■ 論 文 ■

Analysis of Characteristics of the Dynamic Flow-Density Relation and its Application to Traffic Flow Models

동적 교통량-밀도 관계의 특성 분석과 교통류 모형으로의 응용

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목 차

Key word : Online traffic flow model, dynamic flow-density relation, hysteresis, transition, fuzzy logic

요 약

지능형 교통체계(intelligent transport systems)의 구축이 점차 널리 확대됨에 따라 교통류의 실시간 모형화(online traffic flow modeling)의 중요성이 증대되고 있다. 교통량-밀도 관계는 주어진 교통량, 밀도 상황에서 교통류의 행태를 나타낼 뿐만 아니라 거시 교통류 모형의 결과에 많은 영향을 미친다. 현재까지 교통량-밀도관계에 관한 대부분의 연구는 그 관계식을 규명하는데 그치고 있다. 상류부와 하류부의 교통 상태에 따른 교통량-밀도관계의 시간적 변화는 교통류의 모형화에 반드시 고려되어야 할 특성이지만, 현재까지 그에 대한 연구가 폭넓게 이루어지지 않고 있는 실정이다. 본 논문에서는 한 지점에서의 교통량-밀도관계가 시간의 흐름에 따라 분석되었고 states diagram으로 표현되었다. 동적 교통량-밀도관계 (dynamic flow-density relation)는 states diagram으로부터 fuzzy-logic을 이용하여 유추되었고, 거시 교통류모형을 실시간으로 응용할 수 있는 기초를 제공하였다. 동적 교통량-밀도관계를 거시 교통류 모형에 이용함으로써 교통류의 실시간 모형화 과정에서 발생하는 모수추정 (parameter calibration) 문제를 완화하였다.

Ⅰ. Introduction

Traffic flow models have been developed employing various modeling approaches by numerous researchers and provided the basis for understanding traffic flow. Nowadays, traffic flow models are needed for practical traffic control systems as well as for the investigation of characteristics of traffic flow. Sound traffic flow models are an important component for traffic control systems and can give operators useful real-time information about the traffic situations on roadway where the detectors are not densely installed.

However, traffic flow models developed until now cannot be satisfactorily applied to practical traffic control systems because of difficulties in calibrating the parameters of the models. The parameters of traffic flow models have dominant effects on the results of the models and should be calibrated depending on traffic data sets. These properties of traffic flow models are crucial for the online application of the models.

In this research a new modeling approach is developed which can alleviate the calibration problems of the current traffic flow models. This work consists mainly in two parts; first, the analysis of traffic flow characteristics and second, the development of a new online traffic flow model applying these characteristics.

The flow-density relation is one of the basic relations among traffic variables which are used to analyze traffic flow on measurement stations and plays an important role in traffic flow modeling. The relation, however, is proposed only for a stable and stationary traffic state and should be understood as a long-term average relation (e. g. 1 hour intervals). The static flow-density relation is not capable of reacting satisfactorily to current unexpected changes in traffic flow, which would be mandatory for real-time traffic control. For traffic control, a relation based on shorter detection intervals (e. g. 1-5 min. intervals) is required so that the prevailing traffic states can be better observed.

The time series analysis of the flow-density and the speed-density relationship based on short data collection intervals shows the hysteresis phenomena which are not observed during the long time intervals. The hysteresis phenomena have different characteristics during the transitions depending on traffic states. For the analysis of the hysteresis phenomenon the traffic flow is, therefore, classified into various traffic states and the transitions between these traffic states are investigated.

Macroscopic traffic flow modeling is a very effective approach for the description of current traffic situations. However, the performance of the macroscopic models depends mainly on the calibration of the static flow-density relation. The static flow-density relation can be accurately calibrated after the traffic events concerned have ended. The static flow-density relation calibrated beforehand cannot properly react to the change in current traffic situations. If macroscopic traffic flow models are to be used to describe current traffic situations, a dynamic flow-density relation is needed which can react to the current traffic situations and alleviate the calibration problems.

In this research the classification of the traffic states is proposed as an approach to develop a dynamic flow-density relation. Traditionally, traffic flow is classified into two traffic states: free traffic and congested traffic. The two traffic states are subdivided into more traffic states depending on traffic characteristics, in order to apply different flow-density relations depending on traffic states. A dynamic flow-density relation is identified based on the classification of the traffic states, and quantified by applying fuzzy logic. The online traffic flow model proposed in this research is based on a hydrodynamic model applying the dynamic flow-density relation instead of a static flow-density relation.

In this paper, a novel shape of the states diagram is produced and a dynamic flow-density relation is proposed. This paper presents a new approach to on-line traffic flow modeling on freeways, based on the continuum theory and on an on-line process for adapting the flow-density relations dynamically to the changes in the traffic context. The new modeling approach is tested based on the real traffic situations in various freeway sections and compared with an existing macroscopic model

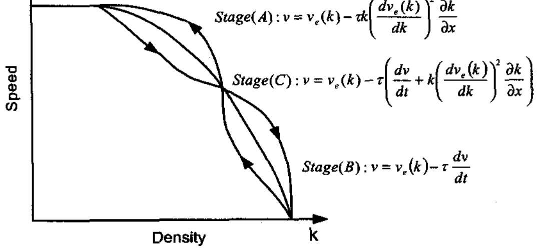
Ⅱ. The hysteresis phenomenon in traffic flow

Hysteresis can generally be defined as a phenomenon in which two physical quantities are related in a manner that depends on whether one is increasing or decreasing in relation to the other (Isaacs, 1996). The representation of the traffic variables as time series shows a hysteresis loop in the flow-density and the speed-density relations on a freeway section with the density first increasing and then decreasing, when congestion builds up and subsequently dissolves.

The first investigation into the hysteresis phenomenon in traffic flow was carried out by Treiterer and Myers (1974) with an aerial survey of a platoon of vehicles. A microscopic analysis showed the asymmetry between the behavior of a vehicle unit in a deceleration maneuver and a similar unit performing an acceleration maneuver. A macroscopic interpretation of this phenomenon is represented by the loops in Treiterer and Myers (1974). Daganzo (1999b) postulated that the loops in Treiterer and Myers (1974) are the result of lane changing. It is thought, however, that during the acceleration phase lane changing happens seldom. Moreover, it was confirmed by traffic data analysis by the authors that this phenomenon happens not only on the passing lane but also on the right lane. The average speed and the flow suddenly increase simultaneously on both lanes without a considerable change in density. Physically this corresponds to a situation that the vehicles of a platoon accelerate simultaneously without diffusing, which leads to a sudden increase in speed with almost no change in concentration (Zhang, 1999). It can be concluded that this is not the result of lane changing but the characteristic of traffic flow.

Zhang (1999) suggested classifying congested traffic flow into three stages according to drivers' responses: (A) anticipation dominant stage, (B) relaxation dominant stage, (C) balanced anticipation and relaxation stage. The anticipation effect is dominant in the situation where the traffic is light, i.e. under free flow conditions, and where drivers have enough spacing ahead to adjust their speeds even before traffic disturbances reach them. On the other hand, the relaxation effect, i. e. retarded reaction, is dominant in the situation where the traffic is heavy and the drivers cannot see approaching traffic disturbances until they reach them, and they can adjust their speed only according to the variation in spacing ahead. The balanced anticipation and relaxation stage is an intermediate stage.

For these three different stages of congested traffic flow Zhang (1999) derived a system of average speed equations. In the stage (A) the speed during acceleration is higher than the speed during deceleration. In the stage (B) the speed



<Figure 1> Stages of the speed-density relation by Zhang (1999)

during acceleration is lower than the speed during deceleration. Since the acceleration and deceleration branches switch positions at the two stages, there must be at least one point in the middle, at which both speeds are equal, i. e. stage (C). The hysteresis phenomenon in the speed-density relation under these conjectures is shown in ⟨Figure 1⟩. In this system of equations $v_e(k)$ is a desired speed to which drivers attempt to adapt whenever it is possible, and τ is a relaxation time constant.

Ⅲ. The flow-density relation as states diagram

Traffic flow has been classified in various ways and the intrinsic characteristics of the traffic states have been investigated theoretically and empirically (Kerner, 1996a; Helbing et al., 1999; Lee et al., 1999). The investigations of Helbing et al. and Lee et al. focussed on the existence of the traffic states based on simulations and data analysis. Kerner et al. (2001) developed an approach to trace and forecast the patterns of congested traffic applying the classification of traffic states.

Generally, traffic flow is classified into two traffic states; free traffic and congested traffic. In this paper free traffic subdivided into free flow state and impeded free flow state. Congested traffic is subdivided into congested, jammed and stopped state. Synchronized state is defined as a transient state between free traffic and congested traffic. Based on the classified traffic states the hysteresis phenomena can be shown clearly and the dynamic flow-density relation can be easily induced and applied to online application of a macroscopic traffic flow model.

Free flow appears at very low traffic demand. In the free flow state there is no interaction among the drivers and stochastically stationary traffic conditions prevail on a section. Kinematic perturbation propagates downstream and fades during the propagation. The free flow state changes only to the impeded free flow state. The speeds between lanes are noticeably different.

Impeded free flow occurs at increased traffic demand and the interaction among the vehicles becomes stronger and speeds between the lanes are still different. Perturbations propagate mainly downstream but also upstream contingent upon extreme behavior of the drivers. There occur transitions to other traffic states depending on the growth of perturbations.

In synchronized state speeds of all lanes are not significantly different. The speed is a little lower than in the impeded free flow state, but still high. On average the flow is as high as within impeded free flow, but with small variance. Depending on traffic situations perturbations propagate upstream or downstream and the synchronized state can change to the congested or the jammed state. The synchronized state was introduced by Prigogine and Herman (1971) theoretically and first observed by Koshi et al. (1983). Kerner (1999) extensively investigated the characteristics of the synchronized traffic which includes synchronized state, congested state and jammed state in this investigation.

In the congested state speed is quite low and can fluctuate extremely while flow remains still high and does not vary significantly. Time developments of speed and flow have a weak correlation in this state, which will be shown using transition indicators later in this paper. The respective data points for the flow and the density are scattered irregularly over a large area in the flow-density relation. The speeds between lanes are roughly the same.

Jammed state occurs if upstream moving shock waves occur due to high traffic demand and heavy downstream traffic conditions. The flow is significantly lower than in the congested state but the speed is not necessarily lower. Time developments of speed and flow have a positive correlation, which will be shown using transition indicators later in this paper. The speeds between lanes are roughly the same. If the traffic flow comes to a standstill due to downstream congestion for a certain time interval, stopped state can be observed in which the maximum density $k_{\max}$ is reached.

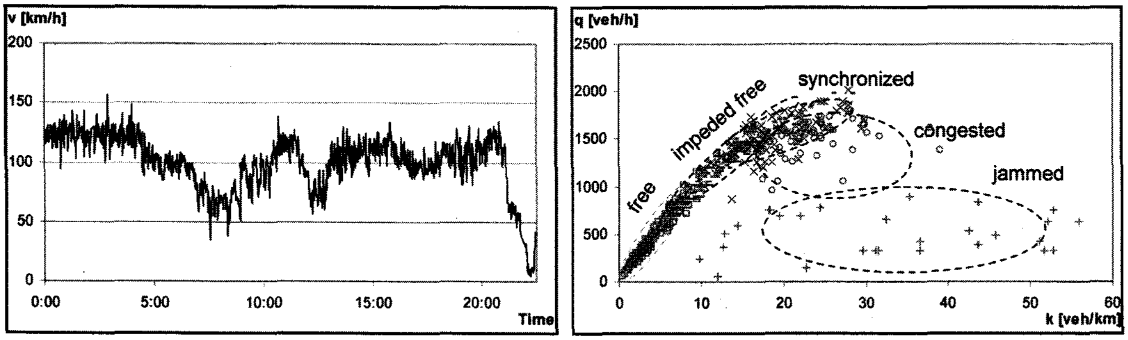
〈Figure 2〉 shows the 1-minute averaged traffic data of Friday, 28 July, 2000, on a section of the 2-lane (in each direction) German freeway A8. The squares (□) represent the free flow state, the dashes (-) the impeded free flow state, the crosses (x) the synchronized state, the circles (○) the congested state and the plus symbols (+) the jammed state.

The traffic states in 〈Figure 2〉 are not sharply defined against each other, but overlap partially because the speed and the flow fluctuate. For the classification of the traffic states herein formulated, decision criteria are defined and verified.

In order to differentiate the free flow state, the impeded free flow state and other traffic states (the synchronized, the congested and the jammed state) the mean and the standard deviation of headways calculated from individual vehicle data are used. The mean of heaways decreases as the traffic volume increases. The standard deviation of headways decreases as the density increases, which is consistent with the fact that the Poisson count distribution is suitable for the description of the vehicle arrivals in free flow and the binomial count distribution is suitable for the vehicle arrivals in congested flow. The standard deviation of headways is found to be very large in the free flow state and decrease rapidly as the density increases. From the values around the critical density the standard deviation is very small and does not change significantly depending on the density values. The mean values multiplied by the standard deviation are very large in the free flow. In the impeded free flow the mean values multiplied by the standard deviation become smaller than in the free flow but still large. In other traffic states (the synchronized, the congested and the jammed state) these values are very small.

For the classification of the traffic state into freely flowing state (the free flow state, the impeded free flow state) and other traffic states (the synchronized, the congested and the jammed state) the speeds of the lanes are compared as well. During the transition from freely flowing state (the free flow and the impeded free flow) to other traffic states (the synchronized, the congested and the jammed state) the synchronization process of the speed of all lanes is a universal phenomenon (Daganzo, 1999b). The multiplied values of the mean and the standard deviation of headways show the same tendencies as the difference in speeds over the lanes.

In order to differentiate the various congested flows the macroscopic traffic variables, i.e. speed,



〈Figure 2〉 Comparison of traffic data for different traffic states (German freeway A8) flow, and density are used. For the identification of transitions, differences between moving averages of flow and speed are applied, which prove to be very efficient in the identification of the transitions between these states.

In the equations q_n and v_n mean the flow and the speed at detection interval n. In this paper the speeds and flows are accumulated over 5 minute-interval (Q_n, V_n). Differences between two accumulated data elements are used for the detection of the transitions in traffic flow. The differences are divided by the sum of both data elements to achieve the normalized indicators for the transitions between the traffic states. By accumulating the short interval values of traffic variables (the speed and the flow) during the long interval, noises are eliminated and real changes in traffic variables remain. The real changes in traffic variables during a time unit are represented by the indicators. If the speed and the flow decrease (or increase) abruptly, the indicators show the minimum (or maximum) values while the gradual changes in the speed and the flow do not give any noticeable variations in the indicators. These indicators were also applied to the online congestion detection and showed encouraging results (Belzner, 2002).

$$Q_n = q_n + q_{n-1} + q_{n-2} + q_{n-3} + q_{n-4};$$

$$V_n = v_n + v_{n-1} + v_{n-2} + v_{n-3} + v_{n-4}$$

$$flow\_indicator_n = \frac{Q_n - Q_{n-5}}{Q_n + Q_{n-5}};$$

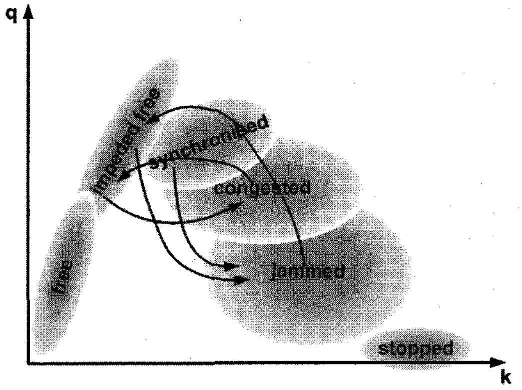
$$speed\_indicator_n = \frac{V_n - V_{n-5}}{V_n + V_{n-5}}$$

For the implementation of the states diagram in the on-line traffic flow model. The traffic states are classified with fuzzy logic which can be used for analyzing complex systems that are not precisely specified and do not have accurately known probability distributions. In this research fuzzy logic combines macroscopic traffic variables and traffic states. The application of fuzzy logic will be explained later in this paper.

The different traffic states and transitions between the states are represented together in a states diagram, see ⟨Figure 3⟩. The trajectories of transitions vary depending on the traffic states associated with the transitions. The transitions between neighboring traffic states are difficult to isolate in the states diagram, therefore, are not analyzed in this paper. Four transitions are analyzed empirically in this paper:

- transitions between impeded free flow and jammed state,
- transitions between impeded free flow and congested state,
- transitions between synchronized and jammed state,
- repeated transitions between synchronized and jammed state.

The speed-density relations of Zhang (1999) can be applied not only to the stages of congested traffic flow but also to the traffic states and transitions between the traffic states defined above. The speed-density relations of Zhang (1999) are represented differently in the flow-density relation depending on the changes in flow and density caused by different upstream



⟨Figure 3⟩ Traffic states and transitions in the states diagram and downstream traffic situations. The transitions between the impeded free flow and the jammed state or between the impeded free flow and the congested state can be represented by multiplying the speed equations of Zhang (〈Figure 1〉) by the density, which corresponds to the relation of traffic variables $q = v \cdot k$ and is represented in Figs. 4a and 4b, respectively. In the repeated transitions between the traffic states (e.g. between impeded free flow and the congested state, between the impeded free flow and the jammed state or between the synchronized state and the jammed state) the hysteresis phenomenon is not as pronounced as in the transitions between long lasting traffic states; see 〈Figure 4c〉.

Ⅳ. Empirical investigation of traffic states and transitions

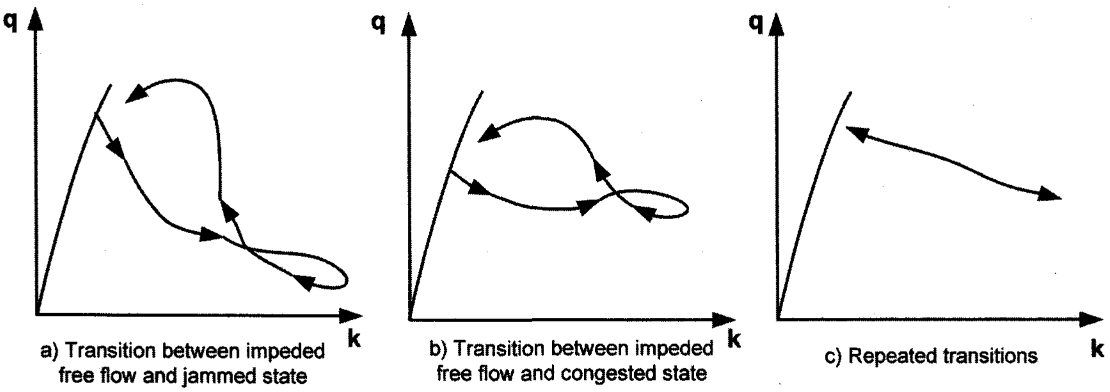
For the empirical investigation of the traffic states defined above and the transitions between the traffic states in the states diagram individual vehicle data on German freeway A8 near Munich (Woltereck, 2000) and 1-minute traffic data on German freeway A5 near Frankfurt (Lange, 1999) were analyzed. In this paper the traffic states and the transitions between them were derived and shown for limited sets of freeway data, although the phenomena mentioned above were observed also in other sets of data not presented here. The characteristics of the traffic states and the transitions are not unique to the examples presented in this paper but are observed also in different data sets.

Speed and flow were aggregated at 1-min-intervals on each freeway section. Density was calculated from the speed and flow values. The aggregated data was not smoothed because the characteristics of hysteresis phenomenon or the relation between the density and the flow can be changed depending on the smoothing level, in particular, during the transition. The traffic states defined above are delimited from each other by means of the traffic data and the criteria explained above. In particular, some transitions are analyzed in detail and represented.

1. Transitions between the impeded free flow and the jammed state

〈Figure 5〉 represents the time series of speed and flow in transition from the impeded free flow to the jammed state and back to the impeded free flow state. The data set includes congestion on a section of the German freeway A8 direction Munich from 11:45 to 13:30 on Saturday, 25 September, 1999.

The transition from the impeded free flow to the jammed state occurs when the traffic demand is

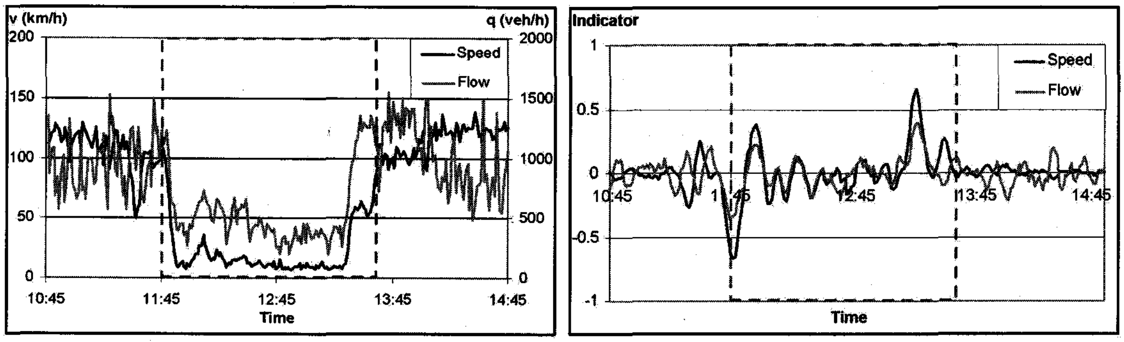


a) Transition between impeded free flow and jammed state

b) Transition between impeded free flow and congested state

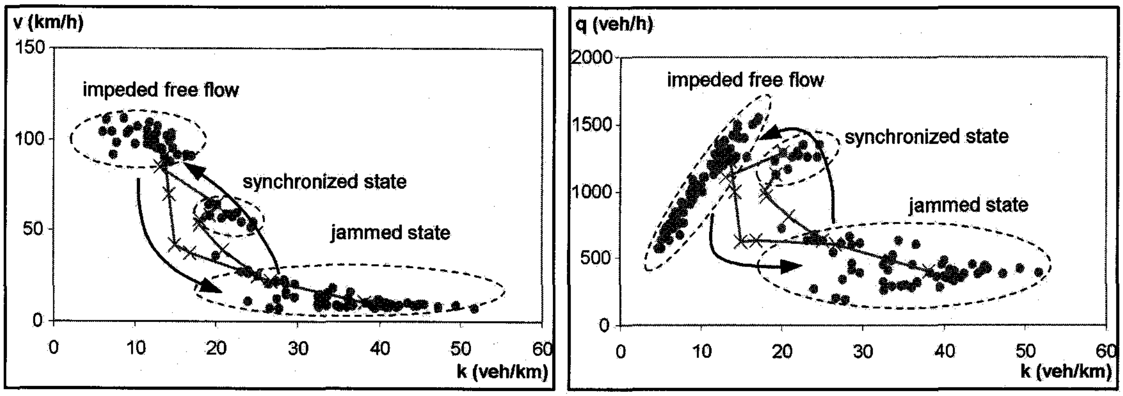
c) Repeated transitions

〈Figure 4〉 Hysteresis phenomena in the states diagram



a) Time development of the speed and the flow

b) The transition indicators



c) The speed-density relation

d) The flow-density relation

⟨Figure 5⟩ Transitions (in thick line) between the impeded free flow and the jammed state

rather high. The speed and the flow drop sharply when the perturbation (congestion) is detected, i.e. the upstream propagating shock wave passes a freeway section. The density increases suddenly in a few minutes after the speed and the flow have dropped sharply; see ⟨Figure 5d⟩. The speed-density relation shows that there is no 1:1 correspondence between speed and density values during this transition. The density values do not change considerably at sharp speed drops and soars. It is also observed by other researchers that the transition to the jammed state occurs when the traffic demand is rather high (Cassidy and Bertini, 1999; Kerner and Rehborn, 1996a). As shown in the following analysis, a transition to the congested state, however, usually occurs when the traffic demand is not so high. The instant congestion dissolves, the vehicles in the congestion can accelerate and a traffic state of high flow with nearly optimal density can be reached. The observed speed-density relation has the same characteristics described theoretically by Zhang (1999). In ⟨Figure 5⟩ the speed does not change significantly in the beginning of the congestion dissipation. After a while the speed, however, begins to increase suddenly without substantial changes in the headway between vehicles. This phenomenon coincides with the microscopic analysis by Treiterer and Myers (1974). The platoon emerging from a disturbance adopts longer headways until it reaches the constant spcacing level at about 45 veh/km, see ⟨Figure 4⟩ in Treiterer and Myers (1974).

The traffic flow returns from the jammed to the impeded free flow state via the synchronized state, i.e. a state of relatively high flow with nearly optimal density. This relatively high flow is a little lower than the capacity of the freeway section. This observed phenomenon that such a high flow value is reached in this state is consistent with the statements of the congestion dissolution by Daganzo (1999b) and Lighthill and Whitham (1955). When the congestion has been dissolved a group of cars captured in the congestion forms a sufficient source of vehicles to increase the flow. Drivers captured in the congestion for a long time tend to accelerate. For a while they, however, still hesitate before they accelerate (retardation phenomenon). This retardation phenomenon is one of the reasons why the density decreases suddenly at the beginning of the transition from jammed to impeded free flow state. Only after the drivers are convinced that the congestion has been dissolved they will accelerate as fast as possible.

It appears in 〈Figure 5c〉 that the speed soars sharply at a higher density value (about 20 veh/km) than it drops sharply (about 15 veh/km). The flow-density relation shows characteristics similar to the speed-density relation. The flow increases to very high values while the density remains nearly unchanged. Obviously uniform acceleration of the platoon in congestion with short spacing and increasing speed is responsible for the high flow.

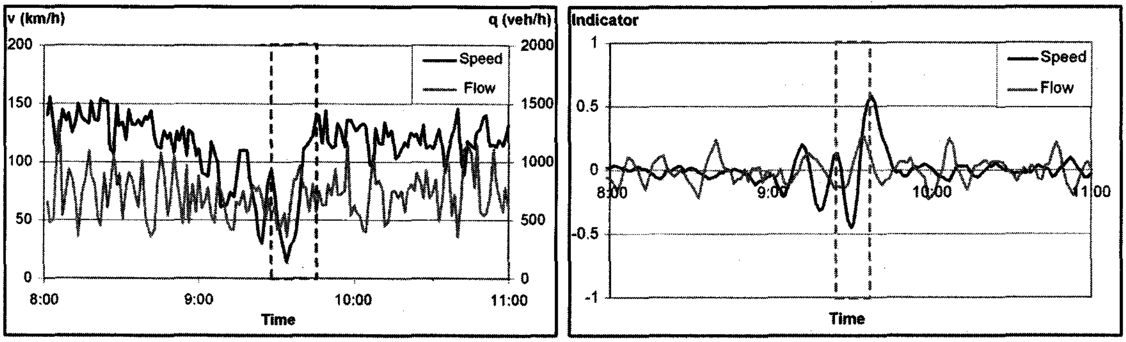
In the transition from the impeded free flow to the jammed state both indicators show the minimum values due to the decrease in the speed and the flow, see Fig 5b. After the transition to the jammed state there are disturbances which show the characteristics of the jammed state. The fluctuations of the speed and the flow are strongly correlated and the correlation is shown clearly by both indicators. In the transition from the jammed to the impeded free flow state the speed and flow indicators show the maximum values due to the increase in the speed and the flow. After the transition the flow fluctuates pronouncedly but the speed does not, which shows the characteristics of (impeded) free flow and is represented clearly by the indicators.

2. Transitions between the impeded free flow and the congested state

The transition from the impeded free flow to the congested state was observed on a section of the German freeway A8 direction Stuttgart on Thursday, 7 October, 1999. This data set includes congested state from 09:30 to 09:40; see 〈Figure 6〉.

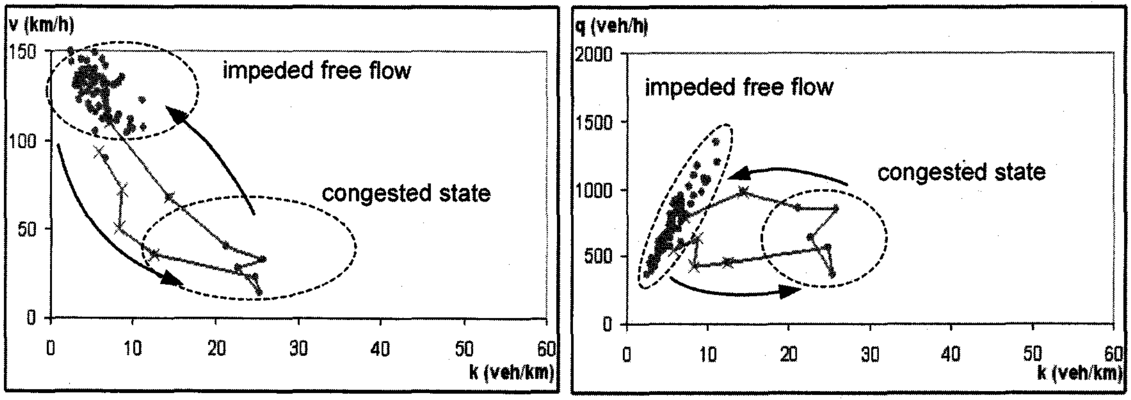
In the transition from the impeded free flow to the congested state the speed decreases suddenly but the flow does not vary significantly. When the traffic flow changes from the impeded free flow to the jammed state there is a period of time in which the flow is high prior to the activation of a traffic jam. However, the data set of the transition to the congested state has no period of high flow, which is an important characteristic for the differentiation between the jammed and the congested state. If the flow were high, traffic flow would develop to the jammed state. In the transition from the impeded free flow to the congested state the flow does not vary significantly with the density increasing, while in the transition from the impeded free flow to the jammed state the flow decreases noticeably with the density increasing, see 〈Figure 5a〉. The direction is influenced by the state of high flow with high density, which is a normal phenomenon of the congestion dissolution. In the transition from the congested to the impeded free flow state these phenomena are not as pronounced as in the jammed state. The state of higher flow at a corresponding density can nevertheless be identified here.

The congested state can be observed very often in the vicinity of ramps of freeways; see also Hall and Lam (1988), and Helbing et. al. (1999). The speed of the main stream is influenced by entering and exiting vehicles in the region of ramps and fluctuates very strongly but the flow



a) Time development of the speed and the flow

b) The transition indicators



c) The speed-density relation

d) The flow-density relation

〈Figure 6〉 Transitions between the impeded free flow and the congested state

does not vary significantly.

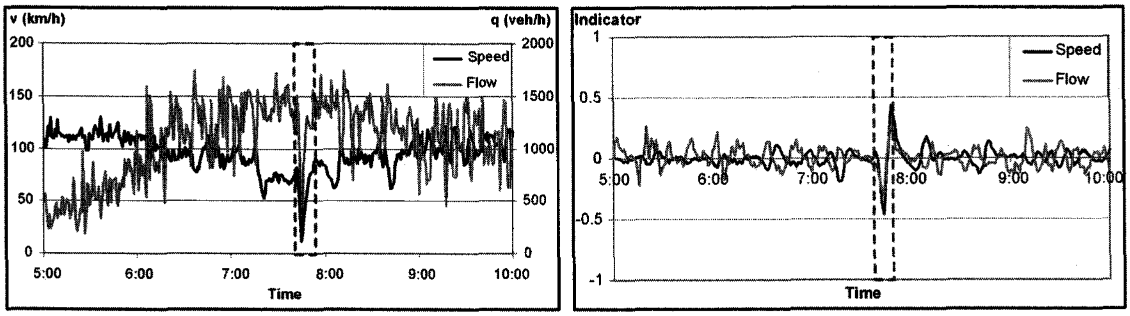
The indicators clearly show that the speed fluctuates largely but the flow does not change pronouncedly during the transitions, see 〈Figure 6b〉. In the congested state the speed and the flow are correlated weakly as in the (impeded) free flow. The peak points of the speed and flow indicators do not occur at the same time.

3. Transitions between the synchronized and the jammed state

At the same densities the speed and the flow in the synchronized state are higher than in the congested or the jammed state but the flow in the synchronized state is a little lower than in the impeded free flow state. The speeds over all lanes on a freeway section are typically nearly the same. The synchronized state can be formed in the transition between the impeded free flow and the jammed state or between the impeded free flow and the congested state.

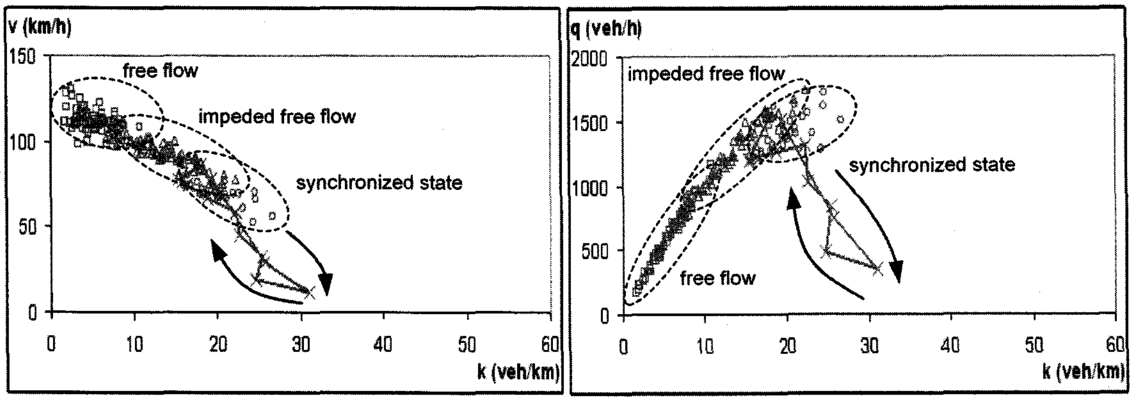
The transition between the synchronized and the jammed state was observed on a section of the 2-lane German freeway A8, direction Munich, on Friday, 14 July 200. Until 6:00 free flow state dominates in the data set. From 6:00 the flow increases and the speed decreases owing to the increased interactions among the vehicles. At 7:20 the speed decreases due to a disturbance. The speed becomes almost the same on both lanes and the flow remains high with a smaller variance, which is a typical attribute for the synchronized state.

From 7:45 to 7:57 the data shows a transition between the synchronized and the jammed state.



a) Time development of the speed and the flow

b) The transition indicators



c) The speed-density relation

d) The flow-density relation

〈Figure 7〉 Transition between the synchronized and the jammed state

At 7:45 the speed and the flow decrease simultaneously. The speed increases again after a few minutes. The traffic flow returns to the impeded free flow via the synchronized state. In the transition from the jammed to the impeded free flow state the traffic state of high flow with high density cannot be observed because the congestion lasts just for a short time and this congestion cannot form a sufficient source of vehicles which increases the flow with the density unchanged.

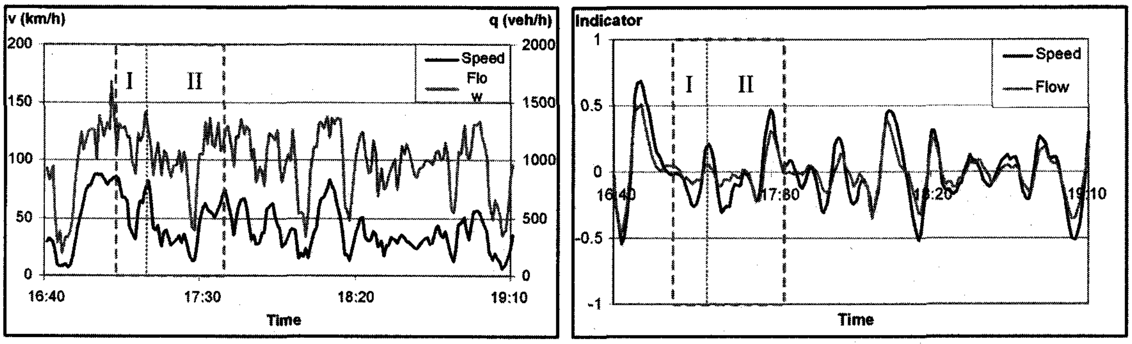
In the impeded free flow the indicators show the weak correlation between the speed and the flow, see 〈Figure 7b〉. In the transition between synchronized and jammed state the indicators show the same tendencies as in the transition between impeded free flow and the jammed state. Both indicators have the minimum and maximum values simultaneously.

4. Repeated transitions between the synchronized and the jammed state

If several short congestions occur one after another on a freeway section the drivers must alternately decelerate and accelerate. Depending on the traffic situation transitions between the impeded free flow and the jammed state, between the impeded free flow and the congested state or between the synchronized and the jammed states are repeated.

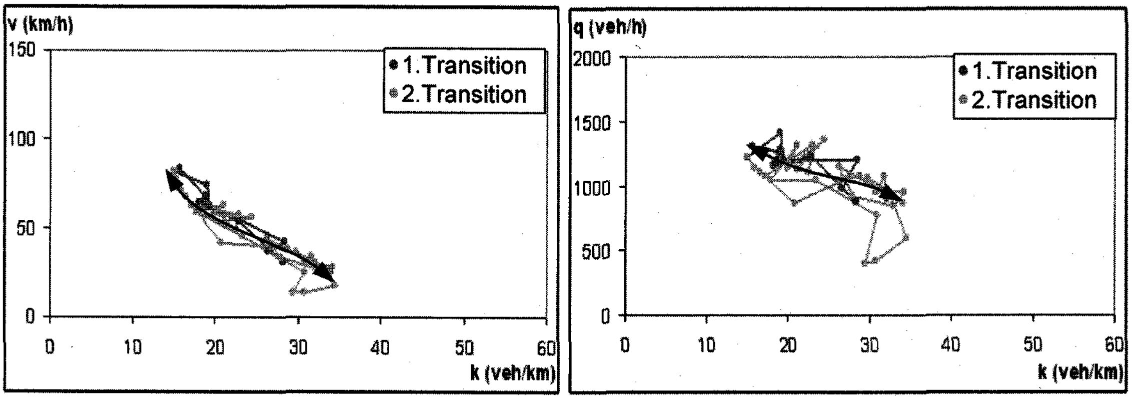
A data set of repeated transitions between the synchronized and the jammed state was collected on a section of German freeway A8 direction Munich on Friday 24, September 1999. The repeated transitions occur from 16:40 to 19:10. The interval from 17:05 to 17:40 was analyzed in detail; see 〈Figure 8〉.

In this period two transitions between the



a) Time development of the speed and the flow

b) The transition indicators



c) The speed-density relation

d) The flow-density relation

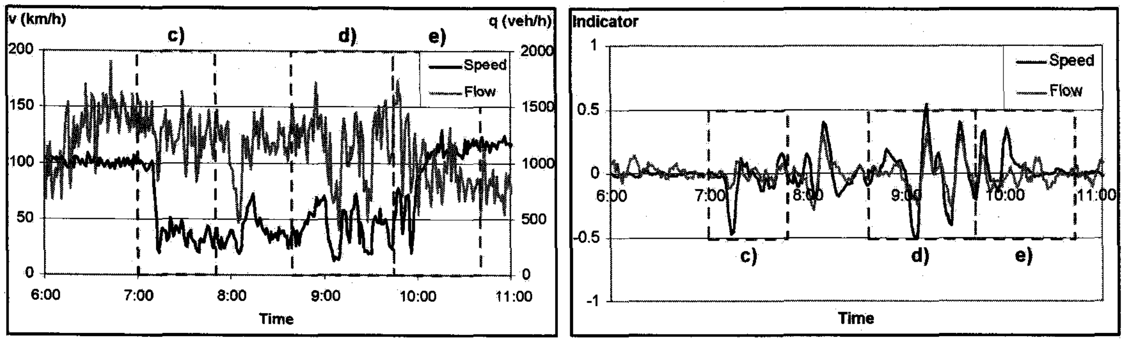
⟨Figure 8⟩ Repeated transitions between the synchronized and the jammed state

synchronized and the jammed state can be seen. The speed fluctuates wildly and the flow follows the same tendency. In the flow-density and the speed-density relation, both variables follow the same trace in the transition from high to low density as in the reverse transition from low to high density. This phenomenon is observed over all lanes simultaneously. In these transition the hysteresis phenomenon is not so pronounced, which was described through the 'J-line' in the flow-density relation by Kerner (1996a). The hysteresis of the speed-density relation predicted by Zhang (1999) cannot be clearly identified in this data set. If this traffic state, however, is considered as a balanced anticipation and relaxation stage this result can be interpreted logically. The transition indicators show a strong correlation between the speed and the flow, see ⟨Figure 8b⟩.

5. Consecutive transitions between traffic states

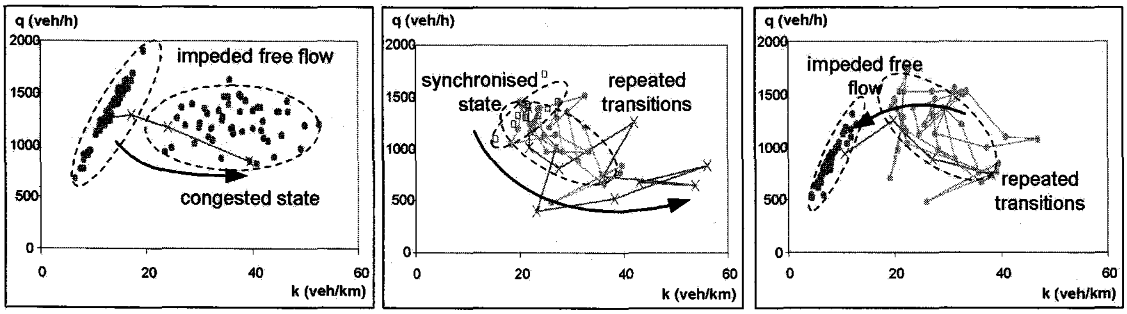
The transitions from the impeded free flow to the congested state and from the synchronized to the jammed state as well as their return to the impeded free flow state and repeated transitions between the jammed and the synchronized state were collected on a section of the 3-lane German freeway A5, direction Mannheim, on Monday, 17 March 1997. Such a sequence of traffic states and transitions occurs from 7:00 to 10:00.

The speed drops sharply at 7:00 while the flow remains high and nearly unchanged; see ⟨Figure 9a⟩. The crosses (×) and lines in ⟨Figure 10c⟩ show the transition from the impeded free flow to



a) Time development of the speed and the flow

b) The transition indicators



c) From impeded free flow to congested state

d) From synchronised to jammed state

e) From jammed to impeded free flow state

〈Figure 9〉 Transitions between several traffic states

the congested state. The time series from 7:00 to 8:00 in Figs. 10a shows the congested state.

At 8:00 both speed and flow increase and decrease once simultaneously. This change results from disturbances which occurred downstream. The traffic flow temporarily changes to the jammed state which partially overlaps the congested state. The short transition from the congested to the jammed state cannot be identified in this analysis.

The speed and the flow increase simultaneously shortly before 9:00. The traffic flow is temporarily in the synchronized state. The synchronized state is, however, influenced by a disturbance developed downstream and changes to the jammed state (crosses (×) and lines in 〈Figure 9d〉). After that, repeated transitions between the synchronized and the jammed state occur and the flow-density relation (gray points and lines in 〈Figure 10d〉) follows the trace of the repeated transitions.

The jammed state returns to the impeded free flow state owing to the decrease of upstream traffic demand. The speed increases and the flow decreases on the detection point. The shock wave moves downstream according to the continuum theory while the individual vehicles decelerate. Therefore, the transition has a shape different from that in 〈Figure 5〉. The transition from the jammed state to the impeded free flow state is represented in 〈Figure 9e〉. From 10:00 onward the traffic flow is again in the impeded free flow state.

The transition indicators show that the speed decreases suddenly at 07:00 while the flow remains unchanged. This situation can be compared with the flow-density relation of 〈Figure 9c〉. The congested state is influenced by disturbances which occurred downstream and the flow and the speed decrease and increase once simultaneously at 08:00. This situation is not analyzed in the flow-density relation.

At 09:00 the synchronized traffic changes to the jammed state. The speed and the flow decrease significantly at the same time. After that, repeated transitions between the synchronized and the jammed state occur and the indicators show the strong correlation between the flow and the speed after the pronounced drop of the speed and flow indicators at 09:00. This situation can be compared with the flow-density relation of ⟨Figure 9d⟩.

At 10:00 the jammed state returns to the impeded free flow state. The indicators show that the speed increases suddenly but the flow remains unchanged and even decreases, which coincides with the characteristics of the transition from the jammed to the impeded free flow state due to the decrease of the upstream traffic demand. From 10:00 onward the indicators show the characteristics of the (impeded) free flow. This situation can be compared with the flow-density relation of ⟨Figure 9e⟩.

V. Application to a macroscopic traffic flow model

This section presents a new approach to on-line traffic flow modeling on freeways based on the continuum theory and an on-line process to adapt the flow-density relations dynamically to the changes in the traffic context.

Off-line models use a static function for the flow-density relation, which is not capable of reacting to changes in the prevailing traffic states in practical traffic control systems. To study the dynamic behavior of the traffic flow on a freeway, the flow-density relation based on short detection intervals (like one minute) was analyzed considering the upstream and downstream traffic conditions observed along a freeway. This analysis leads to an empirical classification of different traffic states, characterized by consecutive phases of traffic bringing about hysteresis phenomena in the states diagram.

For the purpose of on-line traffic controls the continuum flow model of Lighthill and Whitham (1955)was applied and programmed as a cell-transmission model according to Daganzo (1994), but with dynamic sending and receiving functions. These functions are updated at each time interval during the on-line simulation, based on the shock wave theory depending on upstream and downstream traffic data. For the determination of the dynamic sending and receiving functions, traffic states classified and fuzzy logic are employed.

1. Situational cell-transmission model

The cell-transmission model of freeway traffic is a discrete version of the first order continuum (kinematic wave) model of traffic flow that is convenient for computer implementations (Daganzo, 1999a). In the cell-transmission model a freeway link is partitioned into small cells (or segments), and the cell contents (number of vehicles) are updated in the course of time. The average flow is the result of a comparison between the maximum number of vehicles that can be sent by the cell directly upstream of the boundary, those that can be received by the downstream cell, and the maximum flow value. A discrete version of the continuity equation representing the relationship between the density and the flow, and the flow equation used in the cell-transmission model is represented as follows,

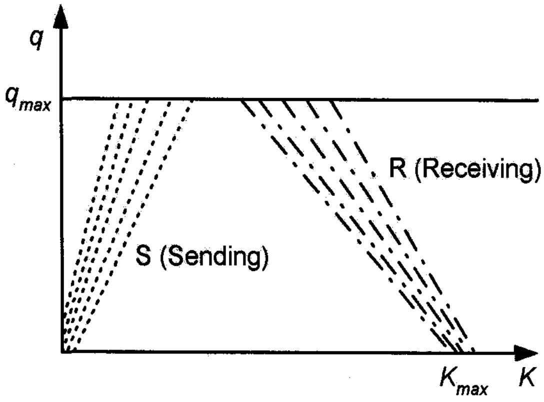
$$k(t+\varepsilon, x) = k(t,x) - \left(\frac{\varepsilon}{d}\right) \left[q\left(t, x+\frac{d}{2}\right) - q\left(t, x-\frac{d}{2}\right)\right]$$

$$q\left(t, x-\frac{d}{2}\right) = \min\{\, S(k(t,x)),\, q_{\max},\, R(k(t,x+d))\}$$

In the continuity equation ε is the time step of iterations and d is the length of the cells. In the flow equation the functions S(k(t, x)), R(k(t, x+d)) and $q_{\max}$ are the sending flow of the upstream cell, the receiving flow of the downstream cell and the maximum flow of the cell. The sending (receiving) flow is a function of the traffic density at the upstream (downstream) cell. The particular form of the sending or receiving function depends on the shape of the freeway's flow-density relation and has a pronounced impact on the model, which is comparable to the flow-density relation in other continuum models.

In the research of Daganzo (1994, 1999a) static sending and receiving functions are used which are determined beforehand and do not vary during the traffic flow simulation. With these static functions traffic dynamics generated by various downstream and upstream traffic situations cannot be described in real time. In this paper dynamic sending and receiving functions are therefore proposed which vary depending on the traffic data at downstream and upstream cells, and the model is named "situational cell-transmission model" in this paper. For the computer implementation a set of linear sending and receiving functions as well as the maximum flow of cells are used, as in the former research of Daganzo (1994), see ⟨Figure 10⟩.

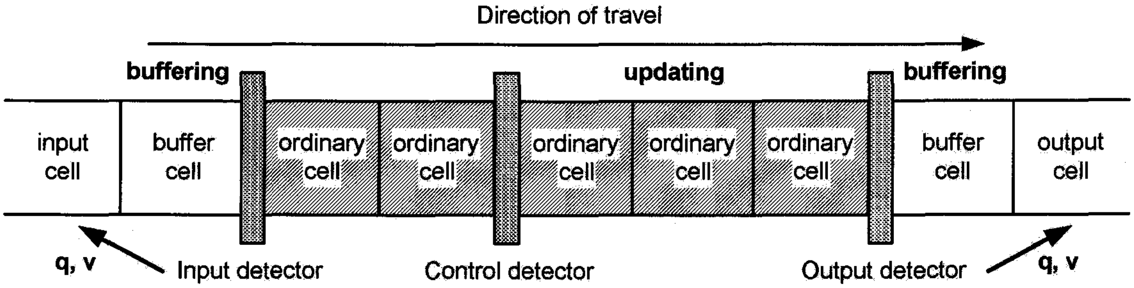
It is assumed, however, that every traffic data fit a branch (either sending or receiving function) in the flow-density relation depending on the shock wave speed. The shock wave speed of traffic data is determined applying fuzzy logic which combines the shock wave speed and traffic states described above. Depending on the traffic data the sending and receiving functions are updated in each interval. With the current traffic data only one branch of the relationship (either sending or receiving function) is determined dynamically and the other branch is determined from the parameters given beforehand. If the shock wave speed has a positive value the sending function with the same tangent value as the shock wave speed is determined and the receiving function is given by parameters. If the shock wave speed has a negative value the receiving function with the same tangent value as the shock wave speed is determined and the sending function is given by parameters. In the dynamic flow-density relation maximum flow $q_{\max}$ is a constant given as a parameter.



⟨Figure 10⟩ Dynamic sending and receiving functions

In the situational cell-transmission model a freeway section is divided into various cells with different characteristics see ⟨Figure 11⟩. The input and output cells have no length and obtain their flow and density values from the detector at the beginning (input) and end (output) of the link, and therefore have no calculation processes. The density and the flow values of the ordinary cells are updated by the continuity and the flow equations in the model.

The buffer cells have no length and absorb possible difference between the traffic data and the model. Most continuum traffic flow models assume that input and output data follow a given flow-density relation, and the traffic dynamics are described in the models depending on the input and output data. In reality the input and output data, however, deviate from the given flow-density relation and change unexpectedly. Most traffic flow models do not react rapidly to the changes in traffic data. The sudden changes in traffic data make most models unstable and induce unreasonable results, i.e. negative density or illogically



〈Figure 11〉 Presentation of a freeway section in the adaptive model

high density values. To avoid this side effect buffer cells are introduced. The updating scheme of density values in buffer cells is different from that in ordinary cells. By the comparison of the traffic data in the input/output cells with the values of the model in the ordinary cells next to buffer cells, the density value is determined as the density of the next iteration in the buffer cells, whose associated flow value is chosen in the flow equation instead of using the continuity equation as in ordinary cells. A mathematical proof of the buffer cell approach and model can be found in Kim (2002).

Contrary to the models of Daganzo (1994 and 1999a) using the same flow-density relation over the whole freeway simulation, dynamic flow-density relations are used in the situational cell-transmission model according to the determination strategy. The input and output cells have no updating scheme, therefore there is no flow-density relation in the input and output cells. The buffer cells next to the input or the output cell have the flow-density relation determined by the input or output data, respectively. The ordinary cells have the flow-density relation determined based on the shock wave speed.

Traffic situation is simplified as the four cases in 〈Table 1〉. Case 1 is explained as an example, and the flow-density relations in the other cases are determined in the same way. If the upstream speed is higher than the downstream speed and the upstream flow is higher than the downstream flow, the flow-density relations in the ordinary cells are determined by the traffic data at the downstream detector. In this determination strategy constants α and β are used to alleviate the logical fault generated by the stochastic characteristics of traffic data. By using high values of α and β the ordinary cells are more influenced by the downstream detector. With this strategy the propagation of the congestion generated upstream as well as downstream can be described satisfactorily for the purpose of traffic control.

〈Table 1〉 The flow-density relation determination strategy

Case	Speed relation	Flow relation	Determination of the flow-density relation
1	v_{up}1) $> v_{down}$	$q_{up} + \alpha > q_{down}$	By the traffic data at downstream detector
2	$v_{up} > v_{down}$	$q_{up} + \alpha \leq q_{down}$	By the traffic data at upstream detector
3	$v_{up} \leq v_{down}$	$q_{up} > q_{down} + \beta$	By the traffic data at upstream detector
4	$v_{up} \leq v_{down}$	$q_{up} \leq q_{down} + \beta$	By the traffic data at downstream detector

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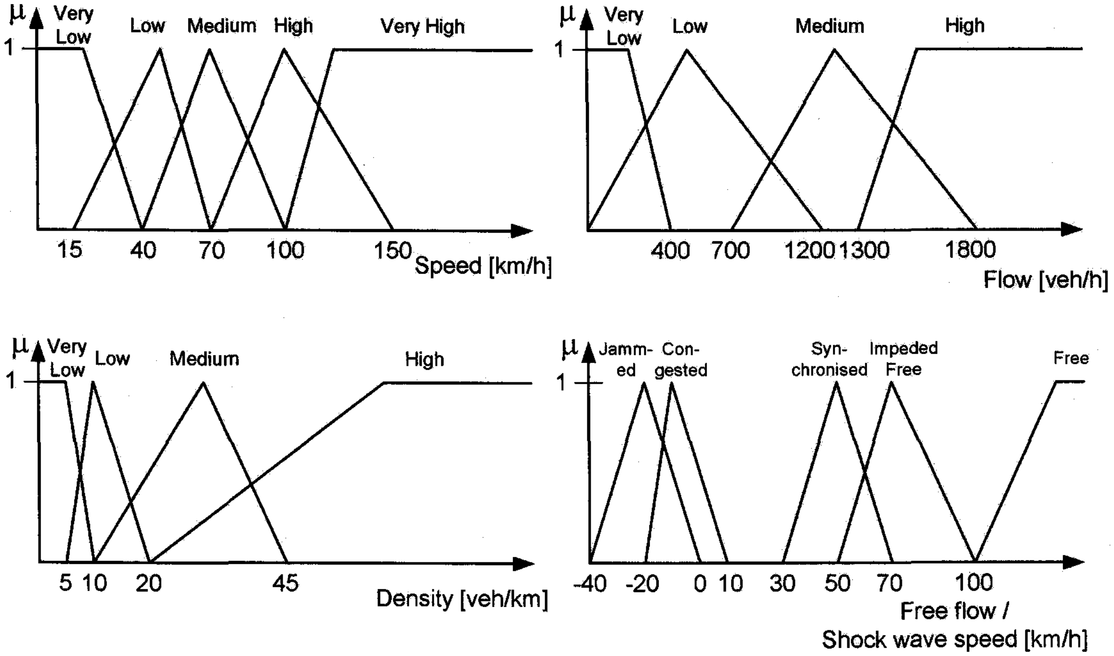
1) v_{up} : Speed at upstream detector



〈Figure 12〉 Membership functions for the input and output variables

2. Traffic state classification with fuzzy logic

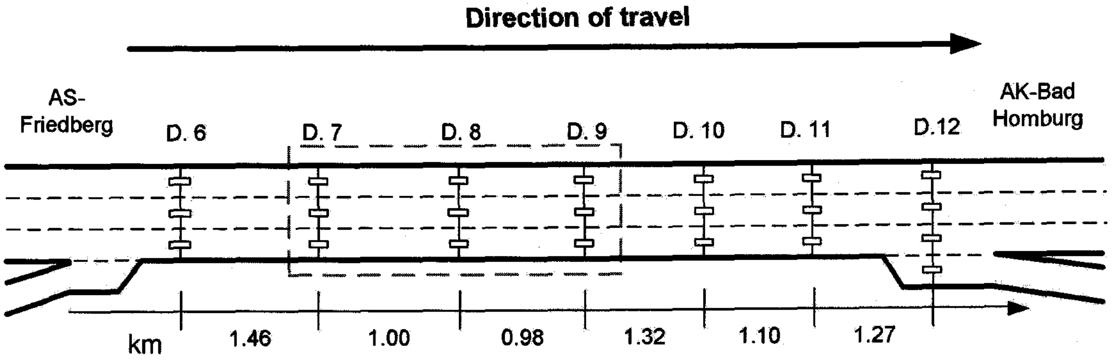
Fuzzy logic is applied for the classification of traffic states and the determination of the dynamic flow-density relations in the situational cell-transmission model. In this procedures speed, flow and density are used as input values and the respective free-flow speed or shock wave speed is inferred as the output. The maximum density and the intersection of sending function with the flow axis in the flow-density relations are determined from the averaged traffic data in a certain interval.

The membership functions for the traffic variables and the shock wave speed are represented in 〈Figure 12〉. The membership functions map the objects (the traffic variables and the shock wave speed) to their membership values between 0 to 1 in the sets. The threshold values of the membership functions are manually adjusted to the states diagram. These threshold values are, however, not as sensitive to traffic data as the parameters in the static flow-density relations.

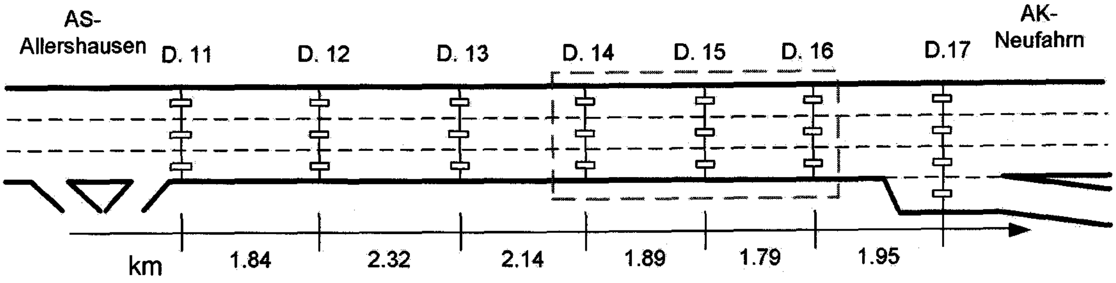
Fuzzy if-then rules are a knowledge representation scheme for describing a functional mapping or a logic formula that generalizes an implication in two-valued logic. These rules represent the relation between the fuzzy sets of traffic variables and the traffic states (〈Table 2〉).

〈Table 2〉 Fuzzy if-then rules

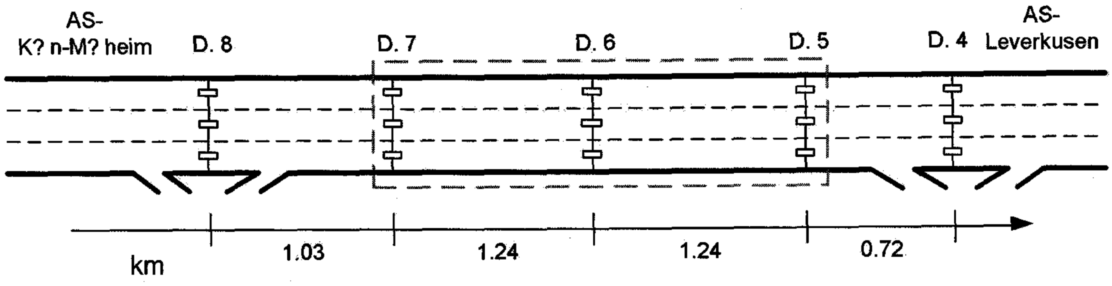
Rule	Input			Output
	Speed	Flow	Density	
1	Very High	Low	Very Low	Free
2	High	Very Low	Very Low	Free
3	Medium	Low	Very Low	Free
4	High	Low	Very Low	Free
5	High	Medium	Low	Impeded Free
6	High	High	Medium	Impeded Free
7	Medium	High	Medium	Synchronized
8	Medium	Medium	Medium	Synchronized
9	Medium	Low	Low	Synchronized
10	Low	Medium	High	Congested
11	Very Low	Low	High	Jammed



a) German freeway A5



b) German freeway A9



c) German freeway A3

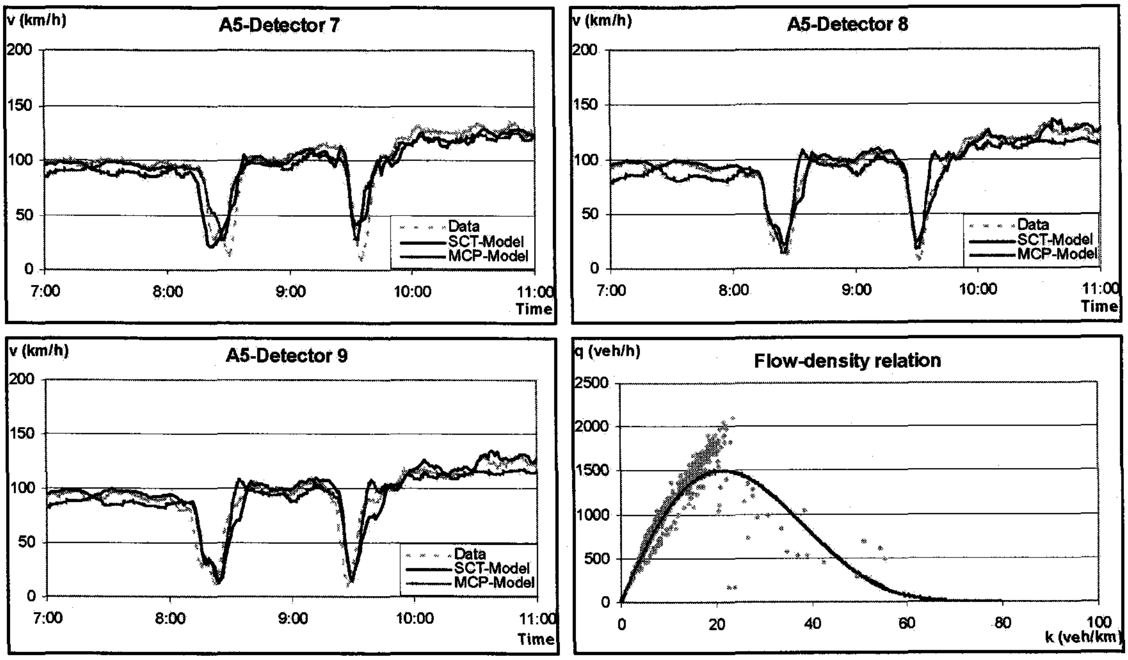
〈Figure 13〉 Schematic presentation of homogeneous freeway sections

3. Results

The performance of the situational cell-transmission model was tested and evaluated applying boundary conditions obtained from real traffic data. The model was tested in homogeneous freeway sections. The results of the model are compared with those of a high order continuum model.

The situational cell-transmission model was tested for various homogeneous German freeway sections A5, A9, and A3 which have 3 lanes in each direction. The traffic data was collected at 1-min. intervals and averaged over the 3 lanes. The dotted lines indicate the test freeway sections. AK and AS represent the junction of freeways and the region of ramps see 〈Figure 13〉. The lengths of the test freeway sections are about 2.0 km (A5), 3.7 km (A9), and 2.5 km (A3).

The traffic data observed at three sets of



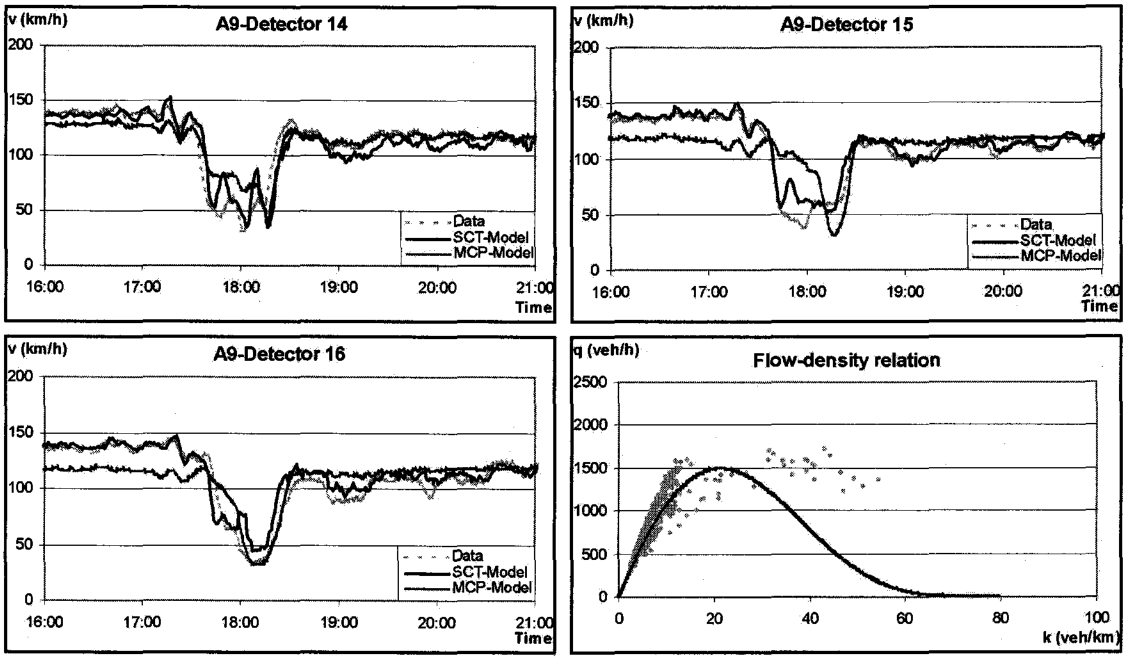
〈Figure 14〉 Results of German freeway A5

detectors is used for the traffic flow modeling and for the performance evaluation of the model in the homogeneous freeway sections. The traffic data of the upstream and downstream detectors is used as the boundary condition of the model.

The simulation results are compared with the traffic data not only of the intermediate detector but also of the upstream and downstream detectors, in order to examine the stability of the first and the last cells of the model. As mentioned before the existing macroscopic modeling approaches have difficulties in describing traffic situations of the first and the last cells correctly and cause unreasonable results if the traffic data deviates from the given flow-density relation, which makes the online application of the traffic flow models difficult.

The results of the situational cell-transmission model was compared with those of a high order continuum model, a modified Cremer-Payne model (Poschinger, 1999) in order to emphasize the importance of the parameter calibration for the traffic flow model. The modified Cremer-Payne model is calibrated beforehand to optimize the simulation results of the German freeway section A5 and the calibrated parameters are used to simulate the other German freeway section A9 and A3.

A set of simulation results and the flow-density relation of the downstream traffic situation (detector 9) of the German freeway section A5 are shown in 〈Figure 14〉 because the downstream traffic situation has more dominant impacts on the macroscopic traffic flow models than upstream traffic situation. In this traffic data two congestions are observed consecutively. Both of the congestions have regular shapes and maintain the shapes during the propagation through the freeway section. This type of congestion matches the basic assumptions of macroscopic traffic flow models very well. The macroscopic traffic flow model using this type of congestion as the boundary condition normally yields good results. In the simulations with the situational cell-transmission model (SCT-Model) and with the modified Cremer-Payne model (MCP-Model)



〈Figure 15〉 Results of German freeway A9

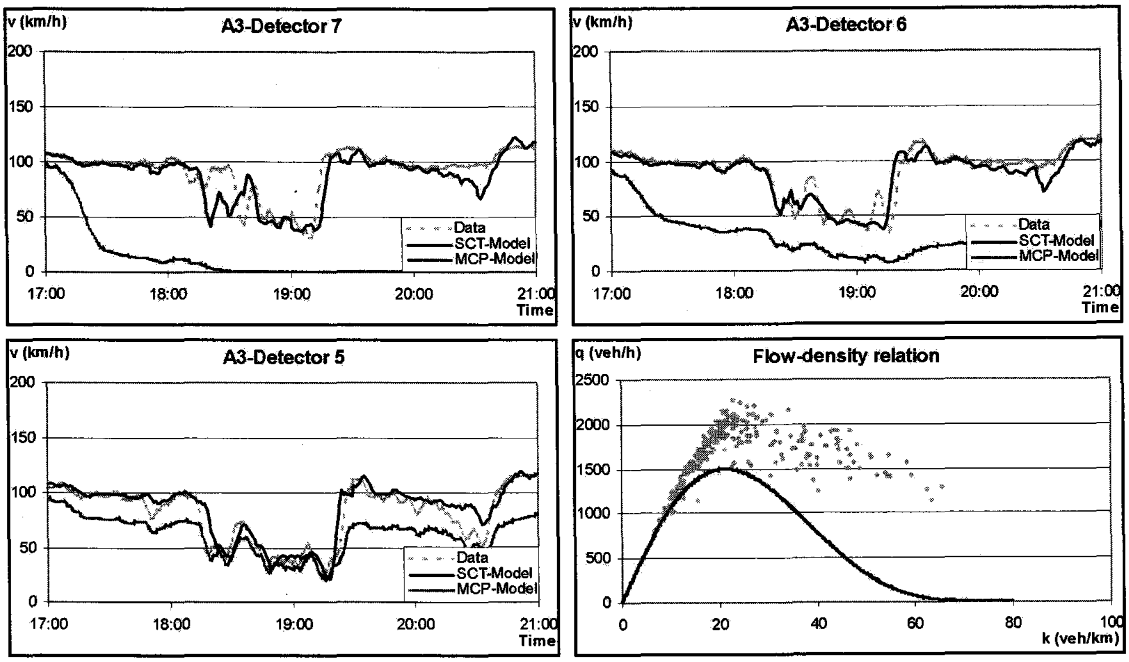
very good simulation results are obtained, too. The parameters of the flow-density relation used in the modified Cremer-Payne model are calibrated to fit the observed traffic data.

A set of simulation results and the flow-density relation of the downstream traffic situation (detector 16) of the German freeway section A9 are shown in 〈Figure 15〉. In this traffic data congestion is observed for about one hour. The congestion has a minor change in shapes of congestion during the propagation through the freeway section. The simulation with the situational cell-transmission model gives very good results but the simulation results with the modified Cremer-Payne model are not quite satisfactory. As can be seen in 〈Figure 15〉, there are discrepancies between the flow-density relation used in the modified Cremer-Payne model and the traffic data in the region of the congested traffic.

A set of simulation results and the flow-density relation of the downstream traffic situation (detector 5) of the German freeway section A3 are shown in 〈Figure 16〉. In this traffic data congestion is observed for about one hour. The congestion has a significant change in shapes during the propagation through the freeway section.

The downstream traffic data (detector 5) shows that the congestion begins at 18:15 and ends at 19:25 and the speed decreases again significantly around 20:30. The upstream traffic data (detector 7) shows that the congestion does not begin until 18:30 and ends at 19:15 which is earlier than in the downstream traffic situation, and there is no speed decrease after that. This boundary condition does not match the basic assumptions of macroscopic traffic flow models very well. The macroscopic traffic flow models using this type of congestion as the boundary condition normally give no satisfying results.

In the situational cell-transmission model, the traffic dynamics of a freeway section are influenced mainly by the downstream traffic situation due to the flow-density determination strategy employed in this research. The situational cell-transmission model describes the propagation of congestion



〈Figure 16〉 Results of German freeway A3

occurring downstream at 18:15, which in reality does not reach the upstream detector. Therefore, the simulation results show the earlier congestion than the traffic data of detector 7. This problem can be alleviated by improving the flow-density determination strategy.

Since the flow-density relation does not match the traffic data the modified Cremer-Payne model cannot describe the traffic dynamics of this freeway section at all. This example shows the sensitivity of the macroscopic traffic flow models to the flow-density relation. The stability problem of the first cell occurs because of the discrepancies between the flow-density relation and the traffic data.

The simulation results of three different cases show that the situational cell-transmission model describes the intermediate and the downstream traffic situations better than the upstream traffic situation. This tendency is due to the flow-density relation determination strategy which depends mainly on the downstream traffic situation and the inherent characteristics of macroscopic models to describe the congestion propagation.

If a static flow-density relation were used for the simulation the static flow-density relation should be calibrated depending on the traffic data each time; see 〈Figure 14, 15, 16〉. In the whole simulation of this research, the situational cell-transmission model used the same parameters and no additional adjustments were needed, which is very important for the online application of the traffic flow model.

The situational cell-transmission model describes the traffic flow satisfactorily for on-line traffic control. Traffic flow can be better simulated with a calibrated static flow-density relation. However, the cell-transmission model with the dynamic flow-density relation can alleviate the critical shortcoming, i.e. parameter calibration problem.

Ⅵ. Conclusion

The flow-density relation was interpreted as a states diagram based on the hysteresis phenomenon detected by dynamic observation of the traffic flow. Traffic states with the same characteristics and the transitions between the states are analyzed by the observation of time series of flow and speed.

Traffic measurements at different consecutive sections on German freeways were studied considering the prevailing conditions. In this way it was possible to classify traffic data according to the prevailing traffic condition, in particular to separate the data into states of traffic which are demand-oriented, i. e. free flow conditions (the free flow and the impeded free flow state) caused by upstream traffic phenomena and various states of congested flow (the congested, jammed state and the stopped state), which are supply-oriented, i.e. caused by the downstream capacity or bottlenecks. A transient state called synchronized state was also observed between them. It could be shown from the empirical analysis that the hystereses within the transitions have different characteristics when displayed in the speed-density and the flow-density relations depending on the traffic conditions and the geometry of the freeway. By means of the empirical investigation of freeway sections the traffic states and the transitions between the states are analyzed and represented together in a diagram of traffic states.

A new procedure for on-line traffic flow modeling was developed based on a cell-transmission model and dynamic flow-density relations. The performance of the situational cell-transmission model shows very good results based on real traffic data on German freeways. The comparison of the simulation results of the situational cell-transmission model and the modified Cremer-Payne model emphasizes that the new macroscopic modeling approach can overcome the parameter calibration problems stemming from the static flow-density relation and describe the basic traffic dynamics caused by prevailing traffic demand and supply conditions. The proposed modeling procedure provides basis for the development of online macroscopic traffic flow models which can be applied in practice to describe traffic situations on freeways where detectors are not densely installed.

However, the situational cell-transmission model cannot overcome the inherent shortcomings of the macroscopic traffic flow model. The performances of the model depend significantly on the boundary conditions. If the boundary condition matches the assumptions of the macroscopic model the performance of the model is very good. Otherwise, the model yields no satisfying results. The test motorway sections were spatially limited and some discrepancies between the upstream traffic data and the simulation results were observed. To alleviate these problems finer determination strategies of the flow-density relation should be developed and applied to the model.

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