



## **New Design Concepts for Transport Infrastructures**

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## **New Design Concepts for Transport Infrastructures**

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### **Abstract**

The commonly used techniques for measuring capacity are mainly based on evolutionary concepts. These have been established due to the lack of detailed traffic information and limited capacity to evaluate the data. This situation has changed but is still far from the optimal state of full information, which surely never will be achieved.

Though having detailed information about traffic flow, mean values are widely used to design transport infrastructures. The Swiss Norm provides factors to calculate hourly values from the average annual daily traffic by neglecting the variance. This could easily lead to wrong assumptions. If non-linear travel-time functions are used e. g. in assignment models, this variance must be included, for a calculation with a mean traffic flow underestimates the travel times.

Other engineering sciences offer modern techniques to build risk sensitive models. The resistance and load are handled as random values and no longer as mean values. A concept similar to the Euro Code is applied to estimate the breakdown probability of roads depending on the traffic volume. This could be used as a proxy for the quality of service and for a detailed cost benefit analysis.

### **Keywords**

Design concepts – transport infrastructure – demand and capacity as random variables

### **Citation**

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## 1. Introduction

In this paper a general design concept should be presented that treats capacity and traffic flow as random variables. That means that these values are described by their distribution and not by their maximum (capacity) or mean value (traffic flow). It will be shown that the traffic flow is normally distributed within time windows. Given the normal distribution calculations of the probabilistic design concept could be simplified and feasible for application. The method shown here could be used to estimate the probabilities of the traffic flow being larger than the capacity for given scenarios. These results could easily be integrated into a cost-benefit analysis with a focus on the most expensive traffic scenarios concerning generalised costs. This design concept is in contrast to the 30<sup>th</sup>-hourly-volume concept which neglects the hours of the highest traffic flow.

### 1.1 Common understanding of capacity and levels of service

Hitherto concepts based on intensive measurements to identify the maximum occurred volume. Qualitative characteristics in combination with parameters had to be found to describe the traffic flow. The basic attributes are car-following distances, mean speed and – by combing both – the traffic flow.

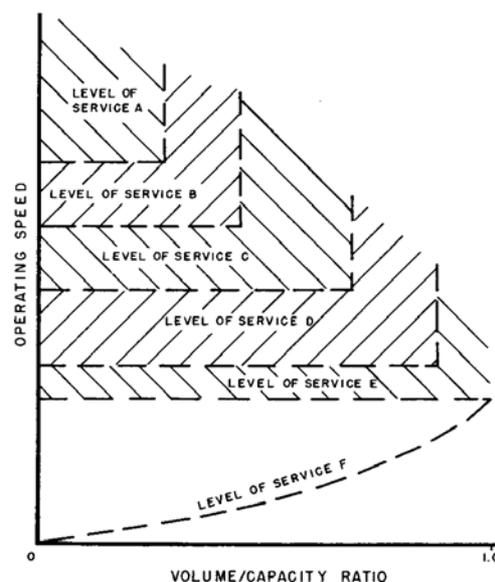
These concepts do not show explicitly a separation of load and resistance of the system. The resistance of the system could be compared with the maximum capacity that was identified by the maximum traffic flow observed for one hour. The expression “maximum capacity” is misleading in this context as it is actually the maximum observed traffic flow. Design concepts in general describe a maximum resistance (capacity) as the mean of a series of strain test of the system till its breakdown. This is a major problem in transport engineering, as it is not possible to run tests under ideal conditions with a controlled traffic load. Nevertheless factors regarding structural facilities and alignment effects have been identified. These variables reduce the maximum capacity under ideal conditions. The load is adapted by not concerning for example 30 hours with the year’s highest volume. This is equivalent to some kind of reciprocal safety coefficient, for it lowers the safety instead of increasing it. But the raw traffic flow describes the load of the system not in every way. Therefore it is seen that a breakdown occurs not only because of a high traffic flow but also while the flow is relatively low.

While Bureau of Public Roads (1950) mainly uses means to describe the traffic flow, later studies tried to explain variability by adding new variables and categories. Improvements

could be found in Highway Research Board (1965). The Poisson distribution is used to describe the distributions of time spacing between vehicles as a function of the traffic volume. A further extension of the existing models is the introduction of levels of service (LoS), regarding the observed coherence that traffic flow is dependent on the actual volume and density. In Highway Research Board (1965) six levels of service (A to F) are defined. Qualitatively they are shown in Figure 1.

The observed behaviour varies from country to country and in time periods of few years. The concentrated efforts of continuous counts made it possible to publish modified distributions of headways and loads to regularly provide fundamental diagrams for many countries.

Figure 1 Levels of Service (LoS) in Highway Research Board (1965)



Source: Highway Research Board (1965)

## 1.2 30<sup>th</sup> hourly volume as design traffic flow

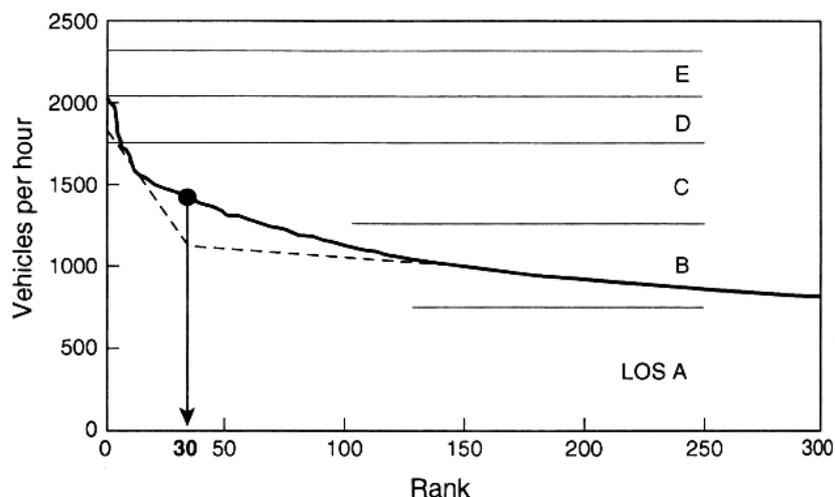
Design concepts commonly use the 30<sup>th</sup> hourly volume, described in Bureau of Public Roads (1950). The 30<sup>th</sup> hourly volume was chosen because of a flattening of the slope at this point. Antusch (1981) adds that this property could only be observed for censuses that mainly consist of commuter and weekday traffic. On weekends an incline of the slope could be found at the 30<sup>th</sup> hourly volume. But nevertheless even for these types of traffic the 30<sup>th</sup> hourly volume should be used as a design measure, because hours with higher traffic volume are

affected by incidents like accidents and special weather conditions. After the 20<sup>th</sup> or 30<sup>th</sup> hourly volume these events could be excluded (Antusch, 1981). In addition to that economic issues support this concept, as a design for hours of larger volumes will lead to a low utilisation ratio. The 30<sup>th</sup> hourly volume could be described as the volume which is greater or equal to 99.66% of the hourly volumes of a year. But this expression is rarely used in practice.

### 1.3 Modifications of the 30<sup>th</sup> hourly volume

The actual publication of the Highway Capacity Manual (2000) (Transportation Research Board, 2000) suggests the design for the 30<sup>th</sup> to 100<sup>th</sup> hourly volume. The practical traffic volume for each direction could be calculated using the proportion of the direction of the hourly peak volume and the average annual daily traffic. These are multiplied by K-factors ranging from 0.091 to 0.1 which describe the grade of urbanisation. This method implies that the average hourly volumes given for a specific hour of a day, for a specific day within a week and for a certain month are independent. It must be assumed that this assumption cannot be held.

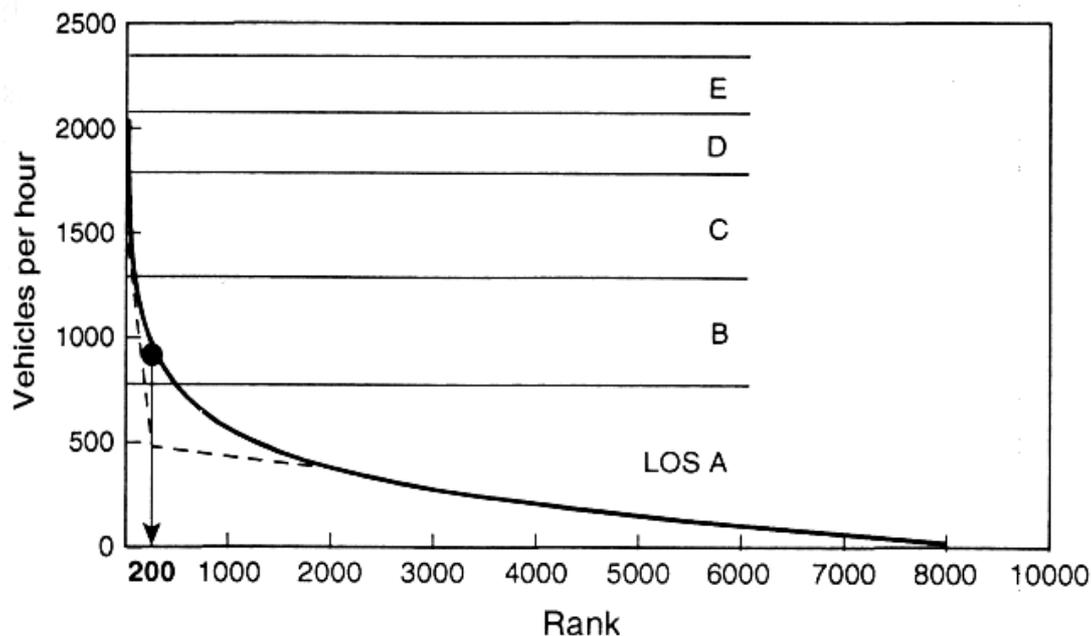
Figure 2 300 ranked hours with the highest traffic volume on the four-lane Trans-Canada-Highway (Highway #1) east of the Rocky Mountains



Hempsey und Teply (1999)

Hempsey and Teply (1999) point out that in the hourly volume diagram the definition of the location of the knee, which should lead to the 30<sup>th</sup> to 100<sup>th</sup> hourly volume, is not unproblematic. Dependent on the resolution and frame of the graph, the knee could be seen at different positions for the same diagram (see Figure 2 and Figure 3). If the position of the kink could not be defined properly then a certain design volume could not be justified, when the thesis of the Bureau of Public Roads (1950) is applied.

Figure 3 8000 ranked hours with the highest traffic volume of the same site as in Figure 2 on the four-lane Trans-Canada-Highway (Highway #1) east of the Rocky Mountains



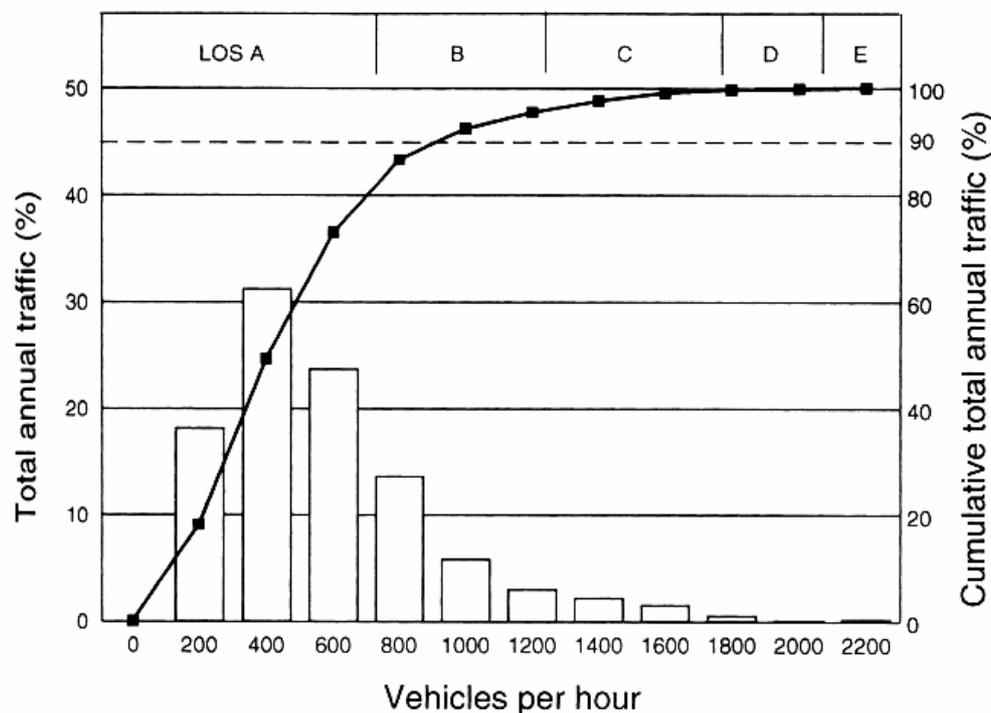
Hempsey und Teply (1999)

The concept of the 30<sup>th</sup> hourly volume is mainly criticised for the negligence of the different states in traffic flow. The rank of a traffic volume gives no information about a possible increase in travel time, the probability of a breakdown or more general about the quality of service. Hempsey and Teply (1999) suggest therefore measuring the percentage of vehicles that could pass a network element at a given level of service. If the simplification is accepted that the level of service could be described by the traffic flow itself, then it could be said that

in 1996 90% of the vehicles on the Trans-Canada-Highway experience the level of service B or better as shown in Figure 4. Hempsey and Teply point out that this method could easily be integrated into cost-benefit analysis, as the percentage of vehicles experiencing the desired quality of service is known. Their analysis show that the principle of a ranked hourly volume may still be feasible and could result in higher ranks of the hourly volumes than given in the Highway Capacity Manual 2000 (Transportation Research Board, 2000: 30<sup>th</sup> to 100<sup>th</sup> hourly volume; Hempsey and Teply, 1999: 200<sup>th</sup> hourly volume).

All methods working with ranked hourly volumes or percentages at a certain level of service have in common that they are highly dependent on the definition of the volume to capacity ratios for each level of service. In addition to that the effects of a lower level of service (e. g. C instead of B) or a higher rank of the hourly volume (e. g. 100 instead of 30) could not be quantified in increased travel times or higher generalised costs.

Figure 4 Distribution of the hourly volumes on the Trans-Canada-Highway in the year 1996



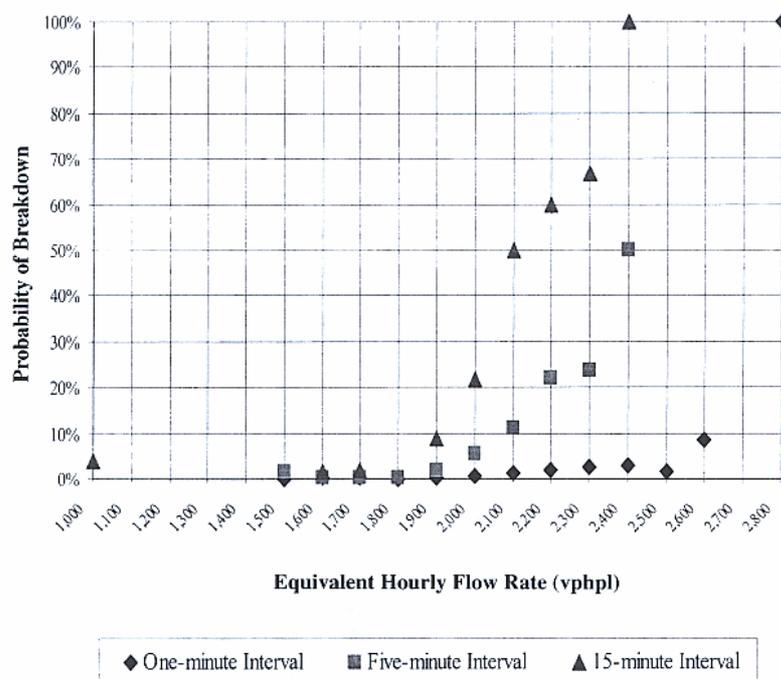
Hempsey und Teply (1999)

## 2. New design concepts

### 2.1 New understanding of capacity

Matt and Elefteriadou (2001) have identified the breakdown probability for the 401 highway in Toronto. They define that a breakdown is observed if the mean speed of all lanes drops for five minutes below a critical speed that separates free flow from congested traffic. In this publication it becomes clear that the capacity cannot be seen as a fixed value but as a random variable. With higher traffic volume the probability of a breakdown increases. However there is no maximum traffic volume that causes a breakdown when the volume is increased by one unit. Figure 5 shows the different breakdown probabilities for given flow rates. A higher volume leads to a higher probability of breakdown but a break down is never inevitable.

Figure 5 Probability of breakdown at given traffic flows, highway intersect 400 in Toronto

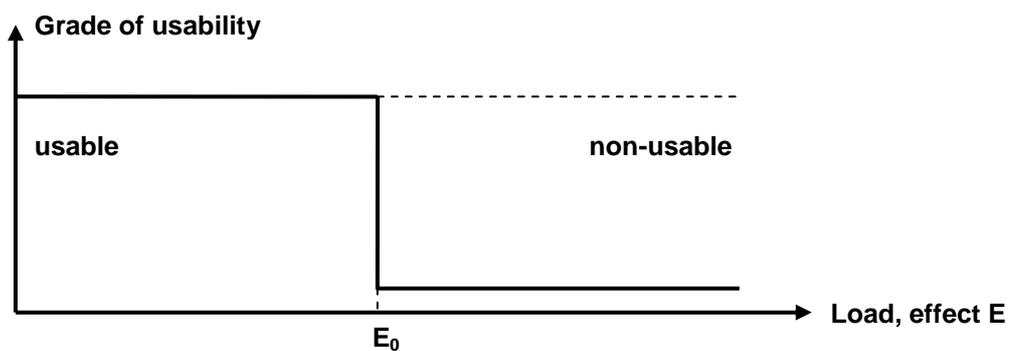


Matt and Elefteriadou (2001)

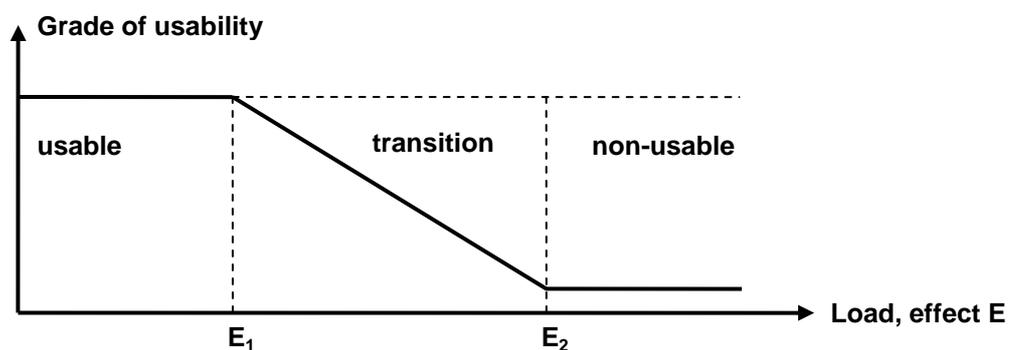
## 2.2 Usability of systems

If a load (e. g. traffic flow) is near to or higher than the resistance (e. g. capacity) of the system its usability may change in various ways. A sudden breakdown of the system could follow after which the system is no more usable. Considering a transport-engineering example like a road with an increasing traffic flow a continuous degradation might be expected. These two different reactions of the system (on an increasing load) are shown in Figure 6 (a and b). This transition from a usable to a non-usable system may be permanent or reversible. For most systems in transport engineering the transition will be reversible (see Figure 7).

Figure 6 Transition from usable to non-usable systems



(a)

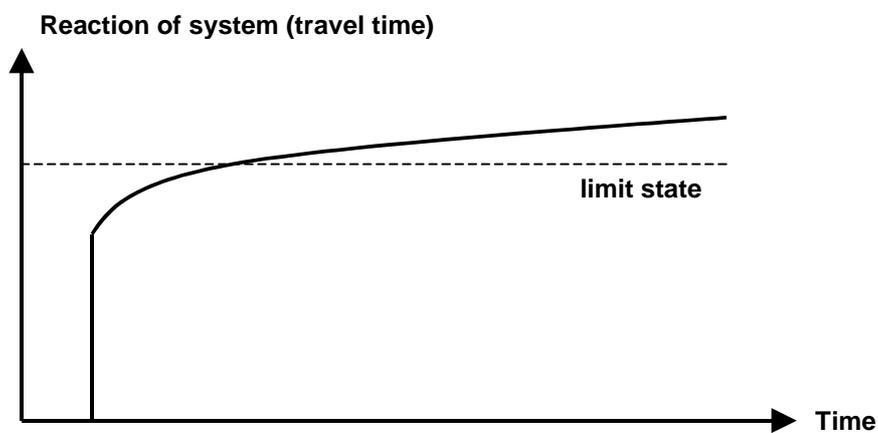


(b)

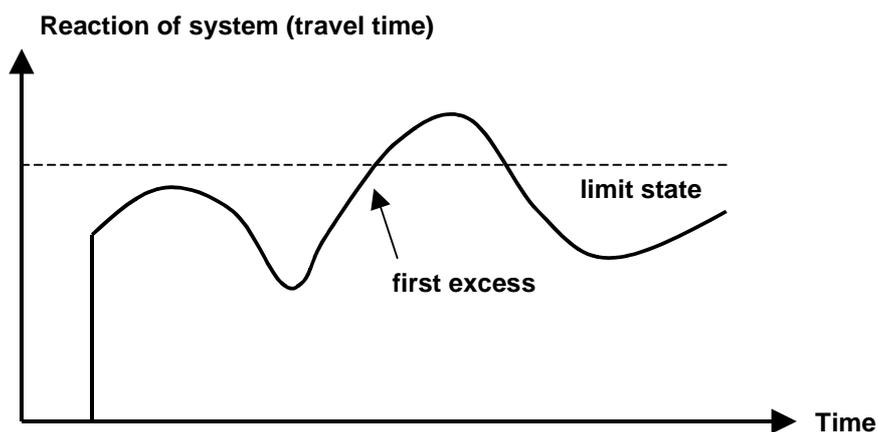
Gulvanessian et al. (2002)

As the dimensioning could not be reduced to a single design load, which the system is capable to handle, the reversibility must be regarded in the design concepts. In transport engineering these systems produce increasing generalised costs if the load (traffic flow) is increased. In addition to that the load could exceed the capacity several times within a time range at different extends.

Figure 7 Transition from usable to non-usable systems



(a)



(b)

Gulvanessian et al. (2002)

## 2.3 Design concept using random variables

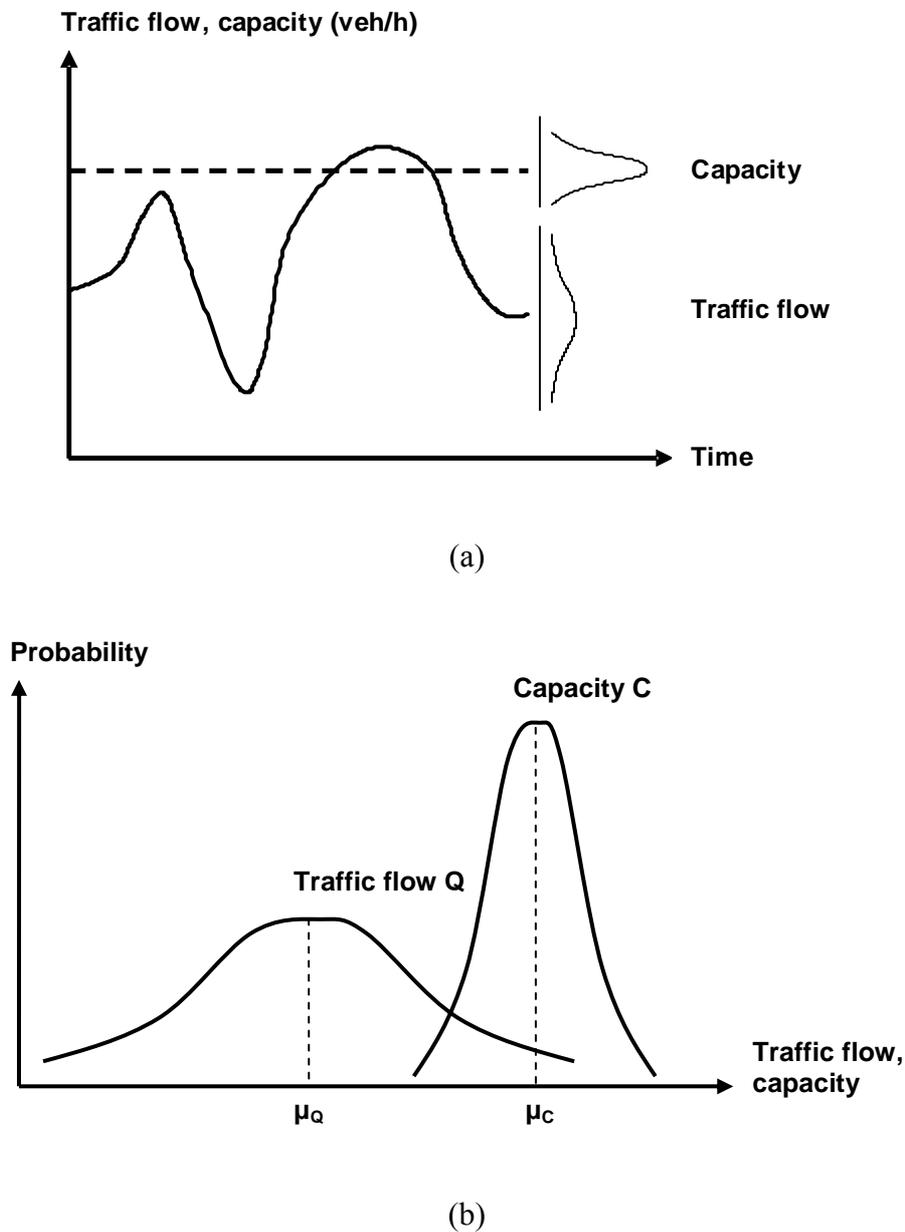
For new design concepts it seems obvious that the capacity cannot be seen as a fixed value but as a random variable (see Matt and Elefteriadou, 2001; Brilon and Zurlinden, 2003). As a result of this, different design concepts have to be found in transport engineering. In other engineering sciences similar scenarios with random variables exist. For example the design concept of the Euro-Norm (EN) in construction engineering gives an idea of the techniques (see Gulvanessian et al., 2002).

The general model is shown in Figure 8. The upper graph (Figure 8 a) shows the link between the hitherto existing model of a fixed capacity and a mean traffic flow to a model consisting of random variables. Both traffic flow and capacity are not described by their mean (estimated by measurements) but by a probability density function.

These probability density functions must be defined for each condition that is to be analysed. As known from the norms (e. g. VSS, 1999; HBS 2001; HCM, 2000) the (mean) capacity varies inter alia due to the percentage of heavy vehicles, the incline, as well as weather conditions. Also density function of the traffic flow (or more precisely the demand) must be defined for each traffic condition. Generally speaking the traffic flow could vary between zero and the capacity (or even above capacity, depending on the definition). A distribution function for this interval describes the average traffic volume, which may not always be useful for a detailed design of transport infrastructures. If data or information about the time series of hourly volumes is known it is reasonable to use conditional probability density functions.

A qualitative example of a traffic state with the corresponding (conditional) probability distributions of capacity and traffic flow can be seen in Figure 8 b. The mean traffic flow is denoted with  $\mu_Q$  and the mean capacity with  $\mu_C$ . As both factors are random variables there is some overlap of both of the density functions even if the traffic flow is much lower than the capacity. Using common methods this situation would not cause any influence to the flow conditions. But it could be seen in the figure that there is a probability that the traffic flow (or demand) exceeds the capacity. This probability is the basis of the EN-design concepts and can be used for a new design concept in transport engineering.

Figure 8 Traffic flow (demand) and capacity as random variables



## 2.4 Derivation of new basic design concept

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  $f_Q(x)$ . The infrastructure element fails to work properly (e. g. travel time increases by an unacceptable factor) if an actual traffic flow  $q$  exceeds its actual capacity  $c$  ( $q$  and  $c$  could be seen as 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 could 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, then the probability that Q exceeds C becomes:

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

The capacity C and the traffic flow Q should be defined in the way that both variables are statistically independent. In the structural reliability theory this case is called the fundamental case. 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 could be found. If the safety margin is defined as:

$$M = C - Q$$

and the probability  $P_f$  could be written as:

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

If C and Q are normally distributed then also M is normally distributed with the mean  $\mu$  and standard deviation  $\sigma$  as follows:

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

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

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

$P_f$  becomes:

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

with the reliability index  $\beta = \mu_M / \sigma_M$ .

## 2.5 Distribution of traffic flow

In the following the distribution of the traffic flow should be analysed. It is assumed that coherence exists between traffic flow and the variance of the flow. If the traffic flow is measured for example over an interval of 60 minutes the flows measured within shorter intervals vary from the 60-minute average. The data basis for this analysis consists of 19 counting stations of 10 motorways (“Autobahn”) during 219 days in Switzerland (ASTRA, 2003). The counting stations separated by direction are listed in Table 1.

Table 1 Analysed counting stations on Swiss motorways

Counting station	Kanton	Direction 1	Direction 2	Days, dir. 1	Days, dir. 2
Mattstetten	BE	Zürich	Bern		4
Deitingen	SO	Zürich	Bern	18	7
Bypass Bern Ost	BE	Freudenbergerp.	Vankdorf	16	14
Gunzgen	SO	Zürich	Bern	14	12
Hunzenschwil	AG	Zürich	Bern	12	15
Muttenz, Hard	BL	Augst	Bern	21	13
Grandvaux Nord	VD	Vevey	Basel	8	10
Bern, Felsenviad.	BE	Wankdorf	Lausanne-Vennes	11	10
Mex	VD	Yverdon	Weyermannshaus	8	4
Denges	VD	Lausanne	Morges	14	10

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

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

For each hourly traffic flow  $q_{60,A,t}$  twelve 5-minute intervals  $q_{5,A,t}$  could be identified. To get comparable values from different road types (different number of lanes) the flow to capacity ratios  $r$  are calculated with the capacity  $C_A$  for each position of the counting stations:

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

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

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

The groups  $G_i$  are of following form:

$G_1$ : all  $r_{60,A,t}$  in the range of  $[0; 1/n[$  ,

$G_2$ : all  $r_{60,A,t}$  in the range of  $[1/n; 2/n[$  ,

...

$G_n$ : all  $r_{60,A,t}$  in the range of  $[n-1/n; 1[$  ,

$G_{n+1}$ : all  $r_{60,A,t}$  in the range of  $[1; n+1/n[$  .

As volume to capacity ratios higher than one could as well have been measured, it is likely that more than  $n$  groups could be built. In addition a few groups may not be built (especially those with very low ratios) due to a lack of measurements.

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

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

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

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

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  $J_i$

$$r_{5,G_i} = r_{60,G_i} \quad (\lim_{J_i \rightarrow \infty} (r_{5,G_i}) = r_{60,G_i}) .$$

In the following the assumption should be proved that the 5-minute ratios are normally distributed within their corresponding 60-minute ratios. For a given mean ratio  $r_{60}$  an interval  $r_{60} \pm \Delta r$  is created to gain multiple measurements of  $r_{60}$  within this interval. For three sample intervals the assumption of normally distributed  $r_5$  within their interval  $r_{60} \pm \Delta r$  should be proved:

- a)  $r_{60} \pm \Delta r$  ( $=q_{60}/C$ ) 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 offer enough measurements of the ratio to avoid random effects and the means of the 60-minute ratios differ very little from the means calculated by the 5-minute ratios indicating that the measurements are valid. The statistics are shown in Table 2. The Shapiro-Wilk test demonstrates significant values that indicate a normally distributed variable.

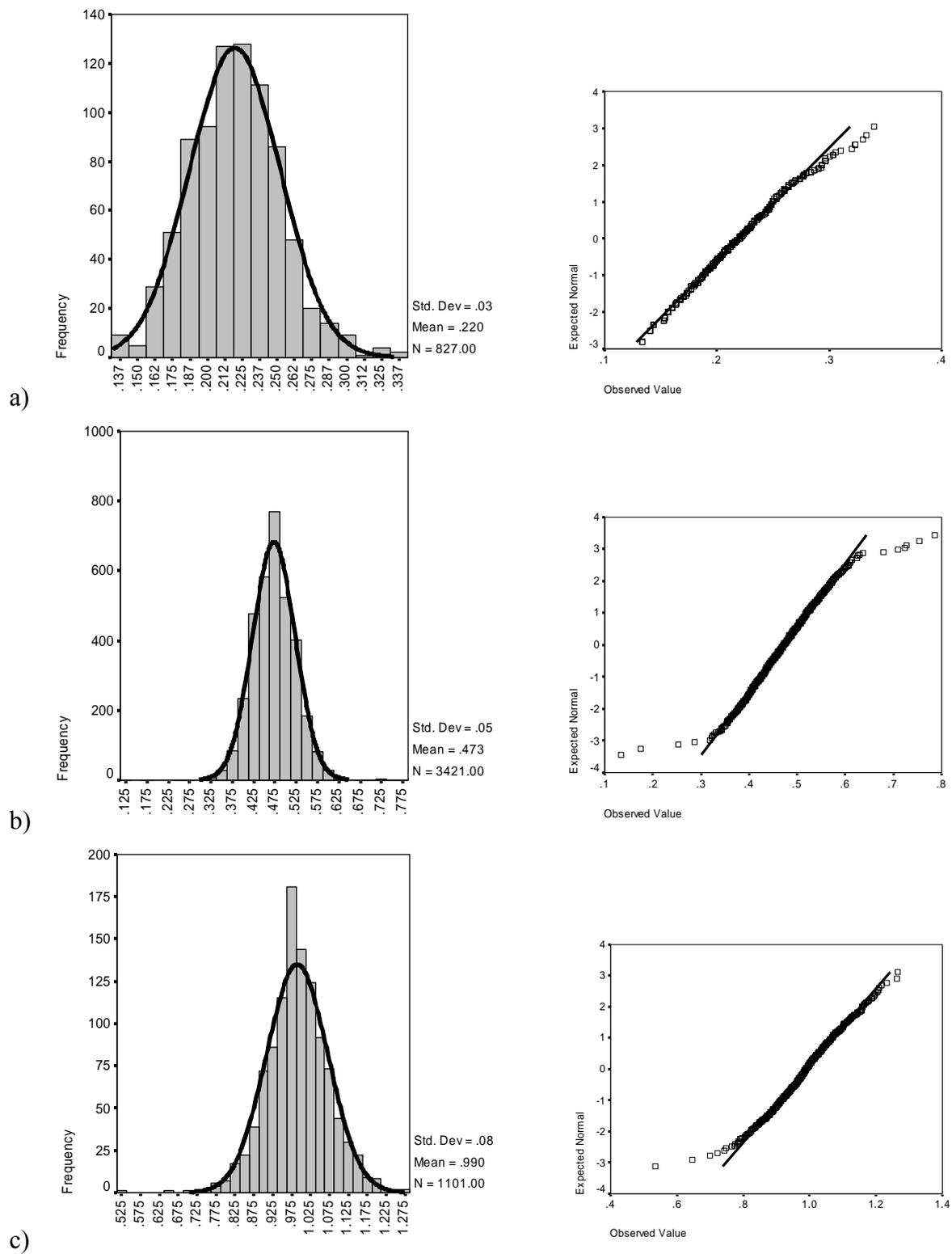
Table 2 Statistics: test of normally distributed 5-minute volume to capacity ratios  $r_5$

Interval of $r_{60}$	Count of means	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 9 shows the graphical analysis of 5-minute volume to capacity ratios as bar charts and normal plots of the three examples a, b and c. In the Q-Q-Plot (normal plot) the theoretical distribution of a normally distributed variable is indicated by the line and 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 with only little difference.

It could therefore be said that the hypothesis of the  $r_5$ -ratios being normally distributed within their 60-minute means can be accepted.

Figure 9 Normally distributed 5-minute volume to capacity ratios ( $r_5=q_5/C$ ):  
Bar chart and normal-plot for three  $r_{60}$  intervals

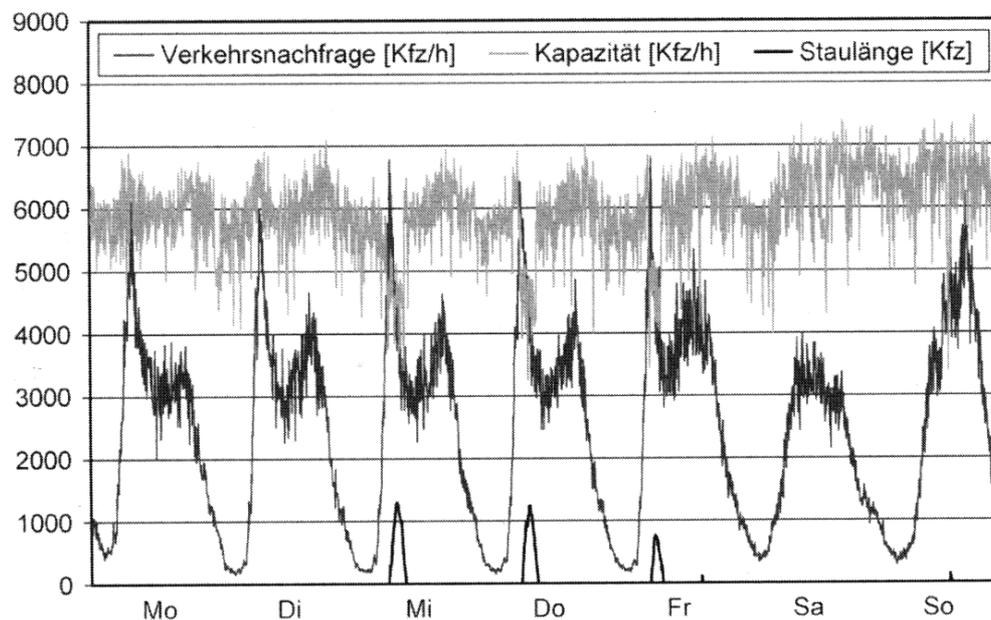


## 2.6 Application

A new design concept is to be embedded into a cost benefit analysis to measure the effectiveness of the investment costs. It is therefore in many cases not favourable to neglect the highest hourly volumes, as it is done with the 30<sup>th</sup> hourly volume method. In many cases especially these high-demand-hours produce the largest percentage of generalised cost over a year. This does not necessarily mean that the transport infrastructures must be able to handle the largest traffic flows, but they have to be taken into account.

Brilon et al. (2004) described an analysis of the traffic conditions of one year on motorways using a macroscopic Monte-Carlo simulation based on traffic volumes. One simulation run for one week can be seen in Figure 10.

Figure 10 Monte-Carlo simulation run of traffic flow for one week  
Traffic flow, demand (Verkehrsnachfrage) in vehicles per hour: grey  
Capacity (Kapazität) in vehicles per hour: black  
Queue length (Staulänge) in number of vehicles: black, bottom graph



Brilon et al. (2004)

A simulation of the traffic for one year gives good information about the expected generalised cost (in this example queuing cost). However this method puts a lot effort into computational power, as many runs are needed to calculate the expected value of queuing length. Having a look at Figure 10 it seems obvious that there are only few potential intervals that could cause

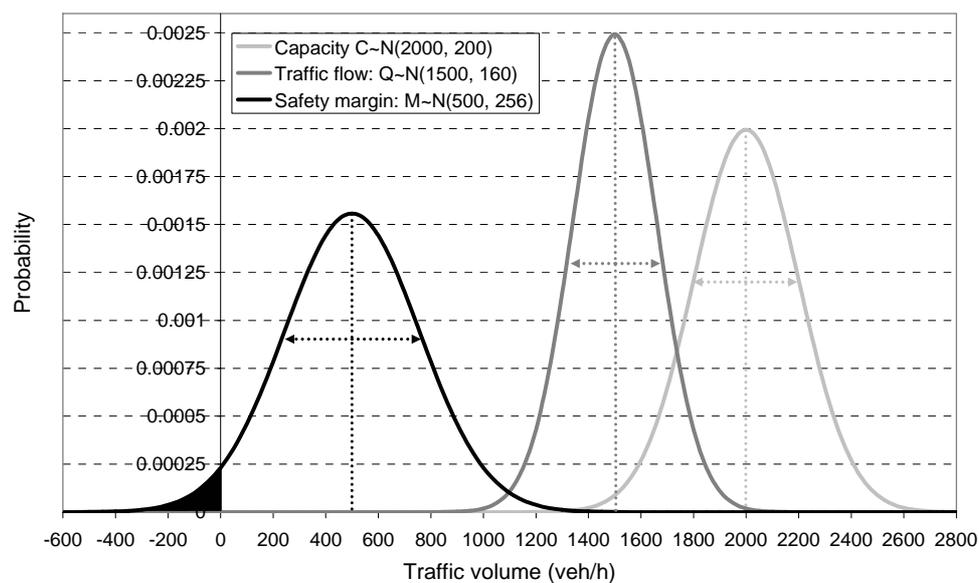
queuing. Considering only the above mentioned traffic states, the amount of calculations needed could be dramatically reduced. An analysis of the frequency of occurrences of traffic volumes at certain states (i. e. weekdays, at night, various weather conditions) will give factors ( $\psi$ ), which will weight the calculated cost of these traffic scenarios.

The generalised cost produced by vehicles that cannot be handled by one network element (queuing) could easily be calculated by the new design concept. This can be done by using traffic flow and capacity as random variables. The safety margin  $M$  was defined as:

$$M=C-Q$$

and can be compared to a probability density function of the differences  $\Delta$  of realisations of  $C$  and  $Q$ :  $\Delta = c - q$ . This means that  $\Delta$  is negative for realisations of  $C$  and  $Q$  where the actual capacity is smaller than the actual traffic flow. In these cases the network element could not handle the current traffic volume. The distribution of the safety margin  $M$  can be used as a proxy for the level of service for a given traffic scenario (see Figure 11). 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 could be graphically interpreted as the marked black area below zero on the x-axis in Figure 11.

Figure 11 Probability density functions of capacity, traffic flow and safety margin



Moreover with the given safety margin it is possible to compute the number of vehicles that are likely not to be handled by the network element within a given time interval. As safety margin  $M$  denotes the random variable built by calculating the difference of  $C - Q$ , the difference  $\Delta = c - q$  can be interpreted as the number of vehicles that could not be handled in the case that  $\Delta$  is smaller than zero. Hence the number of vehicles that are likely not to be handled is given by the negative expected value of  $M$  being smaller than or equal to zero with the probability density function of  $M$   $f_M$  equal to the failure probability function  $f_{Pf}$  and the number of vehicles queuing  $N_{queue}$ :

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

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

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 capacity.

In the example given in Figure 11 with  $C \sim N(2000, 200)$ ,  $Q \sim N(1500, 160)$  [vehicles/hour] and therefore  $M \sim N(500, 256.125)$  the expected number of vehicles that cannot be handled will be:  $N_{queue} = 2.47$  vehicles per hour.

### Example:

Estimated demand of a morning peak: 7:00 – 8:00 h:  $\mu_{Q7} = 1600$  veh/h,  $\sigma_{Q7} = 160$  veh/h,  
 8:00 – 9:00 h:  $\mu_{Q8} = 1900$  veh/h,  $\sigma_{Q8} = 160$  veh/h,  
 9:00 – 10:00 h:  $\mu_{Q9} = 1400$  veh/h,  $\sigma_{Q9} = 140$  veh/h,  
 estimated capacity during this scenario: 7:00 – 10:00 h:  $\mu_C = 2000$  veh/h,  $\sigma_C = 200$  veh/h.

Before and after the given time window the estimated demand is small enough that queuing costs could be neglected. The expected number of vehicles that could not be handled by the given road will be calculated in the following steps:

$$\begin{aligned} 7:00 - 8:00 \text{ h: } q = 1600, \quad sd(q) = 160 &\Rightarrow \mu_M = 400, \quad \sigma_M = 256.12 \\ &\Rightarrow N_{queue} = 6.51 \text{ veh/h;} \\ 8:00 - 9:00 \text{ h: } q = 1906.51, \quad sd(q) = 160 &\Rightarrow \mu_M = 98.82, \quad \sigma_M = 256.12 \\ &\Rightarrow N_{queue} = 60.28 \text{ veh/h;} \\ 9:00 - 10:00 \text{ h: } q = 1460.28, \quad sd(q) = 140 &\Rightarrow \mu_M = 539.72, \quad \sigma_M = 244.13 \\ &\Rightarrow N_{queue} = 1.16 \text{ veh/h.} \end{aligned}$$

The value  $N_{\text{queue}}$  is of the unit vehicles per hour. As in this example the time intervals are equal to one hour, the number of vehicles that could not be handled by the road within the morning peak scenario is the sum of the three partial  $N_{\text{queue}}$  values.

## 2.7 Structure of new design concept

The principals of the presented design concept base on a comparison of the generalised costs of two or more planning scenarios (usually the status quo and a modification of the existing system). The evaluation consists of following steps:

- Definition of capacity
- Estimation of demand
- Identification of possibly “critical” scenarios  $S_i$
- Estimation of frequency  $f_i$  or probability  $p_i$  of occurrence of scenarios (e. g. over one or 20 years)
- Cost calculation (calculation of queuing length) for each scenario  $C_i$
- A proxy for the total cost is calculated by the sum over all  $p_i \cdot C_i$ .

In contrast to the concept of the 30<sup>th</sup> hourly volume concept, which is neglecting the cost of the 30 highest traffic volumes, this concept takes all traffic volumes – or more general all traffic scenarios – into account. Here the intervals with the highest traffic are regarded as these volumes produce a large amount of the total generalised cost over each year.

## 2.8 Outlook

The presented design concept can be applied with little modification to most infrastructure elements. Its big advantage over existing concepts is its scalability in accuracy. The more detailed the demand and capacity estimations are, the more reliable are the results. On the other hand this concept needs quite detailed information about the shape of the demand which has to be analysed. In addition, in this paper the capacity is assumed to be normally distributed within a time window. It has to be verified whether this assumption is true or the error in this assumption is small, as a normally distributed variable simplifies the calculation. Brilon and Zurlinden (2003) assume that capacity can be described by the Weibull-distribution. They evaluate the probability of a breakdown in traffic flow to estimate the capacity. But they neglect the different distributions of the traffic flow at different states. As the (relative) standard deviation of the traffic flow is not the same for each mean traffic flow,

the breakdown probability is also influenced by this variation. This means that the findings of the breakdown probability measurements probably may not be assigned to the problem discussed here.

The method introduced here may require a redefinition of the capacity. In the Swiss Norm the capacity of an infrastructure element is defined as the largest traffic volume that is expected to be passing this section within a given time interval under given road, traffic and operation conditions. Therefore this definition is coherent with the definition needed for the presented design concept.

To integrate this method into a cost-benefit analysis the (additional) travel times due to high traffic volumes and especially queuing have to be assessed. Therefore it has to be evaluated whether common functions like the BPR-function could be applied or different methods have to be found.

One remaining problem is the integration of the proportion of heavy vehicles into this concept. As the percentage of heavy vehicles influences the behaviour of the traffic flow and not really the capacity, it is questionable if a reduction factor should really be bound to the capacity or if this factor should rather be connected for example to the traffic flow. In the concept presented here, it is assumed that the traffic flow and the capacity are independent variables and that an influence of the traffic flow on the capacity has to be avoided. A solution to this problem is the introduction of safety or reduction factors ( $\gamma$ ) that are easy to implement into this concept and will be a topic of the current research.

### 3. Literature

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