Improvements in Traffic Management by using a Control Algorithm based on the Probability of Breakdown

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Abstract
Capacity is one of the relevant values to describe traffic flow on freeway segments. It depends on various conditions such as roadway, traffic, environment and control conditions. In the past, capacity was defined as a deterministic value for given base conditions. Newer research studies, however, prove that capacity has to be interpreted as a stochastically distributed value. The more the traffic flow increases the higher the risk of traffic breakdowns. These characteristics can be used in traffic management applications. An algorithm was developed which is able to anticipate traffic breakdowns and this way allows a preventive control of the traffic flow. In order to deploy the control algorithm into a superior traffic management system, the fundamental evaluation methods were introduced. The designed methods validate the algorithm’s core operation and additionally assess the quality aspects regarding the particular traffic management tasks. The initial results based on the data from Austrian freeways showed that the developed traffic breakdown prediction approach can be successfully employed as a traffic management strategy for predicting capacity events.

KEYWORDS: Probability, Breakdown, Traffic Management, Traffic Control Algorithm, AIX-ProB, ASFINAG

Introduction
Capacity as well as velocity and volume play an important role in rating procedures for the determination of the level of service of traffic systems as well as in traffic control. In recent research, however, capacity is regarded as a probabilistic value, as a temporally variable value that is and not as a deterministic value. An approach for the stochastic description of the capacity is the identification of the breakdown probability. Here, the number of intervals followed by an immediate drop in speed is compared to the number of intervals at smooth traffic flow for traffic classes. Therefore, for each classification of volume, the number of intervals after which a breakdown in velocity immediately occurs within the next interval is compared with the number of intervals with still fluent traffic. The relationship thus describes the risk of a drop in speed for a certain traffic volume.

The capacity of a traffic system depends on different influencing variables. In principle, these variables can be divided into roadway, traffic, environment and control conditions. An important influence on the traffic quality and thus on the capacity emanates from different weather and environmental conditions and should thus be integrated into the strategies for management, control and securing of the traffic flow. These characteristics of traffic that are further investigated in [1] shall be used in traffic management applications. Therefore, an algorithm to improve the speed controls for traffic harmonization was introduced in [2]. A first evaluation based on an extensive test data basis with historic, real offline data is done in [1]. The proposed algorithm was implemented in a
Improvements in Traffic Management by using a Control Algorithm based on the Probability of Breakdown

traffic control system operated by ASFINAG (the national operator of the entire Austrian motorway and expressway network), in order to identify the probability of breakdown.

In the scope of this paper the new control algorithm for traffic management systems will be tested with regard to its stability and suitability in practical application by means of empiric data from Austrian freeways. Focal point of this paper is the evaluation of the implemented algorithm with real online data in a regular, productive scenario. The aim is to set up a universally valid procedure clearly describing the algorithm’s quality measures like control completeness, legitimacy or timing precision. These measures are fundamental for the users (traffic control centres and agencies) in order to determine the expected algorithm performance and outline its benefits.

Probabilistic Description of Capacity

The probability of breakdown of a specific traffic volume can be defined as the quotient from the number of intervals which are directly followed by a breakdown in speed and the number of the intervals at fluent traffic. With the probability of breakdown the risk for a breakdown in speed can be determined for a specific traffic volume.

The probability of breakdown \( p_{c,j} \) at a specific traffic volume \( j \) is determined by the comparison of the number of \( m_j \) and the number of intervals \( n_j \) at fluent traffic:

\[
p_{c,j} = \frac{m_j}{n_j}
\]

with \( n_j \) = number of intervals at fluent traffic \( m_j \) = number of the capacity events that occur at fluent traffic \( m_j \in n_j \)

Figure 1 presents the probability of breakdown in comparison to the traditional fundamental diagram (here: van Aerde Model, dashed curve). The capacity events (black dots) are contrasted with the intervals at fluent traffic using the above mentioned formula and this way the probability of breakdown is determined.

Empiric insights concerning capacity as a probabilistic value were already gathered. In Germany, a commonly used method to determine capacity distributions is based on PLM (e.g. [3], [4], [5], [6]). [7] used the probability of breakdown based on synthetic data to give a stochastic definition of capacity.

Further empiric studies concerning the probability of breakdown were made in the USA and Japan (e.g. [8], [9], [10], [11]). Empiric insights from the German speaking world for the description of capacity with probabilities of breakdown are not available at this point.

**Figure 1: Comparison between fundamental diagram (volume/velocity) and the probability of breakdown**

Application for Line Control Management

Preventive, dynamic speed reduction can delay and reduce congestion and can significantly
Improvements in Traffic Management by using a Control Algorithm based on the Probability of Breakdown

increase traffic safety [12]. Precondition for effective traffic management before traffic breakdown is a reliable anticipation of traffic flow. Goal of preventive speed reduction is to avoid incidents by the use of harmonizing traffic. Besides the actuality of traffic prediction, the spatial gap between detector and signage is relevant for the effectiveness of preventive speed reduction. For these purposes, the algorithm AIX-ProB (Anticipation of Incidents with extended Probability of Breakdown) was developed.

In order to set up a procedure for the determination of the probability of breakdown on freeways, first of all an automated method is needed which is able to identify traffic breakdowns by means of the traffic data. This method has to be solid towards short-term ups and downs of the traffic volume and speed values which have not been smoothed. Apart from this, it should be applicable universally at all detection sites without an extensive parameterization, but nonetheless be able to account for regional characteristic features such as grades or functions of the section.

Besides the identification of capacity events $m_j$, the intervals at stable traffic conditions $n_j$ have to be determined. Therefore, each interval of the time series (as input, short term flow and velocity data of detection sites are required) has to be classified by the following classes:

- Capacity Events $Q_C = m_j$
- Congestion $Q_S$
- Stable Traffic Flow $Q_F$, with $n_j = Q_F + Q_C$
- not classifiable intervals $Q_E$ (e.g. due to errors, unclear situations)

Additionally, the occurring situation for each interval has to be determined. Typically, all influencing factors on capacity should be considered, such as type of traffic (commuter or recreational traffic), prevailing weather situation, visibility (daylight or darkness), seasonal period (winter, summer), traffic variation during the day (morning/afternoon peak hours, off peak hours), road works, incidents and others, if applicable. Basic precondition is that the factors taken into account must be directly measurable or automatically determinable. The resulting situation type is always a combination of all considered sub types (e.g. “weekday with commuter traffic, dry surface, morning peak hour”).

So for each measured interval two classes can be assigned: (a) traffic state and (b) situation type. Based on that information, for each situation type the probability of breakdown can be derived with $m_j$ and $n_j$ for each flow class. With the specific probability of breakdown for different flow classes, by means of linear regression analysis the resulting probability of breakdown curve can be derived. All these calculations can be performed offline based on historic data. In order to assure actuality of the results, a mechanism to disregard the oldest values and integrate the most current data into the determination of the breakdown curves is implemented. The algorithm is thus self-learning. The results of this offline data acquisition are:

- probability of breakdown curves (for usage in traffic control algorithms or traffic engineering studies)
- traffic state for each interval (for further traffic engineering studies)

For all locations, the curves of probability of breakdown for 1 min, 5 min and 15 min intervals are continuously updated, i.e. all data is analysed and grouped in dependency of prevailing conditions. The specific curves to determine the current probability of breakdown are available in a data base.

Second part of the algorithm is an online component to calculate proposals for speed control management. In that component, online traffic data (flow) and the prevailing situation type is needed as input data. Based on the current situation, the corresponding breakdown curve can be chosen. With the measured flow, the prevailing probability of breakdown for the next intervals can be derived directly from the curve. This value is compared with a “strategic” parameter that determines the reaction of the corridor management system. The strategic
Improvements in Traffic Management by using a Control Algorithm based on the Probability of Breakdown

parameters determine the corresponding speed limit that is displayed to the road user. The higher the probability of breakdown, the more restrictive the displayed speed limit so that the corridor management system is able to avoid traffic breakdown by harmonizing traffic. This way, the algorithm enables the corridor management system to act preventively on the traffic flow.

If the proposed speed reduction is more restrictive than the occurring one (set in previous intervals), the new speed reduction is set for a certain period of time (hysteresis, e.g. 3min). It disappears automatically if there was no new activation trigger set within that period of time. The resulting proposed speed limit is compared with the actual traffic speed. If the current mean speed is significantly lower than the proposed speed limit, the final speed limit proposed by the algorithm is adapted accordingly.

Figure 2 shows the data flow of the algorithm. The detailed description of the model to determine a traffic breakdown can be found in [1].

**Figure 2: Data Flow of algorithm AIX-ProB**

### Validation of Algorithm AIX-ProB

The development of validation methods is primarily motivated by the stakeholder needs and aspirations fulfillment. A precise specification of the aspirations and needs enables to effectively aim on the algorithm demanded capabilities, for example the algorithm prediction ability, control timing or reliability. The validation strategy is in principle divided into two steps. First, the focus is put on the Breakdown Recognition investigation as an essential prerequisite for AIX-ProB successful employment. Second, the algorithm performance analysis which consists of the Space Time Analysis and the Detection and False-alarm Rate Ratio is carried out.

**Breakdown recognition**

The description of a traffic breakdown as a transition from a free-flow traffic state into the congested conditions splits breakdown recognition criterion into the two main aspects:

1. Recognition Quality that determines if a transition moment was recognized precisely with a respect to the analysed site.
2. Breakdown Recognition Ability validates whether the recognized breakdowns are reasonable, and on the other hand, whether all the breakdowns were discovered.

The previous description implies that the breakdown recognition validation meets the
Improvements in Traffic Management by using a Control Algorithm based on the Probability of Breakdown

fundamental traffic engineering difficulty rising from the traffic state identification, concretely the problem of disputed situations when an actual traffic state should be considered rather as free flow or when it already belongs to a congested state. Usage of any automatic recognition method – employing likely some combination of actual speed, speed difference, flow rate or occupancy – in this case results in the criteria’s parameterization. The excessive parameterization is in contradiction to the algorithm’s nature and it also decrease criterion robustness. Additionally, it is non-systematic to use another non-validated, untested recognition algorithm to evaluate AIX-ProB’s recognition algorithm that is now a researched object. Having the real traffic data acquired from 104 detectors at the Austrian freeway network, the manual expert validation employing a combination of the fundamental diagram and the speed-time pattern diagram analysis was carried out. A projection of the initially recognized breakdown by AIX-ProB on the fundamental diagram gives a raw overview whether these breakdowns were identified correctly (by analysing a relation between the breakdown and its surrounding intervals position) and thus the algorithm’s recognition ability is outlined. Such a hypothesis becomes more accurate when each breakdown is plotted in the time dimension and its surrounding speed conditions are examined. The speed-time chart delivers a sound mean evaluating the quality recognition aspects.

The previous expertise evaluation was undertaken over the chosen 10 sites where the algorithm within a one month period (June 2012) recognized 69 breakdowns. From the total amount of breakdowns, 65 breakdowns (94%) were evaluated as well recognized.

Analysis in time-space dimension

Whereas the breakdown verification creates an essential prerequisite for successful algorithm running, the analysis in the i, j (time, space) dimension delivers the important operational indicators and outlines an overall algorithm performance. The following table (see Table 1) summarizes the main traits of the analysis.

The results for the introduced criteria are generated over the given time period and roadway stretch with typical 24-hour differentiation. Additionally, the results for the specific sites are provided as well. The algorithm performance can be considered as satisfying when the missing control tends to zero and the speed reduction in time dimension is ranked as excellent. The algorithm can experience a higher rate of the 100 km/h speed reduction mismatches due to the considerable AIX-ProB’s preventive nature, however, the severe mismatches of 30 or 60 km/h have to be minimal.
Improvements in Traffic Management by using a Control Algorithm based on the Probability of Breakdown

**Table 1 – Overview of the time-space analysis**

<table>
<thead>
<tr>
<th>Evaluation Criterion</th>
<th>Principle</th>
<th>Conditions</th>
<th>Used Data</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time relevance</td>
<td>Analyses whether the control is displayed timely and on the other hand, if it disappears sufficiently after congestion.</td>
<td>Before Jam ($\Delta T_\text{J}$)</td>
<td>At recovery ($\Delta T_\text{R}$)</td>
<td>$\text{cng}<em>{i,j}=\text{const.}$ $\text{ctrl}</em>{i,j}=\text{const.}$</td>
</tr>
<tr>
<td></td>
<td>Excellent</td>
<td>5 + 3 min</td>
<td>0 + 2 min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Good</td>
<td>3 + 1 min</td>
<td>2 + 3 min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fair</td>
<td>&gt; 5 min</td>
<td>&gt; 3 min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poor</td>
<td>&lt; 1 min</td>
<td>&lt; 0 min</td>
<td></td>
</tr>
<tr>
<td>Spatial relevance</td>
<td>Counts a number of the intervals where the control appears in upstream early enough before a jam and where the control disappears early after a jam in downstream.</td>
<td>Speed Reduction 100 km/h 80 km/h 60 km/h 100 km/h 80 km/h 60 km/h</td>
<td>$\text{cng}<em>{i,j}=\text{const.}$ $\text{ctrl}</em>{i,j}=\text{const.}$</td>
<td>Analogous to the time relevance criterion - it determines preventive effect with the respect to the spatial extent.</td>
</tr>
<tr>
<td>Control mismatch</td>
<td>Computes a number of the intervals when the specific speed restriction of 100, 80, 60 or 30 km/h is displayed unreasonably</td>
<td>Correct 0 0 + 1 1 0 0 0</td>
<td>$\text{cng}<em>{i,j}$ $\text{ctrl}</em>{i,j}$ $v_{i,j}$</td>
<td>Mismatch criterion indicates the error rate and it also outlines the algorithm reliability according to the required terms.</td>
</tr>
<tr>
<td>Control missing</td>
<td>Determines a number of the intervals where there is no control present despite it is required due to the related traffic conditions.</td>
<td>An interval $i,j$ when no speed reduction is posted and at the same time a $\text{cng}_{i,j}$ value indicates congestion</td>
<td>$\text{cng}<em>{i,j}$ $\text{ctrl}</em>{i,j}$</td>
<td>Important criterion evaluating the algorithm correctness, determining also its operability.</td>
</tr>
</tbody>
</table>

Legend: $\text{ctrl}_{i,j}$ - the one-minute intervals with $i,j$ dimension during which the speed control of 100, 80, 60 or 30 km/h is active; $\text{cng}_{i,j}$ - the one-minute intervals which are determined as congested in the $i,j$ dimension; $v_{i,j}$ - the speed values with $i,j$ dimension with one-minute observation period; $\{i \in I \}$ stands for a one-minute time interval; $\{j \in J \}$ stands for a site number where the numbers are ordered according to sites spatial distribution.

**Detection and False Alarm Ratio**

Detection rate determines what amount of congestion is covered by the control. The false alarm computes an amount of control that is posted unreasonably. The criterion is based on the pattern notation that is showed in Figure 4.

**Figure 4: Detection and False-alarm Rate Analysis Pattern Design**

Once the areas (R, C, C’ and I) are determined, the Detection and False-alarm Rate formulas can be employed:
Improvements in Traffic Management by using a Control Algorithm based on the Probability of Breakdown

\[ \text{Detection Rate } DR = \frac{I}{C} \times 100 \quad [\%] \]

\[ \text{False – Alarm Rate } FAR = \left(1 - \frac{I}{R}\right) \times 100 \quad [\%] \]

Note that the extended congestion pattern (+ ΔT₁, - ΔT₂, + ΔL₁, -ΔL₂) introduces the higher demands on the researched algorithm. The authors set ΔT₁ = 5, ΔL₁ = 1 and ΔT₂ = ΔL₂ = 0 that allows to specifically stress the requirements on the algorithm’s prediction capabilities. Both rates are computed with respect to the actual speed reduction value. Whereas the higher detection and false-alarm rate for the non-severe speed reductions (for example 100 km/h) is expected, the very small values for speed reduction of 30 and 60 km/h are crucial for successful algorithm operation.

Conclusion
The paper presents the possible utilization of probability of breakdown analysis as a tool for traffic management. The authors followed their findings in the previous extensive researches proposing the probabilistic traffic description.

It has been shown that the breakdown probability can be used in traffic engineering applications. The paper presents the variable speed limits control algorithm AIX-ProB with the following main traits:

- AIX-ProB uses only few parameters that are easy to understand.
- In contrast to traditional deterministic control algorithms AIX-ProB’s initial parameterization is fast and it allows to a responsible authority to set the strategic goals – the breakdown probability value (the rest is then self-configured).
- AIX-ProB is self-learning and, therefore, considers temporary and seasonal changes in traffic flow.
- AIX-ProB also considers prevailing weather conditions and traffic composition as well as other influencing factors on capacity.
- AIX-ProB operates anticipatory and is, therefore, suitable for preventive control of traffic flow.
- AIX-ProB describes the capacity is as probabilistic value.

The developed algorithm AIX-ProB enables a preventive interaction on traffic flow. By the use of a dynamic adoption of the suggested speed limit it can be obtained that the resulting speed limit is corresponding to the current traffic situation. So, the algorithm is most effective in case of congestion due to oversaturation.

In order to receive an image about the algorithm performance, complex evaluation techniques were developed. This allows examining the algorithm before it is introduced in real traffic and thus outline the operation indicators same as fundamental quality performance aspects.

The fundamental task was to investigate the algorithm’s traffic breakdown capabilities. This has been done on real traffic data obtained from the Austrian freeway network. The breakdown random nature required the manual assessment of each recognized event. The received results proved good anticipation and recognition abilities of the proposed algorithm.

This is an important outcome for AIX-ProB deployment in wide traffic management practice when in the future the anticipation algorithm would be utilized in a number of traffic control strategies.

Complement to the breakdown analysis, the quality performance evaluation was developed according to the previously discovered freeway network operator aspirations. The Time-Space analysis enables to investigate the required quality measures covering the aspects like what amount of capacity events is not covered, amount of unreasonable control or what is time-relevance of control. These cumulative numerical results, with respect to a specific freeway site and observation period provide to the operator authority not only the algorithm’s quality
Improvements in Traffic Management by using a Control Algorithm based on the Probability of Breakdown

measures but also additional information about the specific freeway conditions (for example it reports a frequent occurrence of short-term capacity events covered by adequate control). The last part of the evaluation delivers the overall quality indicators where Detection rate determines the correctly posted control related the total total amount of capacity events, and False-alarm rate computes the falsely displayed speed limits with respect to the complete control effort. These two indicators clearly describe the overall algorithm quality. This study made it possible to confirm that breakdown probability can be applied in traffic quality evaluation and for traffic control.

References


