Influence of dynamic traffic control systems and autonomous driving on motorway traffic flow

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Abstract
As in many other countries, traffic demand on German motorways is continuously rising, especially during peak hours. Enhancing the road infrastructure by building additional lanes or new motorways is cost-intensive and, due to the complex planning process in Germany, extremely tedious. Thus, the government tries to maximise the performance of the existing infrastructure using dynamic control systems. The development and deployment of autonomous driven vehicles can have positive effects on the capacity of road elements. In this study the effect of dynamic control systems on the traffic flow on motorways is analysed in case studies using microscopic traffic simulation. Furthermore it is outlined that autonomous driving in an environment where access to the motorway is limited to autonomous vehicles only can have a positive effect in terms of higher capacities and more harmonized traffic resulting in fewer traffic breakdowns.

Keywords: telematic system, dynamic traffic control system, dynamic speed sign, traffic flow, motorway, microscopic simulation, autonomous vehicles

1 Introduction

Dynamic traffic control systems have become an effective measure to control traffic on German motorways over the last decades. To estimate the economic feasibility prior to their implementation, cost-benefit analyses are applied, which concentrate on the traffic safety and performance of traffic flow. The traditional deterministic methods of analysis as they are offered in the German guidelines HBS (and also the Highway Capacity Manual (HCM)) do not cover the evaluation of dynamic control systems. Moreover, they cannot regard distinctive local behavioural patterns that may have a significant influence on motorway capacity. However, it is required to predict the effects of a system quite precisely before deciding on implementing a dynamic traffic control system.

In this paper the results of surveys on two motorways sections are presented. In these surveys the effects of dynamic traffic control systems on traffic flow were analysed using microscopic simulation. Additionally the traffic flow on these motorway sections was analysed under the assumption that only autonomous vehicles are using the respective facilities.
2 Telematic Systems on German motorways

Financial resources for the road infrastructure in Germany are limited. On the other hand traffic demand is increasing year by year. The costs to enhance road capacity by building additional lanes are very high and -due to the complex planning process- extremely tedious. Thus, the government tries to maximise the performance of the existing infrastructure. This is aspired by the use of dynamic traffic control systems. In Germany primarily four types of telematic systems are used on motorways:

- Dynamic Traffic Control Systems
- Temporary hard shoulder running
- Ramp metering
- Dynamic Guidance Systems

In this paper the first two of these telematics systems are discussed and therefore described briefly in the following.

Dynamic Traffic Control Systems

Dynamic Traffic Control Systems are used to harmonise traffic flow. These variable signs are able to indicate dynamic speed limits, no passing for heavy vehicles and warning of congestion, work zones or weather conditions. The main functionality, the dynamic speed limit, is varied according to traffic flow, mean speed, or traffic density on the motorway. This harmonizes the traffic flow at high traffic volumes (Pischner, Hangleiter, Lambacher, Trupat, Kühne, & Schick, 2003) and reduces the probability of traffic flow breakdowns (Geistefeldt, 2009)

![Dynamic Traffic Control System](image)

Figure 1: Dynamic Traffic Control System

Temporary hard shoulder running

Using temporary hard shoulder running (THSR) it is possible to increase the capacity of the road segment in peak hours by up to 25% (Geistefeldt & Glatz, 2010). This tool is adapted to the demand, because the hard shoulder is opened for traffic to increase capacity during peak hours, but the hard shoulder is still available for emergencies in the off peak hours.

THSR can be implemented with limited planning and financial efforts compared to the addition of a permanent lane.
To verify whether the hard shoulder is free for use, cameras are applied to monitor the whole section that is meant to be cleared. The variable signs can be set up separately, as it is shown in Figure 2, but integration into a traffic control system increases the acceptance. A dynamic control system may also be needed due to the regulation that a speed limit of 100 km/h as a maximum is required during hard shoulder running.

Figure 2: Sign 223.1-3 (StVO); hard shoulder open for use (1), restricted to emergency use only (2) and end of permitted use ahead (3)

3 Autonomous driving

The capacity of motorways is defined by the number of lanes and their maximum traffic flow between junctions and the maximum possible weaving, entering or exiting traffic flow at intersections. Therefore the capacity depends on the gaps between vehicles. The shorter these gaps are the higher the capacity is. If you assume that an autonomous vehicle is able to drive using much shorter gaps than a human being and still be safe, the capacity should increase using autonomous vehicles. (Friedrich, 2015) points out that the capacity can be increased by about 85 % at the speed of 100 km/h if only autonomous vehicles are using a motorway. This can be reached by a time gap of $t_a=0.5$ s instead of a time gap of $t_h=1.15$ s that is realistic for human time gaps.

Also at weaving, entering or exiting sections on motorways the use of autonomous vehicles should have an effect on the capacity. At these sections not only the time gap between following vehicles, but also the lateral driving behavior has an effect on the capacity. These sections require complex driving maneuvers and decision making by the driver.

To give an outlook what effects on the traffic flow in complex motorway sections autonomous vehicles can have, two case studies are analyzed in this paper. This outlook is given for the maximum effect that can be reached by autonomous vehicles. Therefore a penetration rate of 100 % autonomous vehicles (passenger cars and heavy vehicles) is used in this paper.

4 Microscopic traffic simulation

Microscopic traffic flow simulation has become a popular tool to evaluate traffic flow performance under given external conditions. In urban areas it is commonly used to evaluate the quality of traffic signals and their effect on traffic flow. However, for motorways the application of traffic flow simulation models is still not standard in Germany. In this paper, case studies are presented in which the microscopic simulation has been applied successfully to analyze traffic flow performance on motorways under specific external conditions.

To simulate traffic flow on German motorways the Federal Highway Research Institute (BASt) commissioned the Ruhr-University of Bochum to develop the microscopic simulation model BABSIM
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(Brilon, Harding, & al., 2005). The subsequent versions of the model use fuzzy logic to simulate the driving behaviour that was calibrated for traffic flow on German motorways ((Brilon, Harding, & al., 2007) and (Harding, 2008)). Its parameters can be modified and calibrated to the requirements of any given circumstances.

In the case studies presented in this paper two dynamic control systems (Dynamic speed signs and Temporary hard shoulder runnings) are analyzed and compared to the structural enhancement of the motorway layout. In addition to this an outlook is given what effect autonomous vehicles can have on complex road sections. In the following the implementation of the dynamic control systems and autonomous driving in the microscopic simulation model is described:

4.1 Dynamic speed signs

The Dynamic speed signs have been implemented in BABSIM according to the guideline (MARZ, 1999) using this formula:

\[ Q_{B,P}(i) > Q_{B,zul.v,ein} \text{ oder } [ v_{Pkw,P}(i) < v_{zul.v,ein} \text{ und } D_p(i) > D_{zul.v,ein}] \]  \hspace{1cm} (1)

\[ Q_{B,P}(i) < Q_{B,zul.v,aus} \text{ oder } [ v_{Pkw,P}(i) > v_{zul.v,aus} \text{ und } D_p(i) < D_{zul.v,aus}] \] \hspace{1cm} (2)

with:

- \( Q_{B,P}(i) \) = traffic flow at cross section
- \( Q_{B,zul.v,ein} / Q_{B,zul.v,aus} \) = threshold values for Activation and Deactivation (traffic flow)
- \( v_{Pkw,P}(i) \) = mean speed at measuring cross section
- \( v_{zul.v,ein} / v_{zul.v,aus} \) = threshold values for Activation and Deactivation (speed)
- \( D_p(i) \) = traffic density at measuring cross section
- \( D_{zul.v,ein} / D_{zul.v,aus} \) = threshold values for Activation and Deactivation (traffic density)

The traffic behavior of the BABSIM model has been calibrated for the use of dynamic speed signs by using real traffic data of a motorway section that has been analyzed in another study.

<table>
<thead>
<tr>
<th>Temporary har</th>
<th>3 lanes</th>
<th>4 lanes</th>
<th>3 lanes</th>
<th>4 lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{B,100} )</td>
<td>4800 [veh/h]</td>
<td>5200 [veh/h]</td>
<td>4400 [veh/h]</td>
<td>4800 [veh/h]</td>
</tr>
<tr>
<td>( Q_{B,80} )</td>
<td>5400 [veh/h]</td>
<td>5600 [veh/h]</td>
<td>5000 [veh/h]</td>
<td>5200 [veh/h]</td>
</tr>
<tr>
<td>( v_{80} )</td>
<td>70 [km/h]</td>
<td>70 [km/h]</td>
<td>75 [km/h]</td>
<td>75 [km/h]</td>
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<tr>
<td>( v_{60} )</td>
<td>50 [km/h]</td>
<td>50 [km/h]</td>
<td>55 [km/h]</td>
<td>55 [km/h]</td>
</tr>
<tr>
<td>( D_{80} )</td>
<td>50 [veh/km]</td>
<td>50 [veh /km]</td>
<td>60 [veh /km]</td>
<td>60 [veh /km]</td>
</tr>
<tr>
<td>( D_{60} )</td>
<td>50 [veh /km]</td>
<td>50 [veh /km]</td>
<td>60 [veh /km]</td>
<td>60 [veh /km]</td>
</tr>
</tbody>
</table>

**Table 1: Threshold values for dynamic speed signs**

The traffic behavior of the BABSIM model has been calibrated for the use of dynamic speed signs by using real traffic data of a motorway section that has been analyzed in another study.
4.2 Temporary hard shoulder running

The hard shoulder is activated for use at a traffic flow of 4800 veh/h. At the same time a speed limit of 100 km/h is activated in order to match the requirements of (ARS, 20/2002).

Temporary hard shoulders are not yet fully accepted by drivers as a regular driving lane. Therefore the driving behaviour in the simulation model had to be adjusted for the use of the hard shoulder:

- Heavy vehicles use the hard shoulders just as any other right-hand lane
- Passenger cars enter the hard shoulder only at its beginning
- Passenger cars are not allowed to change onto the hard shoulder through its course, to simulate the lack of acceptance for using the hard shoulders

Using these assumptions a realistic penetration rate of the hard shoulder could be reached. The driving behavior may not be correct at the beginning of the hard shoulder, but the main problem of the case studies in this paper was the weaving behavior at the end of the hard shoulder, which was simulated quite realistic using these assumptions.

4.3 Autonomous driving

The behavioral model implemented in BABSIM is subdivided into small modules, each dealing with one distinct problem or intention of the current driving task. The modules operate independently of each other. Each module provides a situation-based vote for the longitudinal and the lateral movement of the vehicle. Subsequently, the individual votes are combined by applying a procedure that can be described as a virtual fuzzification.

For the assessment of the current driving situation in each module (distance and time gap to the vehicle on front, distances and time gaps to vehicles on adjacent lanes) the well-proven psycho-physical approach by Wiedemann (1974) is adopted. This psycho-physical model uses thresholds where the driver changes his/her behavior meaning that drivers react to changes in spacing or relative velocity only when these thresholds are reached. These thresholds and the regimes they define are determined in the model independently for each driver applying individual parameters (e.g. need for safety, control over the accelerator pedal, precision of speed and distance estimation) that are mostly following a normal distribution. Another key element of the simulation model is the distribution of the desired speed. Each vehicle within the simulation is assigned one value that determines the desired speed depending on the local speed limit. The smaller the variance of the distribution of the desired speed, the more harmony of traffic flow can be observed in the simulation.

Given that machines and sensors are more precise than human beings, a number of adaptations are necessary in order to emulate autonomous driving with the simulation model. For the purpose of this study, the behavioral model was adjusted as follows:

- Need for safety: In the original model, this parameter follows a $N(0.5, 0.15)$ distribution. The higher the value, the more safety distance a driver seeks. As this parameter has a strong impact on the time gaps that result in the simulation, one has to be very cautious when modifying the respective distribution. In theory, it may be assumed that time gaps can be cut in halves in an environment where access to the motorway is limited to autonomous vehicles only. On the other hand drivers will probably still have to be able to intervene and overrule the machine due to legal and safety issues – at least in the near term. Thus, only a moderate reduction of the value (0.4 with a standard deviation of 0) for the need of safety was chosen for the purpose of this study.
- Control over the accelerator pedal. This parameter originally follows a $N(0.5, 0.15)$ distribution. The higher the value, the less control a driver has over the accelerator pedal, which results in a higher deviation between the desired and the actual acceleration.
Assuming that an automatic control of the vehicle is very precise, this parameter is set to 0.01, which means that there is almost no deviation between the computed and the actual acceleration.

- Precision of speed and distance estimation: This parameter originally also follows a $N(0.5,0.15)$ distribution. The higher the value, the better the ability of the driver to estimate speed and distances. Assuming the adoption of high precision sensors for autonomous driving, this parameter is set to 0.99, which is close to a perfect estimate.
- Furthermore, the variance of the distribution of the desired speed can be assumed to be much smaller for autonomous driving. This implies a higher level of compliance and only minor exceeding of the given speed limit. This was incorporated in the simulation by adjusting the mean values and reducing the respective standard deviation for each speed limit.

Overall the described adjustments lead to a more harmonized traffic flow with smaller time gaps.

The general incoming parameters that were used in the case studies, like traffic volume, amount of trucks, speed limits and control parameters for dynamic speed signs were the same in each case to allow a comparison.

## 5 Case Studies

### 5.1 Case Study 1

**Task:**
In this study the traffic flow of a complex motorway section that consists of four entries, five exits and four weaving segments had to be analyzed. A new motorway layout had to be identified to ensure a traffic flow without frequently flow breakdowns.

**Methodology:**
In a traditional way of dealing with capacity limitations, a concept for enhancing the motorway layout, and here especially the layout of entering, exit and weaving segments, was developed to reduce the risk of traffic breakdowns.

Data from loop detectors was used for the calibration of the simulation, which ensured that local characteristics of driving behaviour (like lane choice, speed limit acceptance etc.) are taken into consideration within the simulation.

In Table 2 sketches of the current network and the new concept for the motorway layout are shown. In addition to the traditional approach with structural enhancements the use of autonomous vehicles is analyzed in the current network.
Table 2: Motorway layout in the analyzed concepts

<table>
<thead>
<tr>
<th>concept</th>
<th>description</th>
<th>sketch</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>current network</td>
<td><img src="image1.png" alt="Sketch A" /></td>
</tr>
<tr>
<td>B</td>
<td>new motorway layout</td>
<td><img src="image2.png" alt="Sketch B" /></td>
</tr>
<tr>
<td>C</td>
<td>Autonomous Driving</td>
<td><img src="image3.png" alt="Sketch C" /></td>
</tr>
</tbody>
</table>

**Results:**

In Figure 3 and Figure 4 you can see the speed flow diagrams at two cross sections, as indicated in Table 2. You can see that in the current network the traffic flow breaks down regularly. The new motorway layout produces no traffic breakdowns due to the reduced traffic volume at the bottleneck.

Assuming all vehicles are driving autonomous the capacity of the motorway is significantly higher compared to concepts A and B. There are no regular traffic breakdowns and the capacity is near to the optimum as some the scattering of the mean speed shows at high traffic volumes. The harmonization effect becomes obvious as the distribution of the mean speeds is very low.

![Cross section a](image4.png)

**Figure 3: Speed flow diagram at cross section a**
5.2 Case Study 2

**Task:**
A 5 km long 3-lane segment of a motorway between two major interchanges had to be analysed concerning the question whether dynamic traffic control systems can be used to increase the reliability of the traffic flow operation. This section is characterised by long weaving processes between the entry lane at an interchange and the following exit. Here, the effects of dynamic speed signs and temporary hard shoulder running had to be examined.

**Methodology:**
As mentioned before deterministic methods (HBS, 2015) do not cover dynamic traffic control systems. The microscopic simulation is the only solution to examine the effects of concepts to increase the reliability of traffic flow. The calibration of the simulation model was based on loop detector data from some points along the motorway section. Thus, the calibration process transferred local characteristics of driving behaviour (like lane choice, speed limit acceptance etc.) into the model.

Four concepts have been developed to increase the capacity of traffic flow. In addition, the impact of autonomous driving on the current network was analysed. These concepts are shown in Table 3.
Using regular lane markings as shown in concept B, the through going vehicles – here especially large trucks - have to use the right lane. This means they have to change lanes twice, first at the beginning of this lane and second at the end, to remain on the through direction. The exceptionally marked lane (0.3 m wide block markings) allows the through going traffic to remain on the second lane. At the same time vehicles entering or exiting at the adjacent interchanges are entitled to pass these slower vehicles by using the far right lane. This should encourage drivers to a more strategic lane choice behaviour resulting in a reduced number of lane changes.

**Results:**
The result of the simulation runs was that a substantial increase of capacity at the weaving segment could only be achieved by solution D combined with a dynamic traffic control system. A temporary opened hard shoulder (concept C) and the addition of a regularly marked permanent fourth lane (concept B) were able to increase the capacity compared to the existing motorway design, but did not deliver the optimum solution. Dynamic speed signs alone (concept A) helped to reduce the probability of a breakdown, but could not increase the capacity. The bottleneck mainly caused by heavy vehicles that have to change lanes twice within the long weaving segment -once at the beginning and once at the end of the weaving area- remained.
A special lane marking together with overhead signposting which prevents through traffic from changing to the right lane, combined with dynamic speed signs optimises the traffic flow and increases the maximum throughput during peak hours substantially. This solution turned out to be rather specific for the kind of traffic movement demand patterns in the decisive morning peak.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Morning Peak 6:00-10:00 a.m. [veh/h]</th>
<th>Evening Peak 3:00-7:00 p.m. [veh/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4760</td>
<td>5870</td>
</tr>
<tr>
<td>B</td>
<td>6230</td>
<td>7440</td>
</tr>
<tr>
<td>C</td>
<td>6020</td>
<td>7260</td>
</tr>
<tr>
<td>D</td>
<td>7660</td>
<td>8400</td>
</tr>
</tbody>
</table>

Table 4: Capacities at the bottleneck

In Figure 5 the results of autonomous driving in comparison to the use of a TCS (concept A) is shown at the bottleneck of this motorway section. As you can see the capacity (according to (van Aerde, 1995) increases by 17 % (5567 veh/h) in the morning peak and by 18 % (6904 veh/h) in the evening peak. The capacity of the addition of a lane (concept B) cannot be reached, but nevertheless a substantial increase can be observed.

In the speed flow diagrams you can also see that the scattering of the mean speeds is reduced even in comparison to a TCS.
6 Conclusion

In this paper the results of two case studies are presented. Using a microscopic simulation model it could be shown that dynamic traffic control systems can be used to harmonize traffic flow. These systems do not lead to a higher capacity, but they are able to reduce the probability of flow breakdowns on regular road elements. The effect of dynamic control systems can be optimized by modifying the control parameters. If the system reacts more sensitive to the traffic volume, the harmonizing effect is maximized.

On complex road elements like weaving segments the harmonization of traffic flow can also have a positive effect on the capacity. Needless lane changing should be avoided by traffic control and required lane changing becomes easier for vehicles in harmonized conditions. Thus, also the capacity can be increased under specific conditions. The reason for this is that on a weaving segment not the total traffic volume, but the proportion of weaving movements is the decisive factor for the capacity.

Assuming that autonomous vehicles behave more precisely and effectively it is shown that the capacity of complex motorway sections can be increased limiting access to autonomous vehicles only without the cost intensive enhancement of road infrastructure.

References