

Reliability of Motorway Operation

Werner Brilon

Abstract

Traditionally, traffic on highways is planned and operated with respect to the objectives safety, efficiency, ecology, and cost effectiveness. Meanwhile, however, the target of reliability is turning out as a dominating aspect of traffic performance. It is also creating an advanced sophistication for traffic engineering with the consequence of modified engineering strategies.

What do we understand under the term “reliability”? In the field of highway traffic engineering we subsume as reliability the probability that a highway facility can be used with a sufficient performance which reasonably can be expected as a minimum by road users. This level of traffic quality can be described e.g. for a motorway by a travel speed of 80 km/h over longer distances. On one side regular speeds beyond this level, usually, have no significant benefit to the road user. They are, however, taken into account by traditional economic appraisal procedures. On the other side traffic breakdowns with significantly lower speeds would rather impede drivers’ activity pattern and carriers’ production processes and will, thus, cause significant detriments for the roads users. Usually these breakdowns do not occur on a regular basis. Instead they occur from time to time. The economic loss caused by these occasionally events may sum up to large amounts. Thus, transportation management should more and more focus on these losses caused by bad reliability.

Analysis for German motorways revealed, that delays to traffic are caused to nearly equal proportions by temporary oversaturation, work-zones, and accidents/incidents. These occasional events are the source of major economic losses. To reduce these disprofits a bundle of actions might be taken which go far beyond the traditional approach of traffic engineering. Some solutions as

examples for technical approaches can be: traffic adaptive speed control, ramp metering, overtaking restrictions for trucks, etc. However, in many cases organizational approaches become far more efficient than technical solutions. Examples are: demand management, intelligent workzone scheduling, variable tolls, changes of rules for the police to clear places of accidents and incidents, penalties for drivers or vehicles owners who block the road by incidents or accidents, and others. Moreover, education of drivers towards smooth traffic behaviour may improve the reliability under traffic demand levels near capacity. Within these activities, everything which helps avoiding accidents supports reliability since an accident is always a major source of impediments to traffic flow.

Some mathematical methodologies help to understand and describe reliability of highway operation. Here, breakdown probabilities are a key approach.

These ideas lead over into analysis of traffic operation on motorways for a whole year (whole year analysis, WYA) as the methodology to analyse the combined effects from traffic engineering therapy and organisational treatments. WYA can also include effects of weather, accidents, and incidents on traffic performance. This approach to modern traffic engineering by reliability is receiving increased attention in several countries worldwide.

1. Introduction

Traditional objectives of highway design and operation are safety, traffic efficiency, economic efficiency, and environmental sustainability (cf. Table 1). If we focus on traffic efficiency, the traditional way of understanding is illustrated in Figure 1. We see regression lines representing empirical data points in the speed-flow domain. The maximum flow described by these regression lines is treated as the highest possible throughput of the motorway section which we call capacity. In the guideline procedures for the assessment of traffic flow performance like the German HBS (HBS, 2001) - this capacity is only analyzed for one single peak hour. The American HCM (HCM 2010) treats only the peak 15-minute interval. Such a short interval, then, is representing the performance of the motorway over its whole lifetime. The other 8759 hours of the year are neglected.

Objective	Measure of effectiveness(example)
Safety	Accident cost rates
Traffic efficiency	Average speed of passenger cars
Economic efficiency	Ratio: benefit / costs
Environmental sustainability	Miscellaneous indicators

Table 1 Objectives for highway design and operation

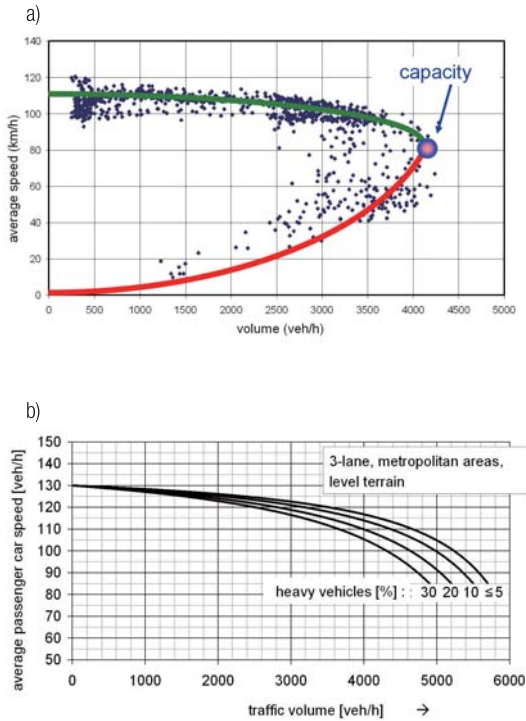


Figure 1 Speed - flow diagram

- a) for a 2 - lane motorway (2 lanes on one directional roadway); empirical values
- b) for a 3 - lane motorway; standardized curves obtained from the draft 2012 of the future German Highway Capacity Manual (HBS 201X, 2012)

The methods being used focus on average circumstances in traffic flow. In reality there is, however, a lot of fluctuation in traffic performance over time and from place to place.

These traditional approaches for traffic performance assessment incorporate a lot of limitations:

- One single peak hour can not represent the whole lifecycle of the infrastructure.
- The highest traffic demands are not taken into account.
- Average speed – as a measure of effectiveness – is not of too much importance to the road users, since an increase in speed does only generate a very small reduction in travel times. Such small amounts of savings in travel time can not be used by the road users for productive activities. Thus, increases in average speeds do not reveal economic benefits. Exactly the opposite, however, is assumed for economic appraisal calculations for infrastructure investments in most countries.
- Moreover, only proper operation of the motorway is taken into account. There is no consideration of disturbances by work-zones, accidents, incidents, or weather.
- Finally, the traditional methods can not account for overloaded conditions (LOS F; LOS = Level of Service) which can not be avoided in the metropolitan motorway networks.

These negative aspects are such important that we need a completely new approach to traffic performance analysis in practice. A new set of measures of effectiveness is required to evaluate traffic efficiency. The new concept should focus on the intrinsic purpose of the motorway network. This is not driving with high speed. Instead, the fundamental purpose of the motorway network is to bring people and cargo from their origin to their destination within a reasonable time. The term “reasonable” must be defined for each traffic facility according to its characteristics. Usually this reasonable time should be that travel time which is achieved if the system runs under capacity conditions.

The new concept must also be able to incorporate realistic conditions as there are accidents, incidents, work-zones, and usual variability of weather, since these deviations from ideal conditions are part of the normal operation of motorways.

To come to such a new approach we should start from the real and main objective of road users: They want to arrive at their destination within a time margin which they can reasonably expect. This applies both for passengers and for cargo. What can they reasonably expect during peak hours? For a motorway this should be the travel time resulting from traffic flow conditions close to capacity. What road users do suspect at most are remarkable delays beyond the reasonable travel time. Such remarkable delays might impede the purpose of their trip significantly.

E.g.: If a driver on the access to the airport would be delayed by one hour with the consequence of missing his plane then the whole trip may be worthless to him. If he would only lose 10 minutes this might not be too severe. Therefore, the value of the lost one hour would be extremely high whereas the 10 minutes would not cause a loss to him. Or: if a truck is operating within a just-in-time supply chain, his 1-hour delay might impede the operation of the whole system whereas a 10 minute delay might be tolerable and not causing any loss. Thus the long delays are the most critical problems to motorway users and the value of time for one complete hour is much higher than the value of 6 times 10 minutes.

2. Definition of reliability

Under these aspects we come to the term of reliability of traffic flow on motorways, which mainly means the reliability of travel times. The term reliability, however, is not easy to handle. In many circumstances just the standard deviation of travel times is proposed to represent reliability. However, a variability of travel times is unavoidable and only large deviations far beyond the average are decisive for unreliability (cf. Figure 2). Therefore, the frequently recommended variance of travel times is only a rather weak representation of reliability. A wider set of performance measures expressing reliability is discussed by Shaw (2003).

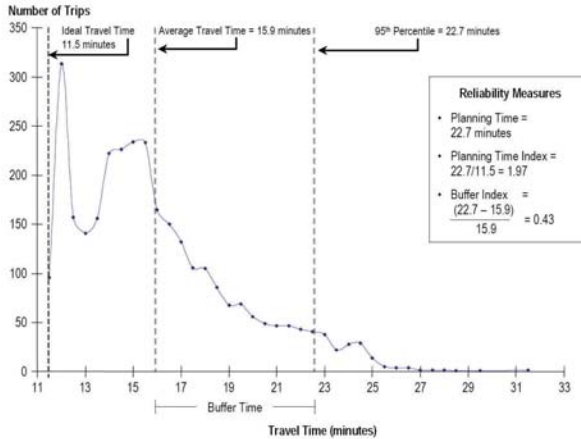


Figure 2 Example for a distribution of travel times (obtained from FHWA, 2005)

A definition of reliability should explain the risk of a remarkable delay since large delays are the objects of unreliability. Therefore, as a basic and more general definition, reliability could be defined as the probability that the system operates at a performance level equal or better than a defined minimum standard. This minimum standard could be incorporated as that level which, usually, is accepted by the public, e.g. LOS D according to guidelines like the HCM (2010) or the HBS (2001). Instead of LOS D also the margin between LOS E and LOS F might be used since this – in most of the international guidelines – is defined as the border between flowing and congested traffic on motorways, which is a more objective factum than LOS D which evolves from subjective definitions.

In this sense e.g. the reliability of a motorway section would be 98 % (or 0.98) if congestion occurs on this link during 2 % of the time.

Beyond this basic definition also more concrete measures might be used to characterize reliability, as there are:

- Probability of congestion (time of congestion / total time)
- Delays per year due to congestion and traffic overload
- Duration of all congestions per year

- Diverse ratios of maximum travel time (or of parameters representing the maximum, like 95th percentile) to average travel time
- and others (see e.g. FHWA, 2005; Shaw, 2003; Margiotta e.a., 2006; cf. Figure 3).

- **variability of travel times**
 - **variance of travel times**
 - **95th percentile of travel time**
 - **travel-time index (TTI)** $= \frac{\text{average travel time}}{\text{travel time (free flow speed)}}$
 - **planning time index (PTI)** $= \frac{95\% - \text{travel time}}{\text{travel time (free flow speed)}}$
 - **buffer index** $= \frac{\text{expected maximum (lost time)}}{\text{travel time (free flow speed)}}$
- **percent of on-time arrivals**
- **sum of lost times due to congestion**
- **probability that a driver experiences congestion**
- ...

Figure 3 Measures for reliability (obtained from FHWA, 2005, and Shaw, 2003)

Unreliability is caused by traffic breakdowns. A breakdown is the operation at speeds and volumes below those characterizing capacity conditions. Such breakdowns can be caused by

- demand exceeds normal capacity
- work-zones with reduced capacity
- incidents (e.g. vehicle malfunction, lost load, ...)
- accidents
- bad weather (rain, storm, ice/snow, bad visibility)
- failure of infrastructure
- other events like: festivals, sporting events, catastrophes, ...

Examples for the relative frequency of sources for congestion on motorways are illustrated in Figure 4.

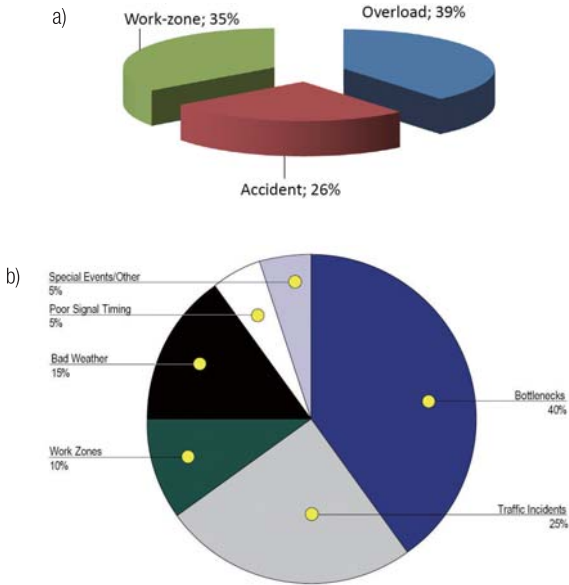


Figure 4 Observed reasons for breakdowns on motorways
 a) in Germany (Wiss. Beirat BMVBS, 2009) b) in the USA (FHWA, 2005)

On this background reliability is a function of

- basic capacity of the infrastructure
- maintenance of the infrastructure
- performance of control systems
- qualification of operational staff and of technical equipment
- quality of vehicles
- behavior of drivers
- weather
- ...

Domain of responsibility

Provider of the infrastructure

Road user

force majeure

3. Two basic features of transportation systems

There are two basic features valid for each transportation system which are important in the context of reliability. The first is the non-linearity of traffic performance. Figure 5 shows an example of the dependency between average delay and the degree of saturation ($x = \text{traffic demand} / \text{capacity}$) for some kind of traffic facility. We see that up to an x of 0.6 the increase of demand does not significantly affect the delay. However, near and beyond capacity (i.e. $x \approx 1$) small increases in demand cause large increases in delay.

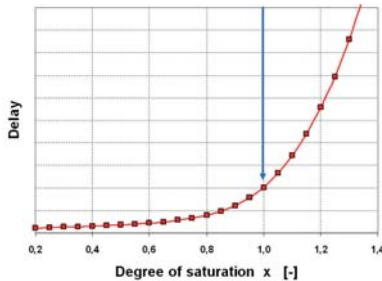


Figure 5 Non - linear relation of delay depending on the degree of saturation

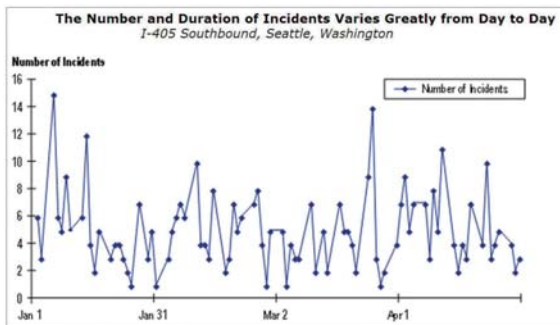


Figure 6 Frequency of disturbances on the I405 in Seattle, USA (FHWA, 2005)

The other feature is: normal operation - like designed – is happening quite seldom and may even be an exception. E.g. in Germany always more than 10 % of the motorway network is under modernization, which means: more than 10 % of the total length is a work-zone with reduced capacity. In addition to that incidents and accidents occur quite frequently impeding normal traffic flow (cf. as an example Figure 6).

4. Randomness of capacity

One rather important aspect for reliability is that the capacity of a motorway facility has not a constant value. As an example Figure 7 shows the traffic volume at one point of a 2-lane (per direction) motorway over one whole day in 1-minute intervals (blue lines, scale on the left). In addition we see in red the average speed as a pattern over the whole day (scale on the right). We see that there were several breakdowns during the day, where the speed dropped rather suddenly to quite low values. Simultaneously also the volume drops. The volumes immediately before the breakdown are marked by a red circle. It can be obtained that these “breakdown volumes” vary over a rather significant range. If we assume that these volumes were the highest which the highway could accommodate at this time and that the breakdown was caused by a further increase of demand, then we find that the capacity showed a large variation at this day.

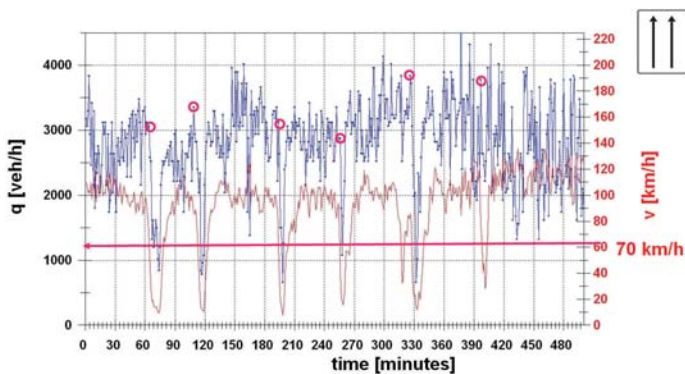


Figure 7 Patterns over time: traffic volumes and average speeds in 1 - minute intervals on a 2 - lane motorway

Figure 8 shows a similar effect from another motorway by the speed-flow diagram. We see again that the breakdown-volumes are distributed over quite a wide range of traffic volumes.

If we follow the dynamics of traffic breakdown and recovery through the speed-flow diagram we always get a picture which is characterized by the schematic diagram in Figure 9. If under fluent traffic conditions, volume is fluctuating, this causes only slight differences in speed (stable flow). Breakdown from fluent traffic can occur at higher volumes, but not necessarily from the highest possible volume. Breakdown leads to a flow which can be called synchronized, since traffic on all lanes has similar speeds. This condition with still rather large volumes and median speeds might be maintained for a significant period. But it can also break down to congested flow with low volumes and low speed (congested flow). From there traffic conditions can recover up to the synchronized flow and from there back to fluent traffic, where the volume of recovery is usually lower than the range of breakdown volumes (= hysteresis phenomenon).

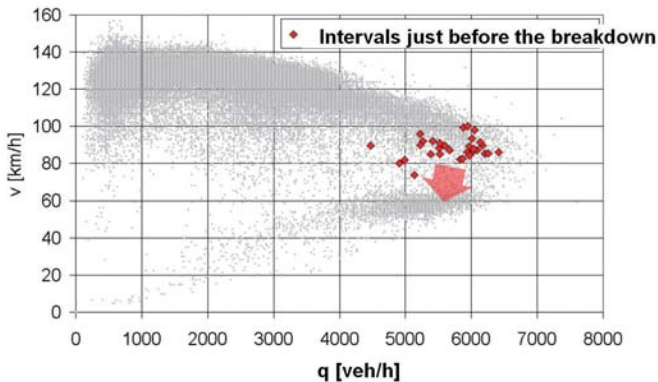


Figure 8 Speed - flow diagram for a 3 - lane motorway in 5 - minute intervals for a whole year. Breakdown - intervals are marked by red dots. These are only breakdowns which have not been caused by a queue spillback from downstream.

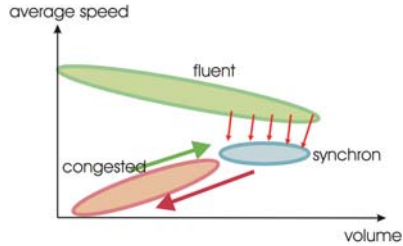


Figure 9 Schematic speed - flow diagram

The important aspect at this point is that the breakdown volume could assume different values (indicated by the red arrows in Figure 9). Since these values do not follow specific regularities they can be treated as random variables. Brilon e.a. (2005) have treated this matter. They have proposed to describe this random variable by a Weibull - distribution where the parameters can be estimated applying a maximum likelihood technique (for more details: see Brilon e. a. 2005 and 2007).

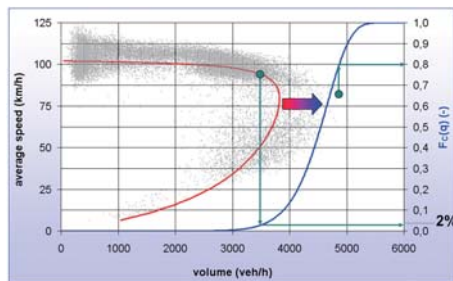


Figure 10 Speed - flow diagram in 5 - minute intervals for a 2 - lane motorway opposed to the corresponding capacity distribution. The speed - flow data points from a whole year are represented by a van - Aerde - curve (van Aerde, 1995)

The application of this concept is illustrated in Figure 10. Here we see a speed-flow diagram together with the capacity distribution function. The right green point is focused on the maximum observed volume. The distribution function tells us that at this point there is a probability of 0.8 that the traffic breaks down (which did not happen in this case). The left green point marks the volume of 90 % of the capacity (in the conventional meaning). Here the distribution function tells us that traffic might break down with a probability of 2 %.

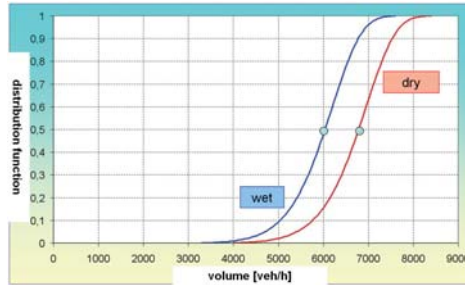


Figure 11 Comparison of the breakdown probability functions for dry and wet road surface on the same motorway (3 lanes, daylight, 5 - minute intervals).

Another example for application is given in Figure 11 for a comparison between wet and dry road surface. Here we see that the probability functions are shifted by nearly 800 veh/h which means: under wet road conditions the capacity on average is about 12 - 15 % lower than with dry road surface.

5. Whole year analysis (WAY)

So far we have only treated breakdown and congestion under normal conditions. In addition also disturbances due to incidents, accidents, and work-zones (which all reduce capacity for a specific period) should be taken into account. The question, however, is which time period should be presumed for the analysis of reliability. Here most authors come to the conclusion that one whole year is a good approach since it should represent all the circumstances which happen to traffic on the motorway over its lifetime or over the visible period for planning.

To simulate these varying circumstances a Monte-Carlo simulation is proposed (Zurlinden, 2003). Here the variability both of capacity and traffic demand can be imitated. The capacity can be generated by a random number generator using a Weibull-distribution. The demand can be represented by typical patterns over time (for a week and for days in the week) whereas the daily demand over the year should be represented by patterns observed in the past on the same motorway or – in case of planning a new section – from comparable links in the network.

Random variability to the demand over time, as it occurs within 5-minute intervals, then can be represented by a factor which is normal distributed (Gaussian white noise; $N(1, 0.1)$).

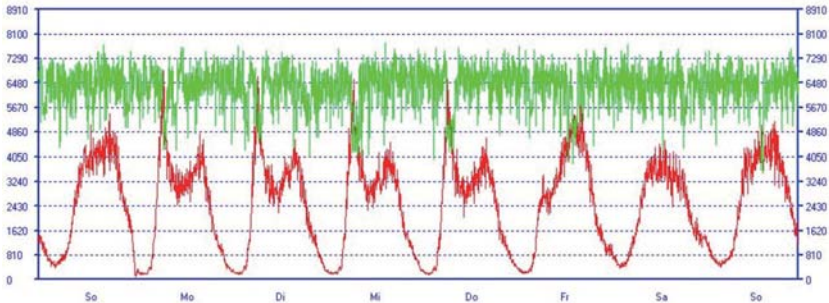


Figure 12 Pattern over time for capacity (green) and demand (red) generated for the WYA in 5 - minute intervals (extract for one week).

In addition to the variability in capacity and demand also accidents, incidents, or even weather conditions (like rain, according to meteorological records) can be modeled as random events.

Also the so-called capacity drop can be included. This is a reduction of capacity which may occur under congested conditions.

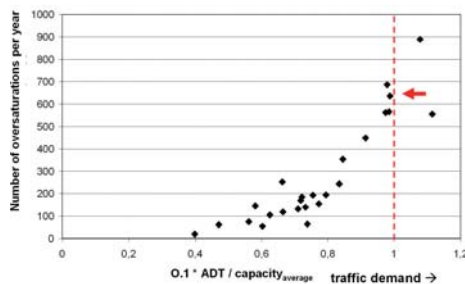


Figure 13 Number of traffic jams per year as a function of traffic demand (expressed as ADT in relation to capacity); result from WYA - calculations for a 2 - lane motorway section.

To model the consequences of demand and capacity within each section of the network and within each time interval models of different precision can be applied. Initially a simple deterministic queueing model was applied (Brilon e.a., 2005 and 2007). More recently also a set of continuity models for traffic flow, which are expected to provide a higher degree of precision, come into use (Brilon e.a., 2010).

As results estimations of the following figures can be worked out:

- duration of congestion
- sum of all delays
- number of vehicles involved into congestion
- economic value of lost times
- parameters according to Figure 3.

Each parameter is obtained as expectation over the whole year or even as expectation for specific periods of the day. As an example, Figure 13 shows how the number of congestions per year increases with larger traffic demands (expressed as demand-ADT). The figure tells us: if the ADT (average daily traffic) is 10 times the average capacity (capacity in the conventional meaning of Figure 1) then around 650 cases of congestion per year (or roughly 2 cases per day) must be expected.

By performing the computational analysis with and without specific assumptions (e.g. with/without the assumptions for accidents) the effects of these assumptions can be estimated; e.g.

- effects of accidents or incidents
- effects of traffic control devices
- effects of specific organizational improvements (like fast accident removal, work-zone management, traffic demand management, etc.)
- effect of structural improvements (like adding a lane, hard shoulder running, etc.)

This kind of analysis has meanwhile been successfully applied in the state of Hessen in Germany.

6. How can reliability on motorways be improved?

The more important instruments in the toolbox of engineers to improve the reliability of motorway traffic are:

- Improve the physical capacity by a sufficient number of lanes at each point along the network.
- High-quality construction of the infrastructure with the consequence of less maintenance
- Adequate traffic control
- Hard-shoulder running
- Work-zone management
- Emergency management (accidents and incidents)
- Demand management
- ...

There is not enough space to discuss all of these points in detail. Thus, in the following only some remarks are given.

6.1 Sufficient capacity

The most effective policy towards reliability is to provide sufficient road capacity by the adequate number of lanes at each point along the motorway. In Germany the widest type of a motorway has four lanes for each direction (Figure 14 b). However there are only rather short sections of this width. Most of the network has only two lanes and significant parts have also three lanes.

The question usually is which dimensions of a motorway are needed. To find an answer it may be useful to analyze the so-called traffic efficiency, which denotes the number of “vehicle*kilometers” driven per hour on a stretch of the motorway (see also Brilon, 2000). This is the term which describes the production of the motorway per time unit. For the operator of the motorway this term should be of higher interest than the volume. Figure 14a describes this term (expectation of traffic efficiency in [veh*km/h], scale on the right; method of calculation see: Zurlinden, 2003 or Brilon e.a., 2005) as it depends on traffic volume. Here it is compared to the classical speed-flow diagram. Analysis reveals that the maximum efficiency must be expected at a degree of saturation x (= demand traffic volume / classical capacity) of 0.9. This result – with

sufficient accuracy – can be generalized for all types of motorways. This is a reason why in the German guideline HBS (2001) the level of service D is terminated at $x = 0.9$.

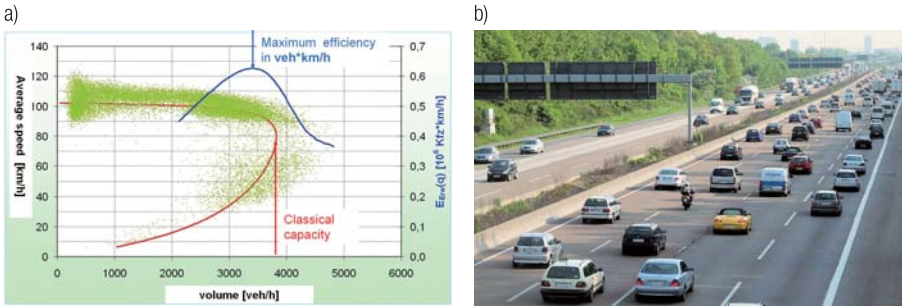


Figure 14 a) Efficiency depending on traffic volume b) 4 - lane motorway A5 south of Frankfurt

Also for traffic control this value should become a target. E.g. by metering ramps the total traffic on the motorway might be limited to this x -value, to generate the maximum utility from the highway infrastructure both under the aspects of road users as from the view of the motorway operator. A toll motorway, for instance, would generate the largest revenues if this target would be gained.

6.2 Hard shoulder running

Hard shoulder running means that the hard shoulder is opened for traffic during peak hours by variable traffic signs (Figure 15). In off-peak times, however, the hard shoulder may not be used – except in case of an emergency or vehicle breakdown. This off-peak use of the hard shoulder is maintained (instead of a permanent lane) to increase safety.



Figure 15 a) Hard shoulder running (HSR) b) End of HSR section

This type of operation must always be combined with a speed limit of 100 km/h as a maximum. It provides a 25 % increase of capacity at a 3-lane (+shoulder) motorway. (For more details see: Lemke, 2003 and Geistefeldt e.a., 2010).

6.3 Work-zone management

Work-zones usually cause a rather significant reduction of capacity. Figure 16a demonstrates this for a 3-lane motorway. On average in this example the capacity is reduced by 9 %. There are, however, also examples where capacity is decreased by 17 % during times of roadway rehabilitation.

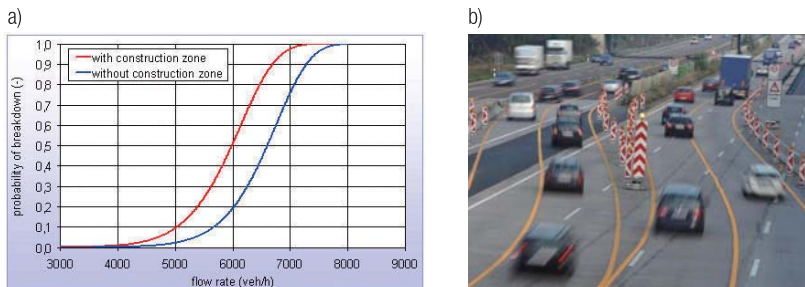


Figure 16 a) Capacity distribution function for a 3-lane motorway (blue) compared to a work-zone with one of the three lanes switched over to the opposite roadway which then carries 4 lanes (4 + 2 system) b) Begin of work-zone at a 4-lane motorway (6 + 2 system)

Since these impediments are not completely avoidable their effect should be kept in minimum margins. This can be achieved by reducing the duration of works. For this purpose rewards might be paid to the construction firms if they manage to keep duration of work short. Also the scheduling of works can reduce the implication on traffic. Works of short duration may be executed during night and weekends and long-time work may be allocated to vacation season. These steps may, however, be in conflict to costs, technical requirements, financial aspects, legal regulations etc. Therefore, a trade-off between working requirements and traffic impacts should be performed. Here the macroscopic simulation (in the style of the above mentioned WYA) turns out to be a very useful tool.

6.4 Safety and incident management

Each accident reduces the capacity of the motorway for a specific period. Therefore, each activity which reduces the risk of accidents is an important contribution to reliability.

The reliability is also improved significantly by all arrangements which reduce the duration of incidents and accident removal. The duration of lane closures (in consequence of accidents) can be reduced by modified strategies for the coordination between police, rescue teams, and road workers. Modern technical recording systems - e.g. 3-D-cameras - can reduce the duration of on-site police investigations of an accident. Both the rescue teams and the attorney's offices should be trained towards larger sensibility for delays suffered by road users to reduce the duration of their work on the site.

In severely saturated sections of the network the continuous presence of one or even more tow-trucks may be useful to remove broken-down or slightly damaged (by collisions) vehicles immediately. In one example of a severely overloaded motorway section WYA-calculations revealed a reduction of delays (resulting from quick vehicle removal by a tow-truck positioned near the motorway) comparable to the effects of an expensive widening of the motorway. In practice, positive experience with tow-trucks patrolling in the motorway network has been gained in Houston/Texas (FHWA, 2005).

There are also considerations to charge owners of broken-down vehicles and even crashcausing vehicles for the value of time lost by other road users. These

charges should discourage drivers from risky behavior and cargo operators from using degraded vehicles.

6.5 Smoothing traffic flow

Several activities are in use to achieve a smooth traffic flow and to avoid any turbulence under saturated traffic conditions. Among these approaches, variable speed limits are the first choice. Here the speed limits are displayed by variable message signs. The level of the limit is selected by an algorithm which takes into account: traffic volumes, percentage of trucks, weather, special events, information about the situation downstream, etc. Also prohibition of overtaking for trucks may be indicated (e.g. for flows > 2000 veh/h on a 2-lane section). These algorithms in Germany are designed separately for each case of application.

These variable speed limits are rather successful on motorway sections with frequent congestion. Even if they do not increase capacity by remarkable amounts, they usually contribute to a significant reduction of delays due to congestion. Regler (2004) reports about a reduction of delays due to congestion of 40 % induced by variable speed control.

What is even more important is the significant contribution to a reduction of accident risks by variable speed control: Siegner e.a. (2000) found a reduction of nearly 30 % (as an average) in accident rates by a before/after study at 10 traffic actuated speed control sites on German motorways.

A problem at variable speed limits, however, is speed enforcement. It is not trivial to coordinate police speed cameras with the displayed speed limits, especially during times of transitions between two speed levels. Therefore, speed enforcement with variable speed limits is still an exception.



Figure 17 Examples for traffic adaptive speed limits.

Speed enforcement under stationary speed limits is also a significant contribution to smoothen traffic flow – however only, if the given limit is in harmony with the local conditions. Here, section control would provide the most significant contribution (KfV, 2012). This is, however, not allowed in Germany due to privacy considerations.



Figure 18 Ramp metering.

Another method to reduce turbulence in traffic flow and to avoid congestion is ramp metering. This, in Germany, is in intensive use in the state of Northrhine-Westphalia. As a generalized experience, times of congestion could be reduced to 50 %, average speed increased by 10 km/h, and the frequency of severe accidents was diminished by 25 % (numbers obtained from the state-DOT). With these figures ramp metering is one of the most significant contributions to traffic reliability on motorways (see also: Jacobsen e.a. 2006).

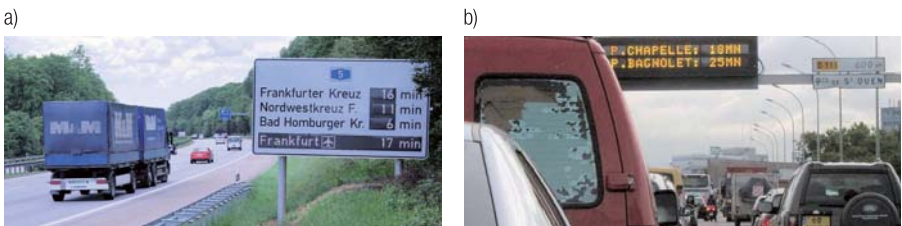


Figure 19 Display of travel times
 a) on the A5 near Frankfurt b) in Paris/France.

Another quite effective action may be the indication of expected travel times to specific destinations. This concept has first been applied in France. Meanwhile it is also used in other countries. The idea is: during times of undisturbed operation the displayed travel time will tell the drivers that hurry is not necessary to arrive in due time. During congested periods, which means display of very long travel times, the driver learns that he has no chance to escape from the expected delay. Thus again, he has no motivation to hurry. Both effects will contribute to less hectic traffic flow and, thus, may also contribute to traffic safety.

In the same sense also on-board navigation systems may affect drivers. From those the drivers may sooner or later learn that fast driving will not lead to a remarkable reduction of the travel time which is indicated (as the expected arrival time) by the navigation system.

6.6 Buffers in the system

It is desirable to avoid spillback of traffic queues from one link within the system into other parts of the network during times of congestion. A spillback beyond upstream interchanges may multiply the negative effects of congestion, when traffic jam is spreading out over several links. Therefore, reliability is improved by buffers imbedded into the motorway network. These are areas where vehicles can be stored in cases of link overflow without impeding other sections of the network.

There is also one additional aspect: Freeway sections offer the largest capacity as long as traffic is fluent (cf. Figure 9). As soon as traffic breaks down the throughput is getting much smaller (capacity drop). Therefore, a breakdown must be avoided as far as possible to achieve the largest possible productivity of the network. To achieve this objective, there should be areas where overflow demand can be stored temporarily. This happens e.g. on the entrance ramps at ramp metering sites. Also tollgates at toll motorways are sometimes used in this sense. It would also be useful to provide such areas upstream from critical sections within the network (cf. Brilon, 2009).

6.7 Demand management

Reliability would also be improved if traffic demand during peak periods could be reduced. Usually it can be assumed that there are many drivers who could choose another time to start their trip without any problem or to use a less sensitive route. These drivers should be motivated to avoid critical routes at critical times.

It is expected that systems of road pricing which charge higher fees during peak hours would be the most effective tool to achieve this goal (Tsekeris, Voß, 2009). This is, however, not applicable in countries where the access to motorways is completely free, like in Germany for passenger cars. But also on toll roads (e.g. tolls are charged from trucks on motorways in Germany) such a time-dependent toll charging is not easily feasible due to political reasons.

Another idea to reduce peak hour traffic demand may be to reward people who do not use motorways during the peaks. Such a scheme has been tested in Netherlands under the name “spitsmijden”. The effect, however, was limited whereas the costs summed up to remarkable amounts (spitsmijden, 2009).

Other attempts to motivate drivers to modify their time of departure, e.g. their start for driving to work, rely on driver information. Several cities, e.g. the city of Seattle (WA/USA; see <http://www.wsdot.com/traffic/traveltimes>), cultivate internet sites to inform their citizens and visitors about expected travel times for the desired departure time and for alternatives to deter them from driving during the extreme peaks.

7. Conclusion

Among all objectives regarding traffic on motorways, safety deserves to remain number one. Beyond safety, all considerations about measures of effectiveness for motorway traffic flow lead to the conclusion that reliability is the most important aspect. It is, however, a complex task to define parameters characterizing reliability.

A mathematical understanding of breakdown probabilities is a key to reliability management. Whole year analysis (WYA) is the adequate method to assess reliability.

Reliability is the instrument to unite improvements of infrastructure and of more organizational (soft) actions under one umbrella. Parameters characterizing reliability always assess the consequences of both kinds of activities in planning and operation of motorways. Thus reliability paves the way towards coordinated improvements in infrastructure improvements, traffic control devices and strategies, and organizational improvements. It helps to assess the consequences of overloaded conditions (LOS F).

Activities aiming on better reliability usually are also effective regarding traffic safety and vice versa. Thus, safety and reliability are two sides of the same medal.

References

- Brilon, W. (2000): Traffic Flow analysis beyond traditional methods. 4th International Symposium on Highway Capacity, Maui, Hawaii, TRB Circular E-C018, pp. 26 - 41
- Brilon, W. (2009): Road pricing as a marketplace. Paper presented at the 2ISFO (2nd International Symposium on Freeway and Tollway Operations), Honolulu
- Brilon, W., Geistefeldt, J., Regler, M. (2005): Reliability of Freeway Traffic Flow: A stochastic Concept of Capacity. Proceedings of the 16th International Symposium on Transportation and Traffic Theory, pp. 125 – 144, College Park, Maryland, Elsevier, ISBN 0-08-044680-9
- Brilon, W., Geistefeldt, J., Zurlinden, H. (2007): Implementing the concept of reliability for highway capacity analysis. Transportation Research Record, No. 2027, pp. 1 - 8
- Brilon, W., Geistefeldt, J., Wu, N., Estel, A. (2010): Modelltechnische Erweiterung von KAPASIM Hessen (Model Extension of KAPASIM-Hessen). Ruhr-University Bochum und Hessisches Landesamt für Strassen- und Verkehrswesen- Verkehrszentrale Hessen, final report
- Elefteriadou, L., Kondyli, A., Brilon, W., Hall, F., Persaud, B., Washburn, S.: Ramp Metering Enhancements for Postponing Freeway Flow Breakdown. TRB Annual Meeting 2011, paper 11-3082, 2011
- FHWA (2005): Traffic Congestion and Reliability. Trends and Advanced Strategies for Congestion Mitigation. Report by Cambridge Systematica, (http://www.ops.fhwa.dot.gov/congestion_report/congestion_report_05.pdf)
- Geistefeldt, J., Glatz, M. (2010): Temporäre Standstreifenfreigabe: das Beispiel Hessen in Deutschland (Temporary hard shoulder running: the example Hessen in Germany). Strasse und Verkehr (Swiss) no. 12, pp. 24 - 27
- HBS (2001): Handbuch für die Bemessung von Strassen (German Highway Capacity Manual). FGSV, Cologne
- HBS 201X (2012): Handbuch für die Bemessung von Strassen (German Highway Capacity Manual). Draft 2012, unpublished, FGSV, Cologne
- HCM (2010): Highway Capacity Manual. Transportation Research Board, Washington D.C.

- Jacobson, L., Stribiak, J., Nelson, L., Sallman, D. (2006) : Ramp Management and Control Handbook.
FHWA(http://ops.fhwa.dot.gov/publications/ramp_mgmt_handbook/manual/manual/pdf/rm_handbook.pdf)
- KfV (2012): 10 Jahre Section Control in Oesterreich (10 years of section control in Austria).
(<http://www.kfv.at/kfv/presse/presseaussendungen/archiv-details/artikel/3257/>)
- Lemke, K. (2003): Temporäre Umnutzung von Seitenstreifen an Autobahnen (Temporary use of hard shoulders on motorways). Strassenverkehrstechnik, no. 8, pp. 409 - 413
- Margiotta, R., Lomax, T., Hallenbeck, M., Turner, S., Skarbadonis, A., Ferrell, C., Eisele, B. (2006): Guide to Effective Freeway Performance Measurement, Final Report and Guidebook, NCHRP web-only document 97;
(http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w97.pdf)
- Regler, M. (2004): Verkehrsablauf und Kapazitaet auf Autobahnen (Traffic flow and capacity on motorways). Institute for Transportation and Traffic Engineering, Ruhr-University Bochum, no. 28, ISSN 1437-8299
- Siegener, W., Traeger, K., Martin, K., Beck, T. (2000): Unfallgeschehen im Bereich von SBA unter besonderer Berücksichtigung der Verkehrsbelastung (Accidents with variable speed signs with special attention to traffic volumes); series „Forschung Strassenbau und Strassenverkehrstechnik“, no 787
- Shaw, T. (2003): Performance measures of operational effectiveness for highway segments and systems. NCHRP Synthesis 311, Transportation Research Board
- Spitsmijden (2009): The effects of rewards in Spitsmijden.
(<http://www.spitsmijden.nl/>)
- Tsekeris, T.; Voß, S. (2009). Design and evaluation of road pricing: State-of-the-art and methodological advances. Netnomics 10, pp. 5–52.
- Van Aerde, M. (1995): A single regime speed-flow-density relationship for freeways and arterials. 74th TRB Annual Meeting, TRB, Washington D.C.

- Wiss. Beirat BMVBS (2009) : Zuverlaessigkeit der Verkehrssysteme (Reliability of Transportation Systems). Consulting paper by the Scientific Advisory Board to the Federal DOT, Germany, published in: Strassenverkehrstechnik, no. 1 und 2, 2009
- Zurlinden, H. (2003): Ganzjahresanalyse des Verkehrsablaufs auf Strassen (Whole year analysis of traffic flow on highways). Institute for Transportation and Traffic Engineering, Ruhr-University Bochum, no. 26, ISSN 1437-8299

Author

Prof. (em.) Dr.-Ing. Werner Brilon
Ruhr-University Bochum, D-44780 Bochum, Germany
E-mail: werner.brilon@rub.de