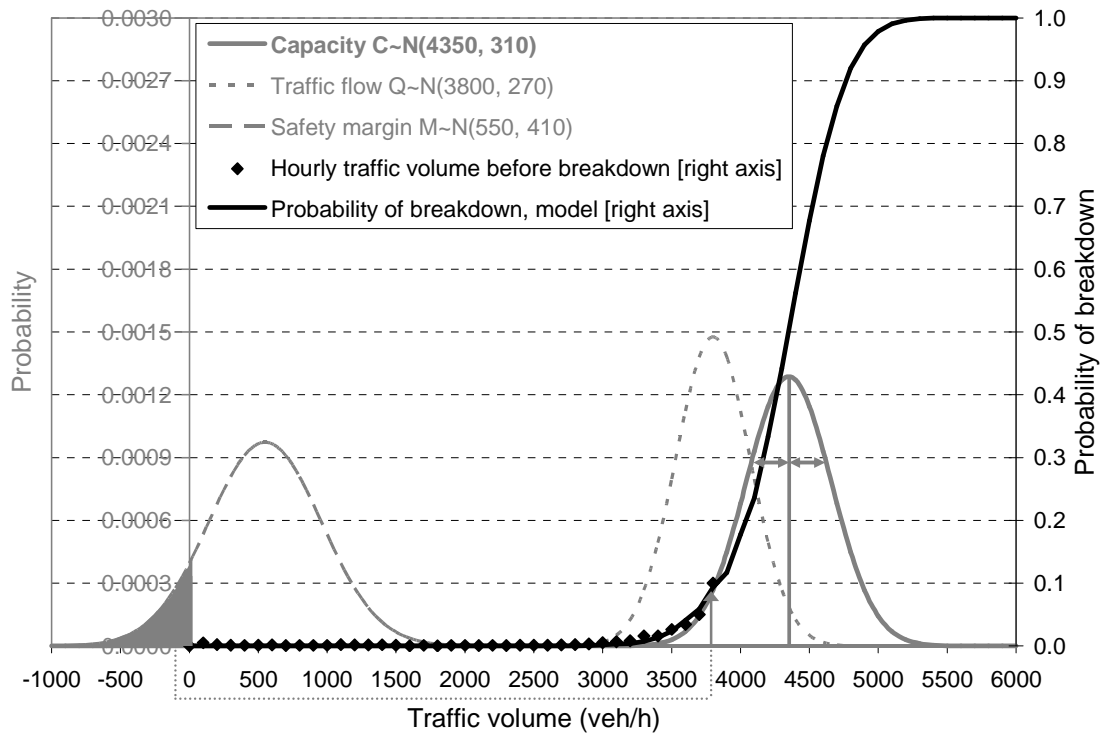
$$\sum_{(Q)} \delta_{\mu_Q}(\mu_C, \sigma_C)^2 = \sum_{(Q)} (b_{\mu_Q}(\mu_C, \sigma_C) - a_{\mu_Q})^2 \rightarrow MIN$$

With the values shown in Figure 2 (hourly volumes before breakdown), this least squares method results in a mean capacity of 4350 veh/h and a standard deviation of 310 veh/h (exact: $\mu_C=4348.3$, $\sigma_C=313.2$, $r^2=0.969$) at the counter Gunzgen (See Figure 6). The dashed curves (traffic flow and safety margin) in Figure 6 give an example showing a mean hourly traffic flow of 3800 veh/h with a standard deviation of 270 veh/h (derivated from Figure 4 for a norm capacity of 3600 veh/h). Knowing the distribution of the capacity ($C \sim N(4350, 310)$) the reserve capacity computes to $M \sim N(550, 410)$. The integration of the probability density function of M over $(-\infty; 0]$ gives the breakdown probability for this scenario (9%). Carrying out these steps for all traffic volumes one obtains the analytical probability function of a breakdown, where the capacity C (μ_C, σ_C) is set to minimize the residuals of the analytical and the measured values.

It is important to note that the estimated capacity cannot directly be compared with the known values from e. g. VSS, 1999, HBS, 2001 or HCM, 2000 as these values are based on different concepts and have therefore a different meaning. In addition, in this example, 5-minute intervals are used to determine the breakdown probabilities, which produce a higher capacity than that which are obtained with other concepts estimating capacity, e. g. with the method of van Aerde (1995). If we define capacity as the volume with a 50% breakdown probability, then the capacity is 4350 veh/h. Knowing that Bovy (2001) suggests a probability of congestion from 2 to 5% as an economic optimum, traffic volumes with high breakdown

probabilities have to be avoided. In this analysis a breakdown probability of 2 to 5% corresponds to an hourly volume of 3460 to 3650 veh/h, being near the norm capacity of 3600 veh/h (from VSS, 1999).

Figure 6 Estimation of capacity based on breakdown probabilities and traffic flow distribution of 5-minute intervals



7. Queuing length estimation

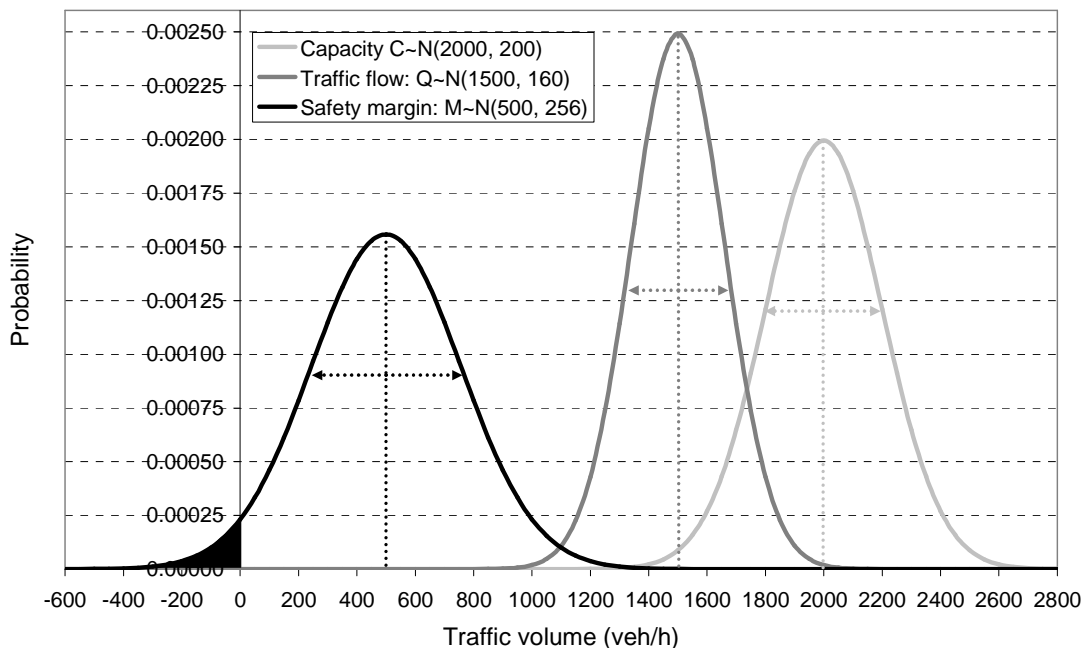
For an application in cost benefit analysis, the expected generalised costs (in this example queuing costs) have to be determined. For example, Brilon *et al.* (2005) estimate these costs by simulating the traffic conditions for one year using a macroscopic Monte-Carlo simulation. However, this method requires a lot of computational effort, as many runs are needed to calculate the expected queuing length. It is obvious that there are only a few potential scenarios that will cause queuing. The necessary amount of calculation could be drastically

reduced by considering only these critical traffic states, which could be summed by weighting them with their frequency of occurrences.

First, the distribution of the reserve capacity M can be used as a proxy for the level of service for a given traffic scenario (see Figure 7). The probability of a traffic volume Q being larger than the capacity C is the probability of M being below or equal to zero: $P(C - Q \leq 0) = P(M \leq 0)$. This probability is the area marked black below zero on the x-axis in Figure 7.

Second, the generalised cost produced by vehicles that cannot be handled by one network element (queuing) could easily be estimated within this framework. The reserve capacity M was defined as $M = C - Q$ and can be compared to a probability density function of the differences (Δ) of realisations of C and Q : $\Delta = c - q$. This means that Δ is negative for realisations c and q where the actual capacity is lower than the actual traffic flow. In these cases the network element could not handle the current traffic volume.

Figure 7 Probability density functions of capacity, traffic flow and safety margin



Hence, the number of vehicles that is likely to experience a breakdown is given by the negative expected value of M being smaller than or equal to zero with the probability density

function f_M equal to the failure probability function f_{Pf} and the number of queuing vehicles N_{queue} :

$$f_{P_f}(x) = f_M(x) ,$$

$$N_{queue} = -E[f_M(x \leq 0)] = - \int_{-\infty}^0 x f_M(x) dx = - \int_{-\infty}^0 x \frac{1}{\sigma_M \sqrt{2\pi}} \exp\left(-\frac{1}{2} \left(\frac{x - \mu_M}{\sigma_M}\right)^2\right) dx .$$

The expected value $E[f_M(x \leq 0)]$ has to be multiplied by -1, as by definition $\Delta = c - q$ is negative if the traffic flow is greater than the capacity.

In Figure 7 one can see an example of a scenario that should last for one hour. Given the values of $C \sim N(2000, 200)$, $Q \sim N(1500, 160)$ veh/h, and therefore $M \sim N(500, 256.125)$ the breakdown probability is calculated with the reliability index (coefficient of variation) $\beta = \mu_M / \sigma_M = 1.952$:

$$P_f = \Phi(-\beta) = 2.54\% .$$

The expected number of vehicles N_{queue} that cannot be handled becomes with $\mu_M = 500$ veh/h and $\sigma_M = 256.125$ veh/h:

$$N_{queue} = 2.47 \text{ veh/h}$$

for the given traffic conditions of the interval considered. This number of vehicles is likely to experience congested traffic flow (lower branch of fundamental diagram), and the remaining vehicles have to be handled in the following interval. The unit of the queue length is vehicles per hour. As in this example the duration of the scenario is one hour the expected queue length after becomes 2.47 vehicles.

8. Structure of new design concept

The proposed new design concept is based on a comparison of the generalised costs of two or more planning scenarios – usually the status quo and a modification of the existing system. It integrates the elements discussed above in the following steps:

- Definition of capacity, as random variable

- Description of the distribution of demand, again as a random variable
- Identification of possible critical scenarios
- Estimation of frequency or probability of occurrence of scenarios employing the idea of a random reserve capacity (e. g. over one or 20 days, months, years)
- Cost calculation (calculation of queuing length) for each scenario
- Total cost estimate calculated as the sum of the expected costs given by the product of the probability of occurrence and the costs of the event over all events.

In contrast to the concept of the n^{th} hourly volume concept, which neglects the cost of the n highest traffic volumes, this concept takes all traffic volumes into account – or, more generally all traffic scenarios. The intervals with the high traffic volumes are evaluated, as these volumes contribute the largest amount to the total generalised cost over each year.

9. Outlook

The design concept presented can be applied with little modification to most infrastructure elements. The general concept of reserve capacity (safety margin) is already shown in the HBS (2001) for unsignalised intersections. A coherent concept for all kinds of infrastructure elements is both a desirable goal and feasible. An advantage of the method in comparison shown in comparison to many existing concepts is its scalability in accuracy. The more detailed the demand and capacity estimations are, the more reliable are the results. In addition, in this paper the capacity is assumed to be normally distributed within a given time window. It has to be verified whether this assumption is true or if the error in this assumption is small enough, since a normally distributed variable simplifies the calculation. Brilon and Zurlinden (2003) assume that breakdown probability can be described by the Weibull-distribution and imply that the capacity also follows a Weibull-distribution, but their discussion does not include the distribution of the flow.

The method introduced here requires no redefinition of capacity in the general sense. In the Highway Capacity Manual (Transportation Research Board, 2000) and in the Swiss norm (VSS, 1999) the capacity of an infrastructure element is defined as the largest traffic volume that is expected to pass a section within a given time interval under given road, traffic and operation conditions. Therefore, this definition is coherent with the definition needed for the design concept presented. However the capacity must be described not only by the expected value but additionally by its variance – or, more generally by its distribution.

However the American (HCM, 2000) and German (HBS, 2001) definitions describe the capacity as the maximum traffic flow that can be accommodated – thus a fixed value.

A remaining task is the integration of the proportion of heavy vehicles into the measurement of capacity. As the percentage of heavy vehicles influences the behaviour of the traffic flow and not actually the capacity, it is questionable if a reduction factor should be bound to the capacity or if this factor should rather be connected to the traffic flow. Here it was assumed that the traffic flow and the capacity are independent variables and that an influence of the traffic flow on the capacity is negligible. If this assumption is not true, a possible solution to this problem would be introduction of safety or reduction factors that are easy to implement into this concept and which will be a topic for the on-going research at ETH.

To integrate this method into cost-benefit analysis, it is necessary to assess the additional travel times due to high demand/capacity situations and due to breakdowns and especially queuing. Consequently, it has to be evaluated whether a queuing model or some functions such as a modified BPR-function could be developed, or if different methods need to be found. A simple solution would be estimate the average speed drops after a breakdown, combined with the average duration of the congested state. But more sophisticated methods may be necessary, as long as they do not complicate the application too much.

A further area of work is the extension of this design concept to networks, as the effect of the joint distribution of breakdowns will need to be assessed in this case (Bates *et al.*, 2002).

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