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Online Traffic Flow Model Applying Dynamic Flow-Density Relations

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Contents

1 Introduction

Traffic refers to the movement of vehicles, ships, trains, or aircraft between one place and another. Society has an ever increasing demand for mobility so that the role of traffic becomes more important. The traffic of vehicles is the most interesting subject for the traffic engineers because it represents a significant portion of total traffic and the inefficient usage of the resources caused by traffic congestion is no longer negligible. The environmental damage caused by traffic congestion cannot be calculated directly and there is no simple remedy.

To alleviate traffic congestion two basic approaches are suggested; construction of new facilities or optimal usage of the existing facilities.

Construction of new facilities is a simple and effective method to alleviate traffic congestion. However, this method cannot be implemented easily nowadays because of limited spatial resources.

The optimal usage of the existing facilities can be achieved by the application of efficient traffic control measures. The efficient traffic control measures are being actively investigated employing advanced technologies. This approach has a great potential to improve the traffic situation. The traffic control measures are composed of traffic states identification processes and traffic control processes.

This research discusses online traffic flow models which provide the basis for the traffic state identification processes.

1.1 Needs for the Online Traffic Flow Model

Traffic flow has been investigated by observing traffic phenomena in real traffic situations and interpreting the traffic phenomena based on traffic flow theory. The traffic flow theory is defined as "the description of traffic behaviour by application of the laws of physics and mathematics" (GERLOUGH and HUBER, 1975).

The traffic flow theory seeks to describe the interactions between the vehicles and their operators (the mobile components) and the infrastructure (the immobile component) in a precise mathematical way (GARTNER ET AL., 1997). The traffic flow theory has been developed to reproduce the characteristics of traffic flow by means of various modelling approaches. The performances of the modelling approaches have been verified by comparison with real traffic data. Traffic flow models provide the basis for understanding traffic flow and focus on the qualitative analysis of traffic phenomena.

Nowadays, various traffic control measures, e.g. ramp metering, route guidance systems, variable message signs, have already been developed and implemented in order to improve the traffic conditions. For the activation and the evaluation of the effectiveness of the traffic control measures, the information of the current traffic state on traffic networks, e.g. delay or travel time of the traffic networks, is very important.

For the realistic information of the current traffic state on traffic networks, the traffic flow of the networks is simulated by traffic flow models reproducing traffic dynamics with actual boundary conditions. For the simulation with online traffic data sound traffic flow models are needed which are reliable for the online quantitative analysis as well as for the offline qualitative analysis of traffic phenomena.

However, most traffic flow models developed for the offline qualitative analysis are not compatible with the online quantitative analysis. Traffic flow models developed for the offline analysis are very sensitive to the parameter calibration. The sensitivity of the parameters leads to the transferability and post-prediction problems, which means that the parameters should be calibrated beforehand each time depending on the traffic data set. This property is critical for the online application of traffic flow models. The shortcomings of the existing models should be improved for the online application to traffic control systems. A group of researchers have tried to apply the Kalman filter approach to solve the parameter calibration problems (CREMER, 1979) and showed encouraging results (POSCHINGER, 1999). However, the application of the Kalman filter approach is limited because the covariance matrix of the Kalman filter approach is very difficult to determine, which has a pronounced effect on the results.

In this research a new approach of online traffic flow modelling is developed based on an existing traffic flow model.

1.2 Required Properties for the Online Traffic Flow Model

The purpose of this research is to develop a new modelling approach of motorway traffic flow, which can reproduce current traffic states well with online traffic data and can be applied to traffic control systems. The following properties are indispensable for online traffic flow models and are considered in the model developed in this research.

Observed phenomena should be considered in the modelling: The observed phenomena in traffic flow should be analysed, theoretical explanations for the phenomena should be found, and the phenomena should be considered in the traffic flow modelling.

The problem of calibration should be alleviated: For the online application the number of parameters in the model should be reduced and the parameters should have clear physical meaning and be easy to calibrate.

The model should be robust: For traffic flow models used in practical traffic control systems, the robustness is a more important property than the ability to describe traffic flow in more detail. Traffic data is composed of the real changes in traffic flow (low frequent components) and the stochastic effects (high frequent components). The shorter the detection interval, the greater the stochastic effects. Traffic control systems use traffic data based on a short detection interval, which has strong stochastic effects. If the traffic flow models are too sensitive to the changes in traffic flow considered by the boundary conditions, the results of the models depend heavily on the stochastic effects and the model often yields illogical results, which is not desirable for the online application of traffic flow models.

Traffic dynamics should be modelled: Though the robustness is an important property of online traffic flow models the basic traffic dynamics should be described depending on the traffic situation.

1.3 Methodology

The macroscopic modelling approach is preferred for an online traffic flow model because of the validation problems of humans' behaviour in the microscopic modelling approach mentioned in DAGANZO (1994). The cell-transmission model, a discrete version of the first order continuum (kinematic wave) models of traffic flow, is extended with the dynamic sending and receiving functions (i.e. the dynamic flow-density relation), the application of buffer cells, and the determination strategy for the flow-density relation in the cells.

The required properties of the online traffic flow model mentioned above are considered in the development of the model and detailed methods for the implementation are represented as follows.

- **Observed phenomena should be considered in the modelling**: In the homogeneous motorway sections traffic flow is classified into six traffic states depending on the characteristics, and a states diagram representing the six traffic states and transitions between the states is proposed. The dynamic sending and receiving functions of the cell-transmission models are determined based on the states diagram. In the motorway sections with ramps traffic flow is classified into three traffic states depending on the propagation of congestion and a new phase diagram is proposed. In the motorway sections with ramps the dynamic sending and receiving functions based on the states diagram are modified by means of the phase diagram.

- **The problem of calibration should be alleviated**: In the extended cell-transmission model there are parameters in the determination process of the sending and receiving functions. The parameters used for the determination of the linear sending and receiving functions have clear physical meanings and are not so sensitive to minor differences in the flow-density relation, which depend on traffic data sets.

- **The model should be robust**: The first order continuum model used in this research is more stable than the high order continuum models which can produce illogical results, i.e. negative density or too high density values. Fuzzy logic used for the determination of the dynamic sending and receiving functions can diminish the stochastic effects of traffic data. The instability problem of the first or last cells (or segments) occurring in the implementation of the continuum models due to the discrepancies between the models and traffic data is alleviated by applying the buffer cell strategies. By using the dynamic flow-density relation the traffic flow model can react satisfactorily to unexpected changes in traffic flow without additional calibrations of the parameters of the model.

- **Traffic dynamics should be modelled**: In the extended cell-transmission model the dynamic sending and receiving functions of the cells are determined based on the shock wave theory depending on the upstream and downstream traffic situation. By this decision strategy of the sending and receiving functions the basic traffic dynamics influencing the current traffic states of the motorway section is represented well enough for the online application, even though traffic dynamics is not as well described as by the offline traffic flow model.

1.4 Outline of the Dissertation

The outline of this research is shown schematically in Fig. 1.1.

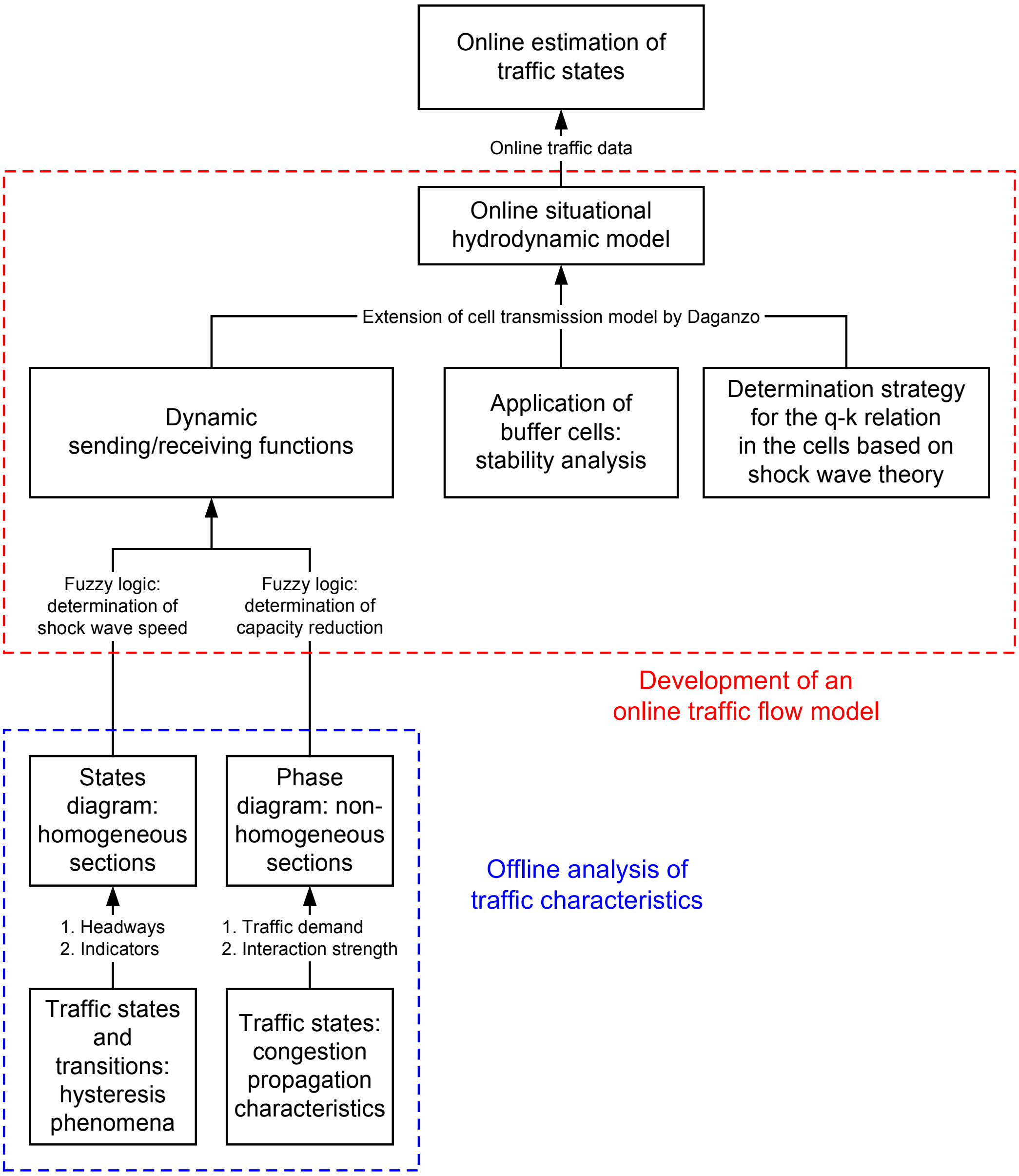


Figure 1.1: Outline of the research

The objective of this research is the estimation of traffic states based on online traffic data applying a sound traffic flow model. This research is composed of two parts, the development of an online traffic flow model, and the offline analysis of traffic characteristics.

An online traffic flow model is developed by extending the cell transmission model of DAGANZO with application of dynamic sending/receiving functions, application of buffer cells, and determination strategy for the q-k relation in the cells. The dynamic sending/receiving functions are determined by the shock wave speed and the capacity reduction which are estimated with fuzzy logic based on the states diagram and the phase diagram.

Traffic characteristics are analysed based on the offline traffic data. In homogeneous motorway sections various traffic states and transitions between the traffic states are analysed and represented in the states diagram. In non-homogeneous motorway sections traffic states are simplified and represented in the phase diagram.

This dissertation is organised as follows;

Chapter 2 contains the overview of the traffic flow models, particularly of the macroscopic traffic flow models in homogeneous motorway sections and in motorway sections with ramps. The first order and the high order continuum traffic flow models are compared, and the properties of each model are presented.

Chapter 3 presents the hysteresis phenomenon in traffic flow. Traffic flow is classified into six traffic states depending on the characteristics, and the transitions between the traffic states are analysed empirically as well as theoretically. The traffic states and the transitions are represented in a states diagram and the dynamic flow-density relation is proposed. For the delimitation of the traffic states, the mean and the variance of headway from individual traffic data are analysed and new transition indicators based on macroscopic traffic variables are developed.

In chapter 4 traffic characteristics of bottlenecks caused by ramps are presented. Shortcomings of the former investigations are analysed and a new phase diagram is presented based on the upstream traffic demand and the interaction strength defined in this research. The interaction strength is proposed as an indicator for the congestion propagation.

Chapter 5 presents a new approach to online traffic flow modelling based on the cell-transmission model and an online process to adapt the linear sending and receiving functions dynamically to the site-specific changes in the traffic context. In this model a motorway link is divided into various cells with different characteristics. In particular, the role of buffer cells to prevent the illogical behaviour of the first or last cells is proved mathematically. The relation between traffic flow and fuzzy logic and the determination process of the dynamic flow-density relation, not only in the homogeneous motorway sections but also in the motorway sections with ramps, are presented.

In chapter 6 the performance of the new model is evaluated. The new model is tested in various homogeneous German motorway sections and in a German motorway section with ramps. The performance of the new procedure shows very good results when compared with real traffic data. These results show that the new macroscopic traffic flow model can overcome the transferability and post prediction problems stemming from the static flow-density relation and describe the basic traffic dynamics caused by prevailing traffic demand and supply conditions.

Chapter 7 concludes this dissertation by emphasising the contributions of this research to the modelling of traffic flow and indicating the future research to improve existing traffic flow models.

2 Dynamic Traffic Flow Models

Researchers from engineering, mathematics, operations research, and physics have proposed numerous traffic flow models with various modelling approaches since 1950. The traffic flow models are classified into macroscopic, mesoscopic, and microscopic models based on modelling approaches. All traffic flow models have their own application areas. None of them are false or correct but models from a certain approach fit the objectives of the application well or not (KÜHNE, 1993).

In this chapter traffic flow models developed by now are briefly surveyed and a few traffic flow models relevant to the model developed in this research are discussed in detail.

2.1 Overview of Traffic Flow Models

Each decade was dominated by a certain modelling approach (HELBING, 2001). In the 50ies, the propagation of shock waves was described by fluid-dynamic models for kinematic waves. The investigations in the 60ies concentrated on microscopic car-following models. During the 70ies gas kinetic models for the spatio-temporal change of the speed distribution were flourishing. The simulation of macroscopic fluid-dynamic models was common in the 80ies. The 90ies were dominated by discrete cellular automata models of vehicle traffic and by the systematic investigations of the dynamic solutions of the models developed in the previous 50 years.

The microscopic traffic flow models describe the dynamics of individual vehicles and their interactions (e.g. car-following models and cellular automata models). The mesoscopic traffic flow models describe the microscopic vehicle dynamics as a function of macroscopic fields (e.g. gas kinetic models). The macroscopic traffic flow models describe the collective vehicle dynamics in terms of aggregate variables; density [veh/km], flow [veh/h] and speed [km/h] (e.g. fluid-dynamic models).

Until now microscopic and macroscopic models are generally used to describe the traffic dynamics and investigated by numerous researchers empirically as well as theoretically. Microscopic models describe the dynamics and interactions of individual vehicles and provide the basic formulations for follow-the-leader traffic theory through which certain characteristics of a stream of interacting vehicles can be described by means of driver-vehicle parameters. Macroscopic models treat the traffic stream as a continuous fluid. The behaviour of individual vehicles is ignored and that of sizeable aggregates of vehicles is considered. Vehicular traffic is not very much like the physical fluids but there are sufficient similarities to make the hydrodynamic theory useful in describing traffic dynamics (GAZIS, 1974).

Microscopic models are more fundamental to the traffic flow theory than macroscopic hydrodynamic models which simply look at a traffic stream as an analogue of a continuous fluid and use fluid rather than driver-vehicle parameters. However, microscopic models assume that the behaviour of an individual vehicle is a function of the traffic conditions in its environment and their assumptions are difficult to validate because humans' behaviour in real traffic is difficult to observe and measure. Even though the behaviour can be measured there are marked deviations in the behaviour of drivers. It is, therefore, not easy to calibrate these behaviours for online applications. On the other hand, macroscopic models are based on the aggregate behaviour of vehicles, and their advantage over microscopic models is that this aggregate behaviour is easier to observe and validate, which makes the online application of macroscopic models feasible.

The microscopic models are useful for the evaluation of effects of new traffic control measures or for predicting the development of the traffic flow in the possible scenarios. The macroscopic traffic flow models are suitable for the description of current traffic states with real traffic data, which is the objective of this research. Therefore, in this research the macroscopic traffic flow models are investigated in depth and applied.

The macroscopic model is classified into the simple continuum model and the high order continuum model based on the assumption of the speed equation. The properties and shortcomings of each model are discussed in the following sections.

The macroscopic models are based on the assumption of the existence of the flow-density relation which describes the equilibrium states depending on the density values. The flow-density relation has dominant effects on the results of macroscopic models. The existence of the equilibrium states, however, is doubtful and the flow-density relation cannot be determined with short interval traffic data. Until now the method of determining the flow-density relation with short interval traffic data has not been investigated, though it is a prerequisite for the application of the macroscopic model to traffic control systems. In this research a decision strategy of the dynamic flow-density relation with short interval traffic data is presented and applied to a macroscopic model.

Macroscopic models developed at first for homogeneous motorway sections have been extended to describe traffic dynamics of non-homogeneous motorway sections. The extended models, however, have inherited shortcomings and need engineering fixes to overcome the problems. The extended models are not capable of being applied to traffic control systems because of difficulties in the calibration. In this research, a newly developed macroscopic model is applied with minor additional modifications to describe the propagation of congestion in sections with ramps.

2.2 Simple Continuum Model

LIGHTHILL and WHITHAM (1955) introduced a method of kinematic waves (the theory of flood movement in rivers) for the analysis of the traffic phenomenon. This 'continuous-flow' approach represents the aggregate behaviour of a large number of vehicles and is applicable to the distribution of traffic flow along long and crowded roads. A theory of the propagation of changes in traffic distribution along the roads was deduced. For the macroscopic description of the theory the flow q [veh/h], the density k [veh/km] and the mean speed v [km/h] are considered as differentiable functions of time t and space x.

The fundamental hypothesis of the theory is that at any point of the road the flow q is a function of the density k. A functional relationship between the flow and the density for traffic on crowded roads was postulated and verified by traffic data. This hypothesis implies that slight changes in traffic flow are propagated through the stream of vehicles along 'kinematic waves'.

A basic conjecture of the simple continuum model is that vehicles are not created or lost along the road. This conservation law of the number of vehicles leads to the continuity equation.

$$\frac{\partial k}{\partial t} + \frac{\partial q}{\partial x} = 0$$

From the continuity equation with the flow-density relation (q = q(k)) and the basic relation between traffic variables (q = v·k), a differential equation of the density (k) is derived.

$$\frac{\partial q}{\partial x} = \frac{\partial q(k(x))}{\partial x} = \frac{dq}{dk}\frac{\partial k}{\partial x}$$

$$\frac{\partial k}{\partial t} + c\frac{\partial k}{\partial x} = 0$$

$$c = \frac{d}{dk}(kv) = v + k\frac{dv}{dk}$$

The general solution of this first order partial differential equation is k = f(x-c·t), where f(x) is an arbitrary function, and the solution of any particular problem consists merely of matching the function f to initial or boundary values (KELLER, 2001).

The simple continuum model of LIGHTHILL and WHITHAM is very instructive and theoretically clear. However, this model has some shortcomings (GARTNER ET AL., 1997):

- In this model, traffic flow should be instantly adapted to the flow-density relation (the equilibrium traffic state) according to changes in the density. It is, however, more realistic that traffic flow is adapted after a certain time delay (reaction time).

- This model allows no deviation from the equilibrium traffic state and unstable traffic states cannot be derived from the model. The abrupt breakdown of traffic flow or the stop-and-go traffic phenomenon beyond a certain critical density cannot be explained.

- This model shows shock wave formation by steepening speed jumps finally to infinite sharp jumps. A macroscopic traffic theory is based on average values which are taken over temporal or spatial areas. Infinite jumps, therefore, are in contradiction to the basics of macroscopic descriptions.

- The formation of shock waves causes numerical difficulties. A finite difference discretisation of the partial differential equation is inappropriate near discontinuities, where the partial differential equation does not hold (LEVEQUE, 1992).

- The dynamics of traffic flow results in the hysteresis phenomena generated from a retarded behaviour of vehicle platoons after emerging from a disturbance compared to the behaviour of the same vehicles approaching the disturbance. This model cannot describe such phenomena.

2.3 High Order Continuum Model

The simple continuum model of LIGHTHILL and WHITHAM went undeveloped due to an inability to find meaningful refinements which can overcome the shortcomings of the model explained above. PAYNE (1971) proposed a method of relating macroscopic variables and car-following theories for the development of dynamic macroscopic models which specifically include the feature of a finite reaction time. PAYNE developed an extended continuum model which uses a dynamic speed equation.

$$\frac{dV}{dt} = \frac{1}{\tau}\left(V_e(\rho) - V\right) - \frac{D(\rho)}{\rho\tau}\frac{\partial\rho}{\partial x}$$

The term $(V_e(\rho)-V)/\tau$ is denoted by the relaxation term. The relaxation term allows for the delayed adjustment of the stream to a prespecified speed $V_e(\rho)$ as a result of reaction time and braking or acceleration procedures. The term $(D(\rho)/\rho\tau)(\partial\rho/\partial x)$ is denoted by the anticipation term. The anticipation term allows for the fact that drivers adjust their speeds in advance to changes in density lying ahead (LEUTZBACH, 1988).

CREMER (1979) modified the anticipation term to better describe the behaviour of traffic flow at low densities. Besides, he applied the model to practical traffic control systems and calibrated the parameters with traffic data. KÜHNE (1984) added a viscosity term to smooth the strong change of the densities (shock waves).

PHILLIPS (1979) presented a new kinetic traffic flow model by modifying the BOLTZMANN equation of PRIGOGINE (1961). KERNER and KONHÄUSER (1993) developed an equation of motion based on the NAVIER-STOKES equations and performed extensive numerical investigations for the behaviour of their macroscopic traffic flow model.

The high order traffic flow models have a similar structure and behaviour even though the models are derived from different approaches. The high order models can alleviate the shock wave problem by applying diffusion terms. The reaction time is also considered in the models. The high order models can derive the unstable states by the interplay between anticipation and relaxation effects in the model. The high order models have a critical density, above which uniform flow conditions are unstable and the wave is oscillating with an ever-increasing amplitude. The stop-and-go traffic phenomenon can be explained with the oscillating waves. The models can simulate the different paths (hysteresis phenomenon) in two transitions from free flow to congested flow and from congested flow to free flow.

The high order models, however, have their own problems (DAGANZO, 1995):

- Any high order model that smoothes all the discontinuities (shock waves) produces negative flows and speeds (i.e. wrong way travel) under certain conditions.

- The estimates of the relaxation time (τ) and the anticipation coefficient ($D(\rho)$) obtained from various empirical studies are too large to admit a reasonable physical interpretation (DEL CASTILLO ET AL., 1993). The estimates depend on the discretisation scheme.

- In high order models one shock wave speed is greater than the average speed of vehicles. This is highly undesirable because it means that the future conditions of a traffic element are, in part, determined by what is happening behind it. This is contrary to the basic assumption of anisotropy that traffic flow is influenced only by the traffic situation ahead.

- In high order model there are more parameters to calibrate than in the simple continuum model of LIGHTHILL and WHITHAM.

As DAGANZO (1995b) explained in his research, high order refinements of the simple continuum model of LIGHTHILL and WHITHAM do not improve the deficiencies in a proper way. In the practical applications, the finer description of shock structure is not critical and the improved accuracy of the high order models is lost by the descretization schemes. Therefore, the simple continuum models suffice for the practical applications and are applied to develop an online traffic flow model in this research.

2.4 Cell-Transmission Model of DAGANZO

DAGANZO (1994) developed the cell-transmission model to overcome the numerical difficulties caused by substituting the difference equation for the partial differential equation. The cell-transmission model of motorway traffic is a discrete version of the simple continuum (kinematic wave) models of traffic flow that is convenient for computer implementations. It belongs to the GODUNOV family of finite difference approximation methods for partial differential equations (DAGANZO, 1999a). The solution of the cell- transmission model is close to the exact solution of a differential equation with no side effects, while other difference approximation methods (e.g. LAX's method) can cause undesirable effects, e.g. the negative speed of the vehicles in the cell (DAGANZO, 1995a). In the cell-transmission model the speed is not updated directly, but calculated from the updated flow and density, which is different from the high order models with their separate speed updating processes.

In the cell-transmission model a motorway 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 (k) and the flow (q), and the flow equation used in the cell-transmission model are 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 motorway'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 a previous research of DAGANZO (1994) the sending function S(k) and the receiving function R(k) were suggested as linear functions vk and $w(k_j - k)$. In these functions v, k_j and w are constants denoting, respectively, the free-flow speed, the maximum density and the backward wave speed with which disturbances propagate backward when traffic is congested. In another research of DAGANZO (1999a) the sending and the receiving functions were postulated as nicely fitted curves with traffic data at downstream and upstream cells. But the exact formula for the curves were not suggested in the investigation; see Fig. 2.1.

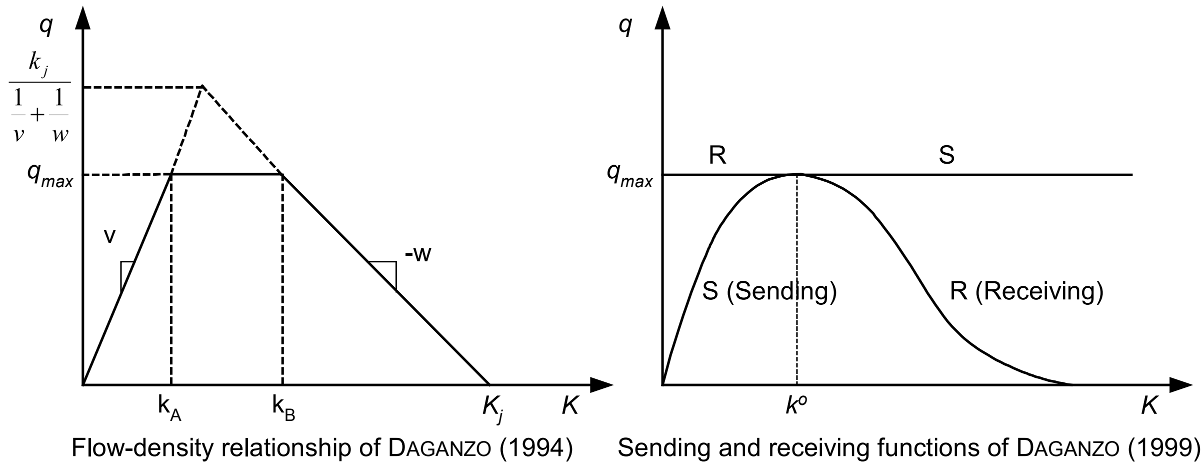


Figure 2.1: Sending and receiving functions of DAGANZO

2.5 Extended Cell-Transmission Model with Dynamic Sending and Receiving Functions

The macroscopic models are based on the assumption of existence of the flow-density relation which describes the equilibrium states depending on the density values. The flow-density relation has significant effects on the macroscopic traffic flow models. The flow-density relation, however, has problems as following.

- The flow-density relation describes the equilibrium state of traffic flow, but the existence of the equilibrium state is questionable, in particular in the unstable density region.
- Even though the equilibrium state exists there are no efficient methods to determine the flow-density relation with the short interval traffic data.
- Macroscopic traffic flow models depend on the flow-density relation significantly. Therefore, the validation process of the model and the calibration of the flow-density relation is identical.
- The flow-density relation is not transferable. The flow-density relation must be newly adjusted depending on the data set.

In the research of DAGANZO (1994, 1999a) the static sending and receiving functions are used which are determined beforehand and do not vary during the traffic flow simulation. With these static functions complicated traffic dynamics generated by various downstream and upstream traffic situations cannot be described in real time.

In this research dynamic sending and receiving functions are proposed, which vary depending on the traffic data at downstream and upstream cells. The dynamic sending and receiving functions are based on the assumption that every traffic data fits 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 the classification of traffic states and fuzzy logic, which are discussed in detail in the next chapter.

2.6 Extended Model in Non-homogeneous Motorway Sections

The traffic dynamics of non-homogeneous motorway sections is very complicated and has not been investigated in depth yet. Some researchers tried to describe the complicated traffic dynamics by extending the traffic flow model for homogeneous motorway sections with modifications of the model.

CREMER and MAY (1985) and PAPAGEORGIOU ET AL. (1990) extended a macroscopic dynamic traffic flow model (PAYNE model) to reproduce traffic flow of bottlenecks such as lane drop or a merging on-ramp flow by minor modifications of the continuity equation and terms in the speed equation of the model.

The approaches of CREMER and MAY, and PAPAGEORGIOU ET AL. make the speed equation more complicated and increase the number of parameter to calibrate. Improved results can be obtained from the extended models with more parameters. However, the calibration effort of more parameters is not negligible. The parameter calibration is very sensitive depending on the data set, which is critical for the online application of the model.

On the other hand, some physicists (HELBING ET AL., 1999; LEE ET AL., 1999, 2000) investigated the traffic flow of motorway sections with an on-ramp employing the phase diagram empirically as well as theoretically. In the phase diagram various traffic states with different characteristics are represented depending on the upstream traffic demand and the on-ramp flow. Characteristics and analytical conditions for transitions between the states are investigated, too. The details of the phase diagrams are discussed in chapter 4.

In this research traffic flow of motorway sections with an on-ramp and an off-ramp is analysed based on a new phase diagram, and the propagation of congestion is simulated based on the situational cell-transmission model with minor modifications.

2.7 Summary

For an effective traffic control on motorways proper traffic flow models are required which can describe the traffic situation satisfactorily in real time.

In this chapter traffic flow models developed until now are briefly surveyed and a few traffic flow models which are relevant to the model developed in this research are discussed in detail. Each decade was dominated by a certain modelling approach and there is no generally predominant model for all application objectives. Some models from a certain approach may fit to objectives of an application better or not.

Traffic flow can be described in microscopic or macroscopic ways. The microscopic models are useful mainly for the evaluation of effects of new traffic control measures or for predicting the development of the traffic flow in the possible scenarios. The macroscopic traffic flow models are suitable for the description of current traffic states with real traffic data, which is the objective of this research. Therefore, in this research a macroscopic traffic flow model is improved and applied to the online description of traffic flow.

From the analysis of macroscopic traffic flow models it is concluded that though the high order models are intended to improve the simple continuum model, they have their own inherited problems and the improved accuracy of the high order models are not so pronounced in the practical applications (DAGANZO, 1995b). Therefore, the simple continuum model is selected for the objective of this investigation, the description of the current traffic situation with online traffic data.

The cell-transmission model, a variant of the simple continuum model, is extended with dynamic flow-density relation which can overcome the shortcomings of the static flow-density relation. The extended cell-transmission model is applied not only to the homogeneous but also to the nonhomogenous motorway sections applying a new phase diagram.

3 Hysteresis Phenomenon in Traffic Flow

The flow-density relation provides a simple way of illustrating traffic flow behaviour on a motorway section under different flow q [veh/h] and density k [veh/km] conditions. Various models have been used to describe the relation between these variables and empirical evidences show that these models have difficulties in describing the observed phenomena.

The flow-density relation has mainly been used for the assessment of transportation facilities, for which estimates of certain characteristic constants of the flow-density relation (e.g. free flow speed, capacity of a freeway section etc.) are required. In order to obtain stable values of these characteristic constants the individual traffic data is mainly averaged during the 1-hour interval as in the German Highway Capacity Manual "Handbuch für die Bemessung von Straßenverkehrsanlagen" (BRILON ET AL., 1997). This long-interval static relation is not capable of reacting satisfactorily to current unexpected changes in traffic flow, which would be mandatory for real-time traffic control. For the traffic control, shorter detection intervals, e.g. 1-5 min. intervals, are required so that the prevailing traffic states can be better observed. As shown in the last chapter, the flow-density relation has a dominant effect on the results of the continuum traffic flow model.

The time series analysis of the flow-density and the speed-density relation based on short data collection intervals shows the hysteresis phenomena which are not observed during the long intervals. For the analysis of the hysteresis phenomenon traffic flow is classified into various traffic states and the transitions between these traffic states are investigated in particular. The hysteresis phenomena are analysed taking into account the various upstream and downstream traffic conditions. It is shown from the empirical analysis that each traffic state and hysteresis in the transitions have different characteristics depending on the traffic conditions.

In this chapter, a novel shape of the states diagram is produced and a dynamic flow-density relation is proposed for an online traffic flow model employing this states diagram.

3.1 Flow-Density Relations

The speed-density relation of freeways interpreted as being linear by GREENSHIELDS (1935) exerts dominant influences on the relation between the flow q [veh/h] and the density k [veh/km]. LIGHTHILL and WHITHAM (1955) conjectured a flow-density relation from the information that at low density values the speed v = q/k was regarded as a function of the flow and at high density values the headway N/k was regarded as a function of speed v = q/k. The flow-density relation of LIGHTHILL and WHITHAM is shaped into a parabolic curve, single-regime flow-density relation, whose maximum value of the flow shows the expected value of the capacity of a motorway section; see Fig. 3.1.

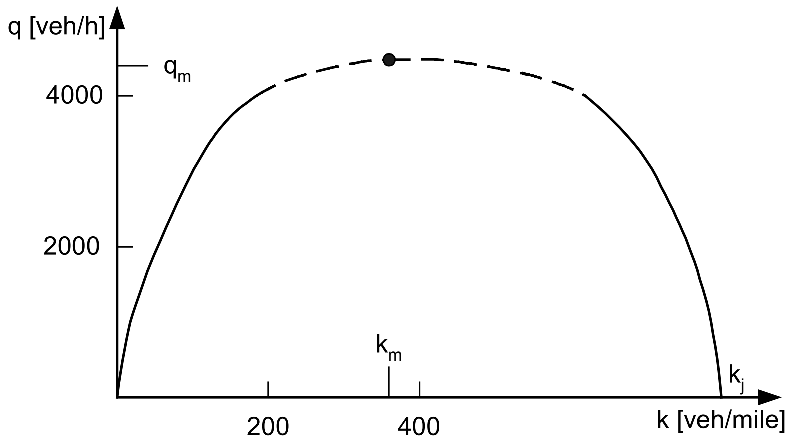


Figure 3.1: The flow-density relation of LIGHTHILL and WHITHAM (1955)

Since LIGHTHILL and WHITHAM proposed the single-regime flow-density relation, many researchers have attempted to define the mathematical form of the flow-density relation and to verify it theoretically and empirically. GAZIS, HERMAN, and ROTHERY (1961) derived a general macroscopic relation for the traffic variables from the microscopic car-following theory describing the motion of the two cars.

However, the relation derived by GAZIS ET AL. becomes less and less realistic as traffic becomes less and less dense. To overcome this problem, EDIE (1961) derived a complementary theory for free traffic conditions from a modified car-following model by imposing an upper limit on stream speed. EDIE first suggested two different models for the flow-density relation, one for free traffic and the other for congested traffic and the existence of some kind of change in traffic state; see Fig. 3.2.

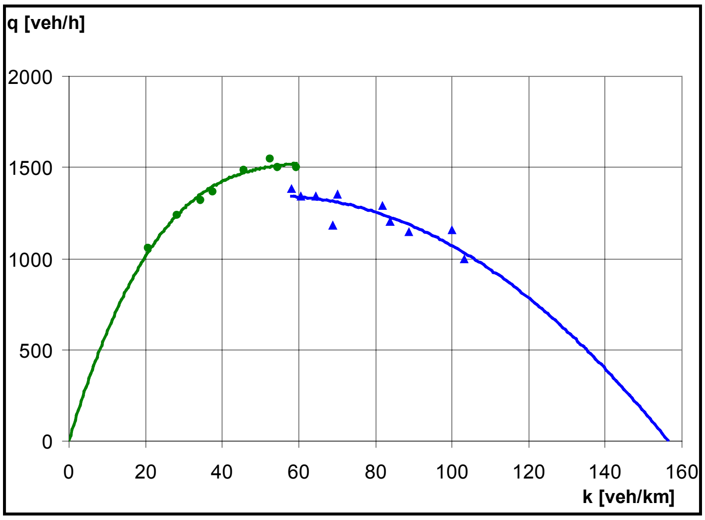


Figure 3.2: The flow-density relation of EDIE (1961)

MAY and KELLER (1967, 1968) developed two-regime traffic flow models based on the generalised car-following model of GAZIS ET AL. (1961), and also showed that a hyperbolic function describes congested traffic better than a parabolic function; see Fig. 3.3.

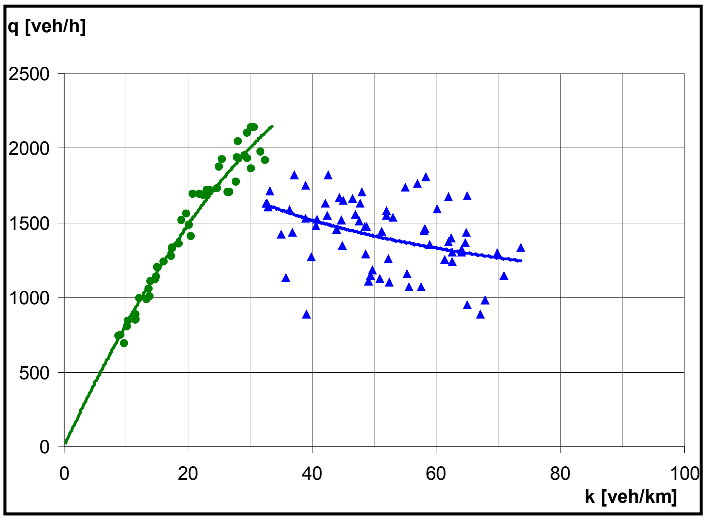


Figure 3.3: The flow-density relation of MAY and KELLER (1968)

By analysing the traffic data collected on the Tokyo Expressways KOSHI ET AL. (1983) postulated that the free flow and congested flow form not a single downward concave curve on the flow-density plane but a shape like a mirror image of the Greek letter lambda (λ). They also classified the vehicles in the free flow condition into two groups (only followers in free flow and leaders + followers in free flow). They also pointed out that the flow-density relation in the congested region is not downward concave as represented by Greenshields' and Greenberg's models, but upward concave; see Fig. 3.4.

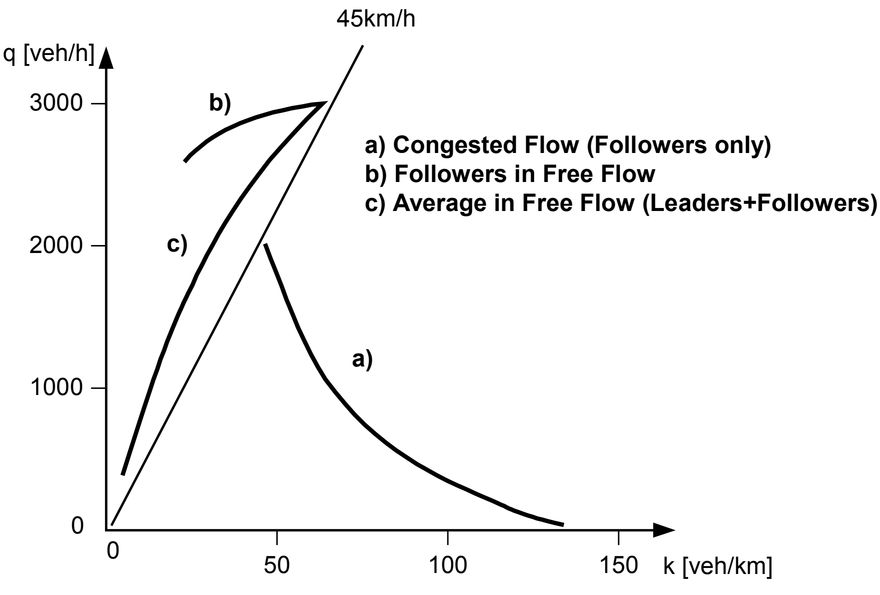


Figure 3.4: The flow-density relation of KOSHI ET AL. (1983)

KERNER (1999) classified traffic flow into 3 traffic states (free flow, synchronised flow and jam) and investigated the formation of traffic jams and the transitions between the traffic states empirically as well as theoretically.

He describes the synchronised flow as a state in which drivers move with nearly the same speed on the different lanes of motorways. In the synchronised flow the speed is relatively low and the flow can be nearly as high as in the free flow. The synchronised flow is distributed broadly in the flow-density relation and is represented as the hatched region in Fig. 3.5.

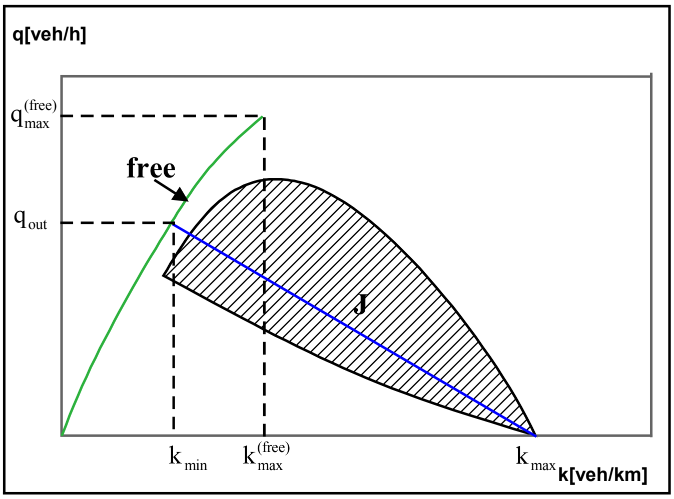


Figure 3.5: The flow-density relation of KERNER (1999)

The line 'J' in the flow-density relation represents the propagation of a jam. The slope of the line 'J' is the propagation speed of a jam. The line 'J' is not a part of the flow-density relation but a characteristic line of a jam, which has the coordinates (k_{min}, q_{out}) and (k_{max}, 0). In this flow-density relation q_{out} means the outflow rate from the jam and k_{min} is the average density in the outflow from the jam.

3.2 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. The representation of the traffic variables as time series shows a hysteresis loop in the flow-density and the speed-density relations on a motorway section with the density first increasing and then decreasing, when congestion builds up and subsequently dissolves.

3.2.1 The Investigation of TREITERER and MYERS

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. This survey covered a time interval of 238 seconds and a distance of about 5.3 km travelled by a platoon of about 70 vehicles without lane changing to investigate kinematic disturbances, i.e. upstream moving shock waves.

A microscopic analysis showed the asymmetry between the behaviour 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 loop B in Fig. 3.6 where the circular trajectory of the traffic flow depending on the density can be seen. After emerging from a kinematic disturbance (shock wave) the platoon accelerates from 40 to 64 km/h and the flow increases from 1800 [veh/h] to almost 3000 [veh/h] without an appreciable change in density (see loop A in Fig. 3.6).

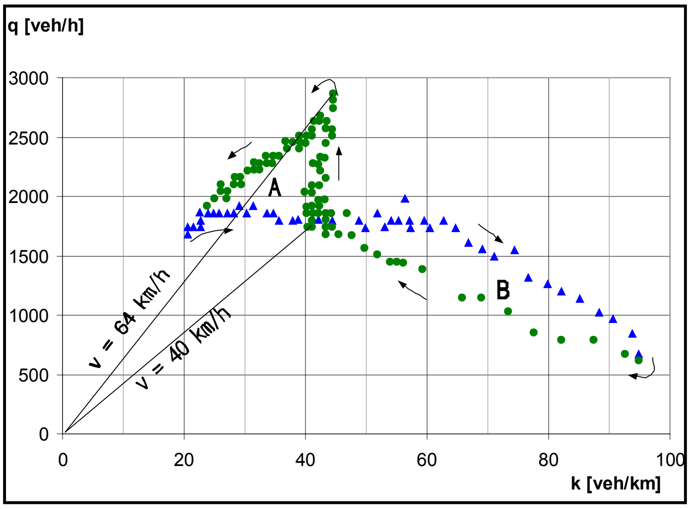


Figure 3.6: The flow-density relation of TREITERER and MYERS (1974)

DAGANZO (1999b) postulated that the loops in Fig. 3.6 are the result of lane changing. It is thought, however, that during the acceleration phase lane changing happens seldom. Moreover, traffic data shows 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, though the pattern of speed increase is different on each lane because of the different composition of cars and trucks. 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.

In the flow-density relation, these different properties of traffic flow upon traveling through the shock wave can be explained if a distinction is made between whether the flow has been measured during the acceleration or the deceleration phase.

The hysteresis phenomenon and various traffic states are obvious in the flow-density relation if the flow-density relation is conceived as a representation of the time series of the density and the flow on a motorway section, i.e. for a certain time interval a prevailing traffic state is observed on the section, which is determined by the interplay between downstream and upstream propagating traffic situations.

3.2.2 The Investigation of ZHANG

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 traffic is not so heavy, 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 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.

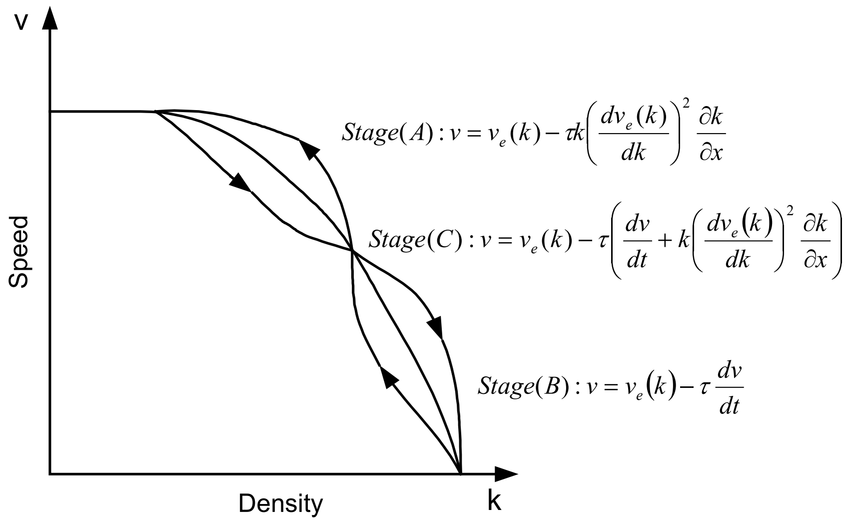


Figure 3.7: Stages of the speed-density relation by ZHANG (1999)

For these three different stages of congested traffic flow ZHANG (1999) derived a system of average speed equations. In stage (A) the speed during acceleration is higher than the speed during deceleration. In stage (B) the speed 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 Fig. 3.7. 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.

3.3 The Flow-Density Relation as a States Diagram

Theoretical and empirical research and the data analysis in this investigation show that traffic flow is classified into various traffic states which can be represented in the flow-density relation. More sophisticated traffic states and transitions could be deduced if more detailed data were available.

3.3.1 Classification of Traffic States

At lower traffic demand **free flow** appears. In the free flow state stable and stochastically stationary traffic conditions prevail on a section and kinematic perturbation (shock wave) propagates downstream according to the continuum theory of LIGHTHILLL and WHITHAM (1955). The speeds of various lanes are noticeably different.

Impeded free flow occurs at increased traffic demand and when the interaction among the vehicles becomes stronger and speeds of various lanes are still different. Perturbations propagate mainly downstream but also upstream contingent upon extreme behaviour of the drivers. The traffic state is meta-stable. The concept “meta-stable” was introduced by PRIGOGINE and HERMAN (1971); KERNER and KONHÄUSER (1994) employed it for specific traffic states.

According to LIGHTHILL and WHITHAM the kinematic waves propagate upstream as soon as the capacity of a motorway section is exceeded. The kinematic waves of traffic flow, i.e. the shock waves, propagate opposite to the direction of travel. The vehicles react to the shock waves first with deceleration and after a while with acceleration in order to pass through it. The traffic state is unstable.

Depending on the speed and direction of shock waves **congested state** will occur. In the congested state speed is quite low and can fluctuate extremely while flow remains still relatively high and does not vary significantly. Speed and flow have a weak correlation in this state. 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 not significantly different.

Jammed state occurs if upstream moving shock waves occur due to high traffic demand and heavy downstream traffic conditions. In the jammed state traffic flow is so unstable that even small perturbations can grow and change the state of traffic flow. The flow is significantly lower than in the congested state but the speed is not necessarily lower.

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.

In **synchronised state** speeds of all lanes are roughly the same. 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. Perturbations propagate upstream or downstream depending on traffic situations. Because the synchronised traffic is meta stable this state can change to the congested or the jammed state if the perturbations exceed the threshold. The synchronised 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 synchronised state.

In the unstable region the traffic flow on a motorway section is mainly characterised by the traffic states caused by the passage of shock waves with different speed and direction, which can bring the traffic flow to a standstill and then return it to the free flow state. Therefore, the traffic states on a motorway section are influenced significantly by the geometry of the section, e.g. distances to on-/off-ramps or changes in the number of lanes and by the capacity reduction due to accidents or incidents.

Fig. 3.8 shows the traffic data of Friday, 28 July, 2000, on a section of the 2-lane German motorway A8. The light green points show the free flow state, the dark green points the impeded free flow state, the blue points the synchronised state, the orange points the congested state and the red points the jammed state. It can be seen that the traffic data within the same density and flow area stems from different traffic situations.

The traffic states in Fig. 3.8 are not sharply defined against each other, but overlap partially because the speed and the flow fluctuate and have slightly different mean values depending on the traffic situations even in the same traffic state. The transitions between neighbouring traffic states are difficult to isolate in the states diagram. For the classification of the traffic states herein formulated, decision criteria are defined and verified. In order to differentiate free flow (the free flow and the impeded free flow state) and congested flow (the synchronised, the congested, and the jammed state) the mean value and the variance of headways are calculated from individual vehicle data and the differences between the average speed of all lanes are tested. In order to differentiate the various congested flows the macroscopic traffic variables, i.e. speed, flow, and density are used. For the identification of transitions, differences between moving averages of flow and speed are applied, which proves to be very efficient in the identification of the transitions between these states. The delimitation of the traffic states is discussed in detail in section 3.5.

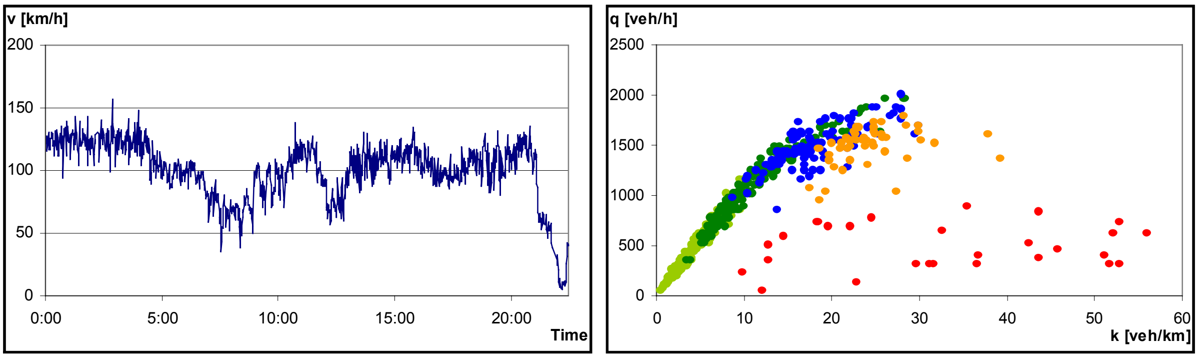


Figure 3.8: Comparison of data for different traffic states (German motorway A8)

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 analysing 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 in chapter 5.

3.3.2 Transitions between Traffic States

The different traffic states and transitions between the states are represented together in a states diagram; see Fig. 3.9. The different traffic states can be distinguished according to typical types of transitions or probabilities of transitions.

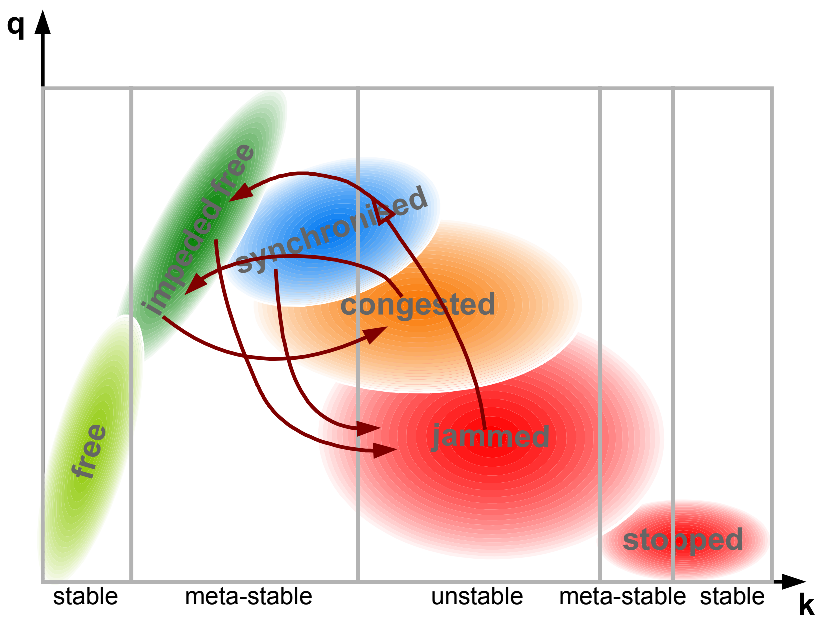


Figure 3.9: Traffic states and transitions in the states diagram

Four transitions are analysed empirically in this paper:

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

The assignment to the neighbouring states of congested and jammed traffic in the states diagram depends upon respective the flow or the speed of the shock waves which are conditioned by the related traffic conditions.

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 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 and downstream traffic situations. The transitions between the impeded free flow and the jammed state, respectively, between the impeded free flow and the congested state can be represented by multiplying the speed equations of ZHANG (Fig. 3.7) by the density, which corresponds to the relation of traffic variables $q = v \cdot k$ and is presented in Figs. 3.10a and 3.10b. In the repeated transitions between the impeded free flow and the congested state or between the impeded free flow and the jammed state the hysteresis phenomenon is not as pronounced as in the transitions between long lasting traffic states; see Fig. 3.10c.

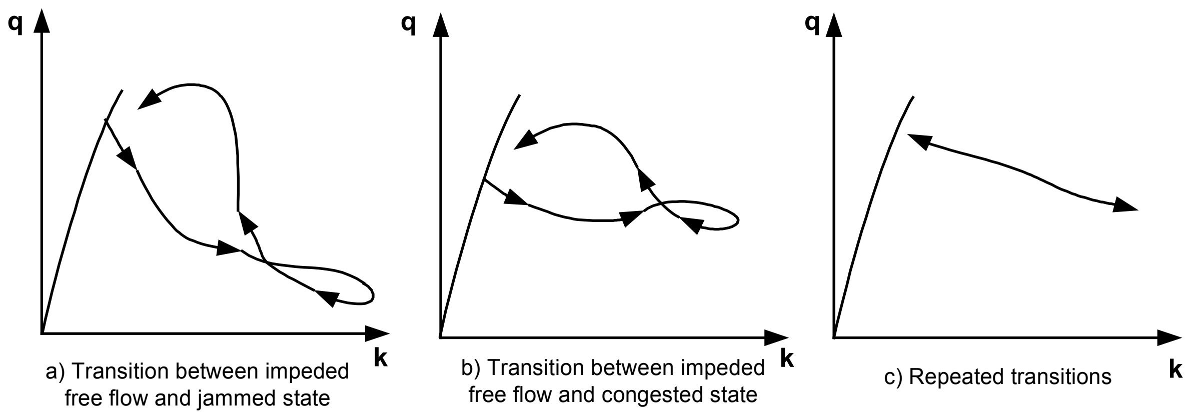


Figure 3.10: Hysteresis phenomena in the states diagram

3.4 Empirical Investigations 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 the German motorway A8 near Munich (WOLTERECK, 2000) and 1-min. traffic data on the German motorway A5 near Frankfurt (LANGE, 1999) were analysed. The speed and the flow were aggregated at 1-min intervals on each motorway section. The aggregated data was not smoothed because the characteristics of hysteresis phenomenon or the relation between density and flow, respectively, can be changed depending on the smoothing level, in particular, during the transition.

Shorter data aggregation intervals were suggested for the exact analysis of the hysteresis phenomenon (ZHANG, 1999). From the analysis of the individual vehicle data, however, 1-min. data aggregation intervals are sufficient to distinguish between the acceleration and deceleration stage. With shorter data aggregation intervals, e.g. 20 or 30 secs., there is more data scattering, and the analysis of the hysteresis phenomenon becomes more difficult.

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 analysed in detail and presented.

3.4.1 Transitions between Impeded Free Flow and Jammed State

Fig. 3.11 represents the time series of the speed and the 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 motorway A8 direction Munich from 11:50 to 13:20 on Saturday, 25 September, 1999.

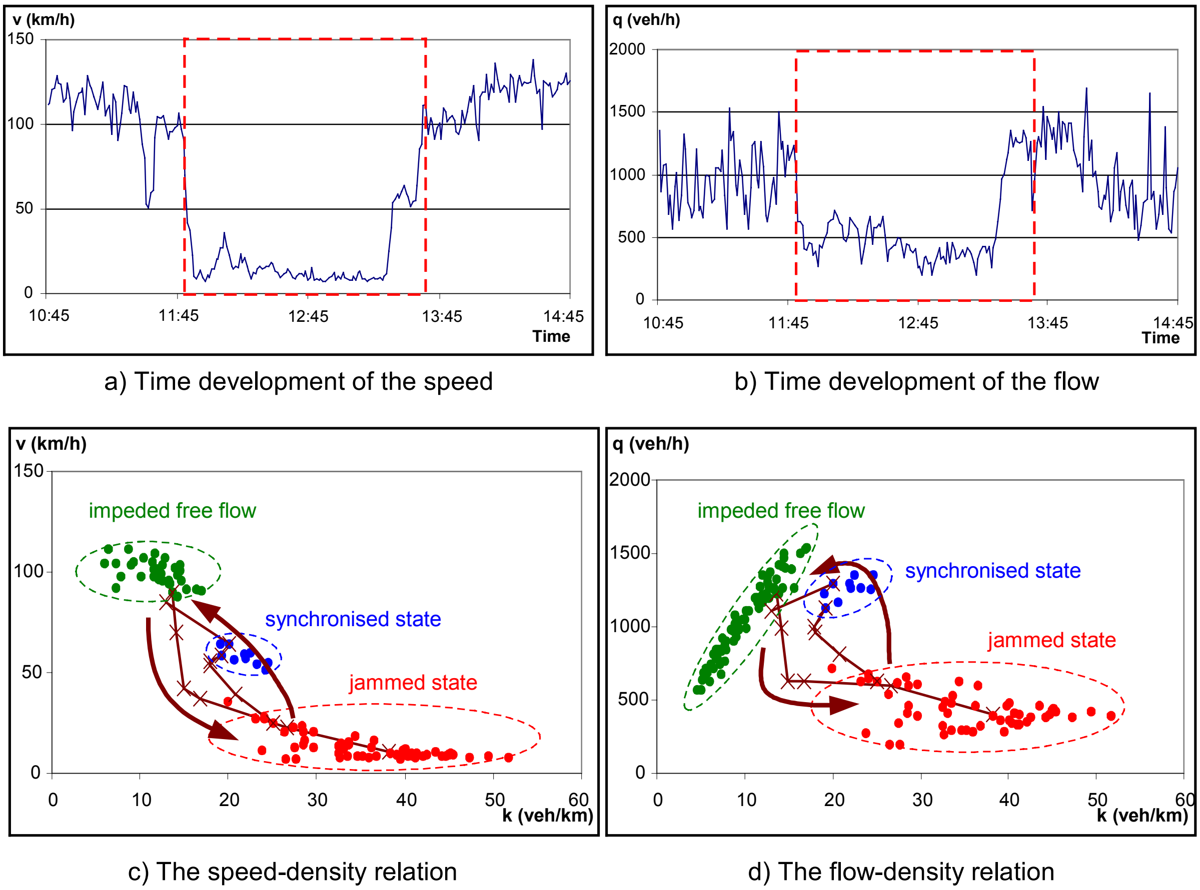


Figure 3.11: Transitions between the impeded free flow and the jammed state

The transition (in brown) from the impeded free flow to the jammed state occurs when the traffic demand is rather high. The speed and the flow drop sharply when the perturbation (congestion) is detected, i.e. the upstream propagating shock wave passes a motorway section. The density increases suddenly in a few minutes after the speed and the flow have dropped sharply; see Fig. 3.11d. 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 a congestion dissolves, the vehicles in the congestion can accelerate and a traffic state of high flow with nearly optimal density can be reached. The hysteresis of the observed speed-density relation has the characteristics described theoretically by ZHANG (1999) and coincides with the microscopic analysis by TREITERER and MYERS (1974). The platoon emerging from a disturbance adopts longer headways until it reaches the constant headway level at about 45 veh/km; see Fig. 3.6. At this time the speed begins to increase without substantial changes in the headway between vehicles.

The traffic flow returns from the jammed to the impeded free flow state via the synchronised 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 motorway 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 the congestion forms a sufficient source of vehicles to increase the flow. For a while they still hesitate before they accelerate (retardation phenomenon). It 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.

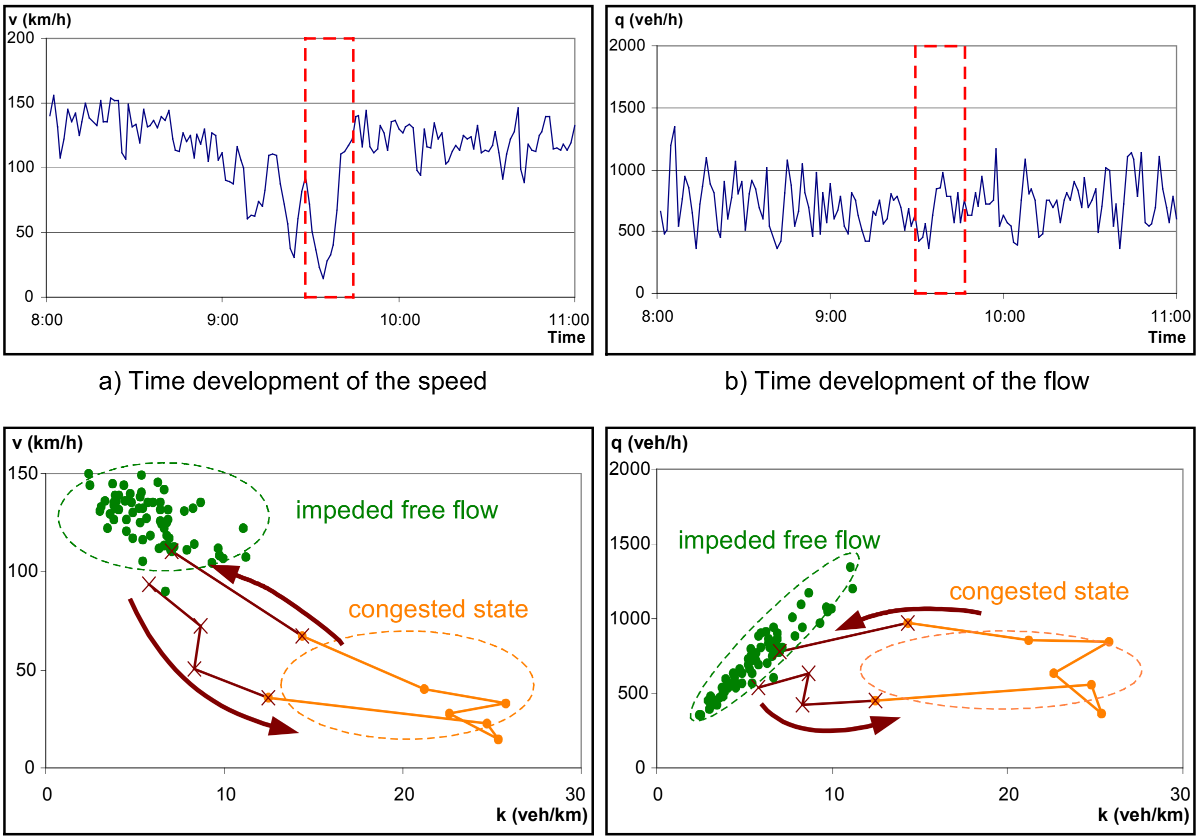
It appears in Fig. 3.11c that the speed soars sharply at a higher density value (about 20 veh/km) than it drops sharply (about 15 veh/km). The flow-density relation shows characteristics similar to the speed-density relation. The hysteresis in the flow-density relation, i.e. the transition from the jammed to the impeded free flow state, has a counterclockwise direction. The flow increases to very high values like loop A in Fig. 3.6, 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.

The density values at which the speed suddenly increases are different depending on the downstream traffic situation. The transitions from the jammed to the impeded free flow state look different depending on the data set though the tendency is the same, i.e. in the transition to the jammed state the flow drops suddenly, and in the transition to the impeded free flow state the flow increases suddenly.

3.4.2 Transitions between Impeded Free Flow and Congested State

A transition from the impeded free flow to the congested state was observed on a section of the German motorway A8 direction Stuttgart on Thursday, 7 October, 1999. This data set includes congested state from 09:20 to 09:40; see Fig. 3.12.

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 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 congested state the flow decreases noticeably with the density increasing; see Figs. 3.11a and 3.11b. The hysteresis in the congested state has a counterclockwise direction. The direction is influenced by the state of high flow with high density, which is a normal phenomenon of the congestion dissolution.



a) Time development of the speed

b) Time development of the flow

c) The speed-density relation

d) The flow-density relation

Figure 3.12: Transitions between the impeded free flow and the congested state

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. This leads to a hysteresis which has a counterclockwise direction.

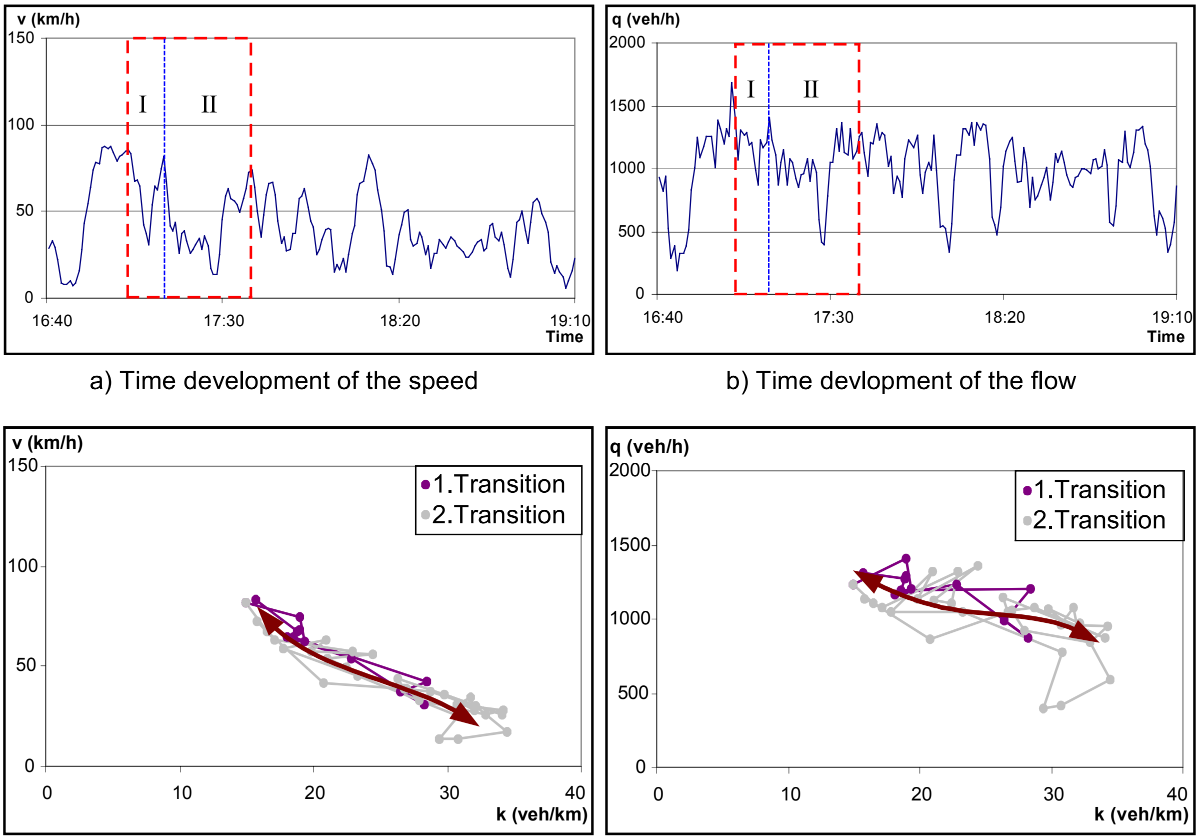
The congested state can be observed very often in the vicinity of ramps of motorways; see also HALL and LAM (1988), and HELBING ET. AL. (1999), respectively. The speed of the main stream is influenced by entering and exiting vehicles in the region of ramps and fluctuates very strongly. On the other hand, the flow does not fluctuate significantly.

3.4.3 Repeated Transitions between Impeded Free Flow and Jammed State

If several short congestions occur one after another on a motorway section the drivers must alternately decelerate and accelerate. According to the traffic situation transitions between the impeded free flow and the jammed state or between the impeded free flow and the congested state are repeated depending on the speed and direction of shock waves.

A data set of repeated transitions between the impeded free flow and the jammed state was collected on a section of the German motorway 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 analysed in detail; see Fig. 3.13.



a) Time development of the speed

b) Time devlopment of the flow

c) The speed-density relation

d) The flow-density relation

Figure 3.13: Repeated transitions between the impeded free flow and jammed state

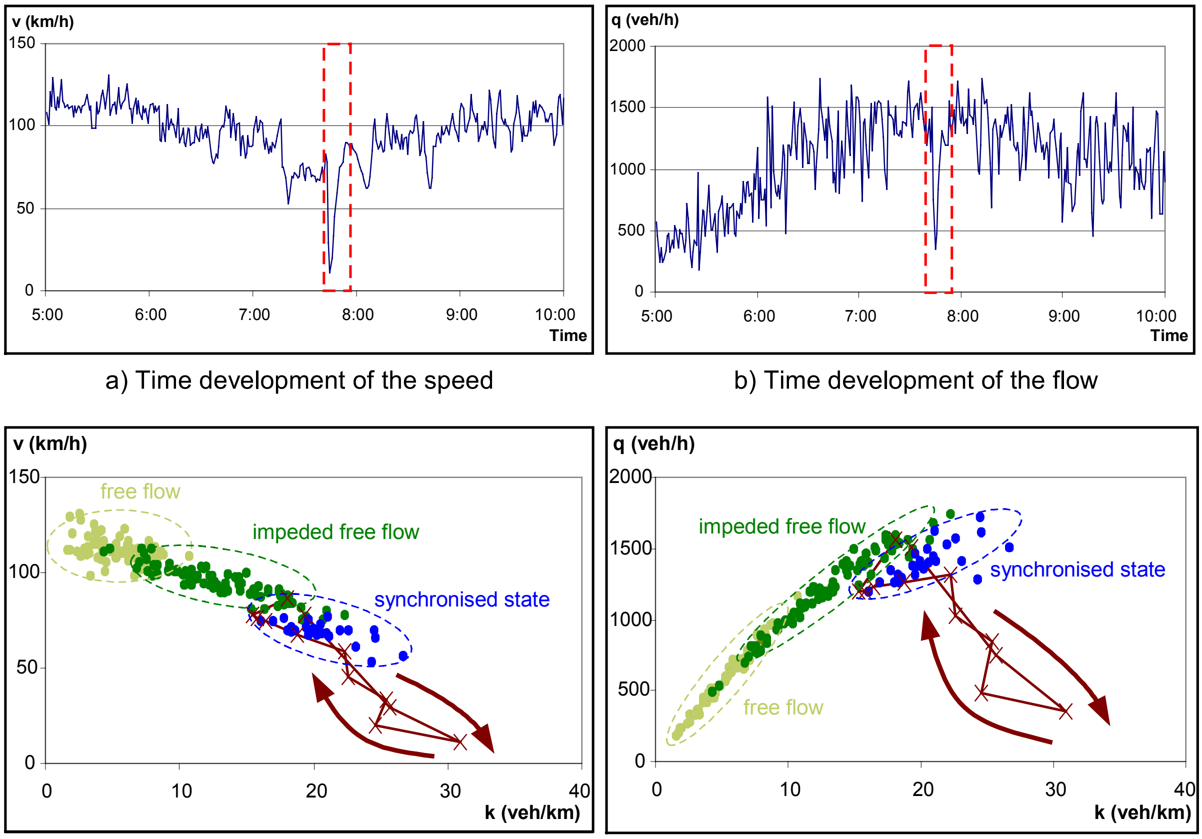
In this period two transitions between the impeded free flow and the jammed state can be seen. The speed fluctuates wildly and the flow follows the same tendency. In the flow-density and the speed-density relation, both variables follow the same trace in the transition from high to low density as in the reverse transition from low to high density. This phenomenon is observed on all lanes simultaneously. In these transitions the hysteresis phenomenon is not so pronounced, which was described through the 'J-line' in the flow-density relation by KERNER (1996a); see Fig. 3.5.

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 traffic flow remains in the meta stable state.

3.4.4 Transitions between Synchronised and Jammed State

At the same densities the speed and the flow in the synchronised state are higher than in the congested or the jammed state but the flow in the synchronised state is a little lower than in the impeded free flow state. The speeds on all lanes on a motorway section are typically nearly the same. The synchronised 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. A transition between the synchronised and the jammed state was observed on a section of the 2-lane German motorway A8, direction Munich, on Friday, 14 July 2000.

Until 6:00 the 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 synchronised state.



a) Time development of the speed

b) Time development of the flow

c) The speed-density relation

d) The flow-density relation

Figure 3.14: Transition between the synchronised and the jammed state

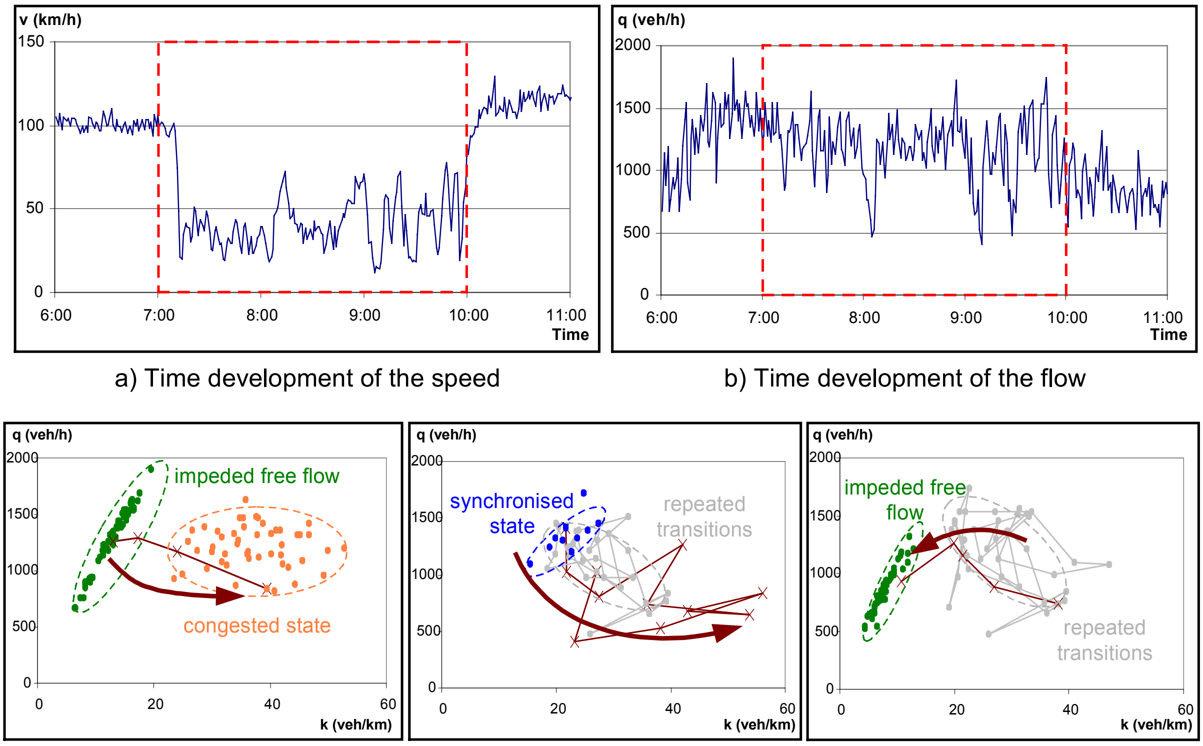
From 7:45 to 7:57 the data shows a transition between the synchronised and the jammed state. At 7:45 the speed and the flow decrease simultaneously. The speed increases again after a few minutes. The traffic flow returns to the impeded free flow via the synchronised state. In the transition from the 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.

3.4.5 Consecutive Transitions between Traffic States

The transitions from the impeded free flow to the congested state and from the synchronised to the jammed state as well as their return to the impeded free flow state and repeated transitions between the jammed and the impeded free flow state were collected on a section of the 3-lane German motorway 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 Figs. 3.15a+b. The brown data values and lines in Fig. 3.15c show the transition from the impeded free flow to the congested state. The time series from 7:00 to 8:00 in Figs. 3.15a+b 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.



a) Time development of the speed

b) Time development of the flow

c) From impeded free flow to congested state

d) From synchronised to jammed state

e) From jammed to impeded free flow state

Figure 3.15: Transitions between several traffic states

The speed and the flow increase simultaneously shortly before 9:00. The traffic flow is temporarily in the synchronised state. The synchronised state is, however, influenced by a disturbance developed downstream and changes to the jammed state (brown points and lines in Fig. 3.15d). After that, repeated transitions between the impeded free flow and the jammed state occur and the flow-density relation (grey points and lines in Fig. 3.15d) follows the trace of the repeated transitions. In the repeated transitions the speed and the flow increase to the level of the synchronised state.

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 Fig. 3.11. The transition from the jammed state to the impeded free flow state is represented in Fig. 3.15e. From 10:00 onward the traffic flow is again in the impeded free flow state.

3.5 Delimitation of Traffic States

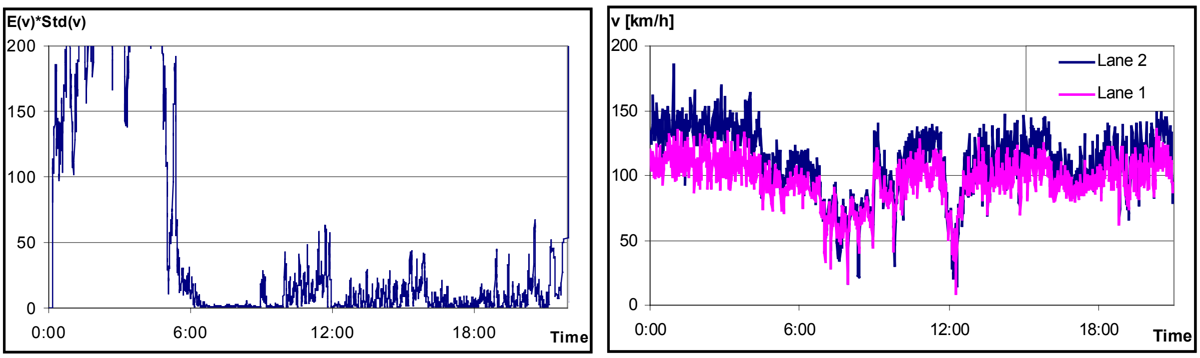
In order to differentiate free flow (the free flow and the impeded free flow state) and congested flow (the synchronised, the congested, and the jammed state) the mean and the standard deviation of the headway are calculated from individual vehicle data and the differences between the average speed of all lanes are tested. For the identification of transitions, differences between moving averages of the flow and the speed are applied, which prove to be very efficient for the identification of the transitions between the traffic states.

3.5.1 Headway of Vehicles

For the analysis of the headway the mean and the standard deviations of 50 vehicles were calculated. Through the analysis of the headway the free flow and the impeded free flow can be classified from the other traffic states (the synchronised, the congested and the jammed state). In the free flow the mean and the standard deviation of the headway are very large. In the impeded free flow the mean and the standard deviation are smaller than in the free flow but still large. In other traffic states these values are very small. By the multiplication of two values the differences can be amplified and are easier to distinguish.

As DAGANZO (2001) explained in his behavioural theory, the synchronisation process of the speed of all lanes is a universal phenomenon during the transition from free flow (the free flow and the impeded free flow state) to congested flow (the synchronised, the congested, and the jammed state). For the classification of the traffic state into free flow and congested flow the speeds of all lanes are compared, too.

The multiplied values of the mean and the standard deviation show the same tendencies as the comparison of the speeds of all lanes. During the transition from free flow (the free flow and the impeded free flow) to congested flow (the synchronised, the congested and the jammed state) the multiplied values decrease sharply and the speeds of all lanes become nearly the same; see Fig. 3.16.



a) The mean × the standard deviation b) The time development of the speed

Figure 3.16: The headway analysis and the comparison of speeds

3.5.2 Indicator for Detection of Transitions

In the flow-density relation the transitions have different characteristics depending on the related upstream and downstream traffic conditions. The different characteristics can be only qualitatively observed in the flow-density relation and it is also difficult to determine the beginning and the end of the transitions due to stochastic characteristics of traffic data.

For the practical application of the transitions to traffic control systems the transitions should be detected and classified quantitatively. In this research new indicators are developed to detect and classify the transitions between the traffic states. The indicators are applied to the traffic data of the transitions explained in section 3.4. It is shown that the indicators reproduce the transitions of the flow-density relation exactly.

3.5.2.1 Methodology

The transition indicators are based on the following two assumptions.

- The transitions from one traffic state to another occur for a short time.
- The flows and the speeds of the traffic states before and after the transitions are significantly different.

The 1-min. interval values of the flow and the speed are accumulated during a given interval (in this research 5-min. interval); see Fig. 3.17. 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 normalised indicators for the transitions between the traffic states.

$$Q_n = q_n + q_{n-1} + q_{n-2} + q_{n-3} + q_{n-4}; \quad V_n = v_n + v_{n-1} + v_{n-2} + v_{n-3} + v_{n-4}$$

$$flow\_indicator_n = \frac{Q_n - Q_{n-5}}{Q_n + Q_{n-5}}; \qquad speed\_indicator_n = \frac{V_n - V_{n-5}}{V_n + V_{n-5}}$$

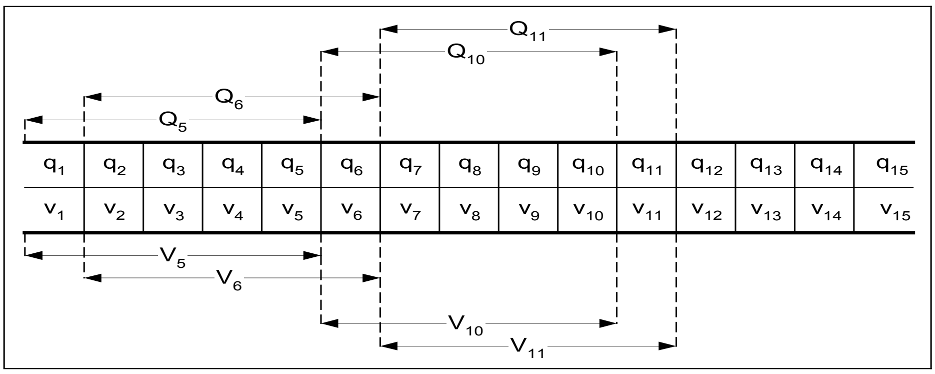


Figure 3.17: Scheme for data accumulation

By accumulating the short interval values of traffic variables (the speed and the flow) during the long interval, noises (the high frequent components) are eliminated and real changes in traffic variables (the low frequent components) remain. The real changes in traffic variables during a time unit are represented by the indicators. The same magnitude of changes in traffic variables can have different effects on traffic flow and traffic behaviour depending on the transition intervals during which the traffic variables change. The sudden changes in traffic variables during a short interval have more significant effects on traffic flow than the changes during a long interval.

If the accumulation intervals get longer, the differences of the accumulated values become greater and the detection of the transitions becomes easier and more reliable. The detection of the transitions is, however, delayed as long as the accumulation interval, which is critical for online traffic control systems. The desirable interval for both prompt and reliable detection of the transitions must be determined. From the data analysis, a 5-min. interval is found to be suitable for both criteria.

The flow and the speed indicators have the same range of values (i.e. from –1 to 1) by the normalisation and both indicators can be compared. The changes in the speed and the flow due to the generation or the propagation of disturbances in the unstable traffic states with the low speed and the low flow are amplified by the normalisation. A shock wave propagation through congestion, for example, can be easily observed through the normalised indicators.

In the following section, the indicators are shown to reproduce the characteristics of the transitions and compared with the hysteresis phenomena in the flow-density relation of the traffic data in section 3.4.

3.5.2.2 Empirical Results

a) Transitions between Impeded Free Flow and Jammed State

Fig. 3.18 shows that both speed and flow drop at 11:45 and soar at 13:10. The speed and flow indicators show the changes clearly.

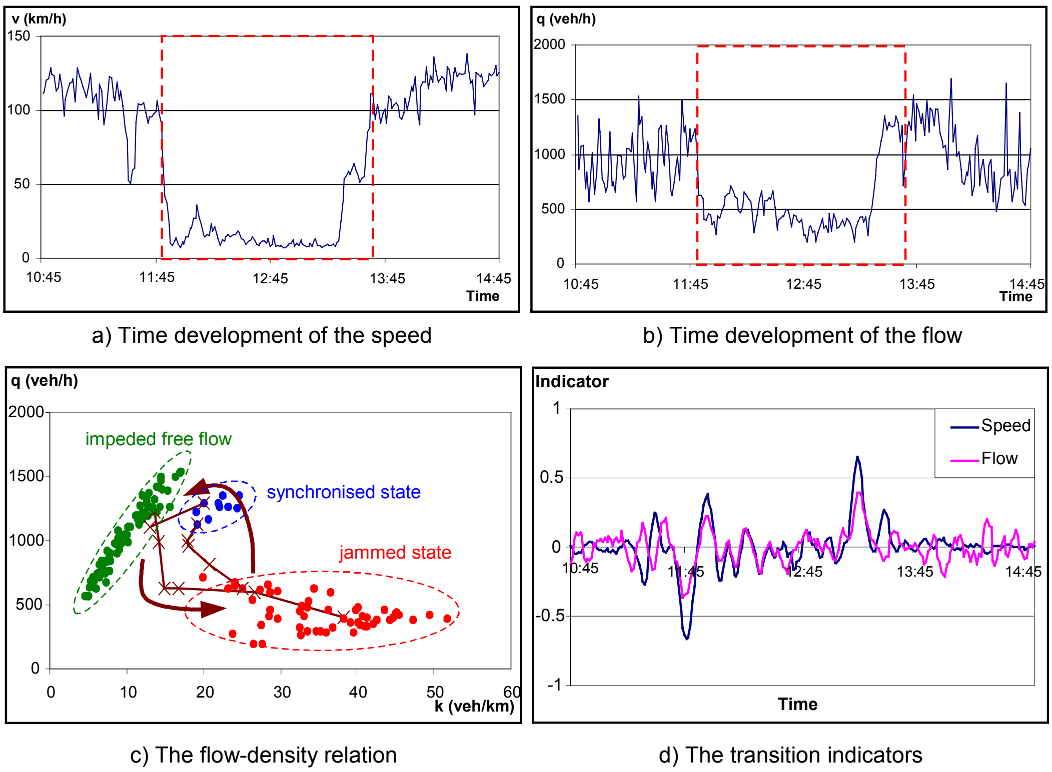
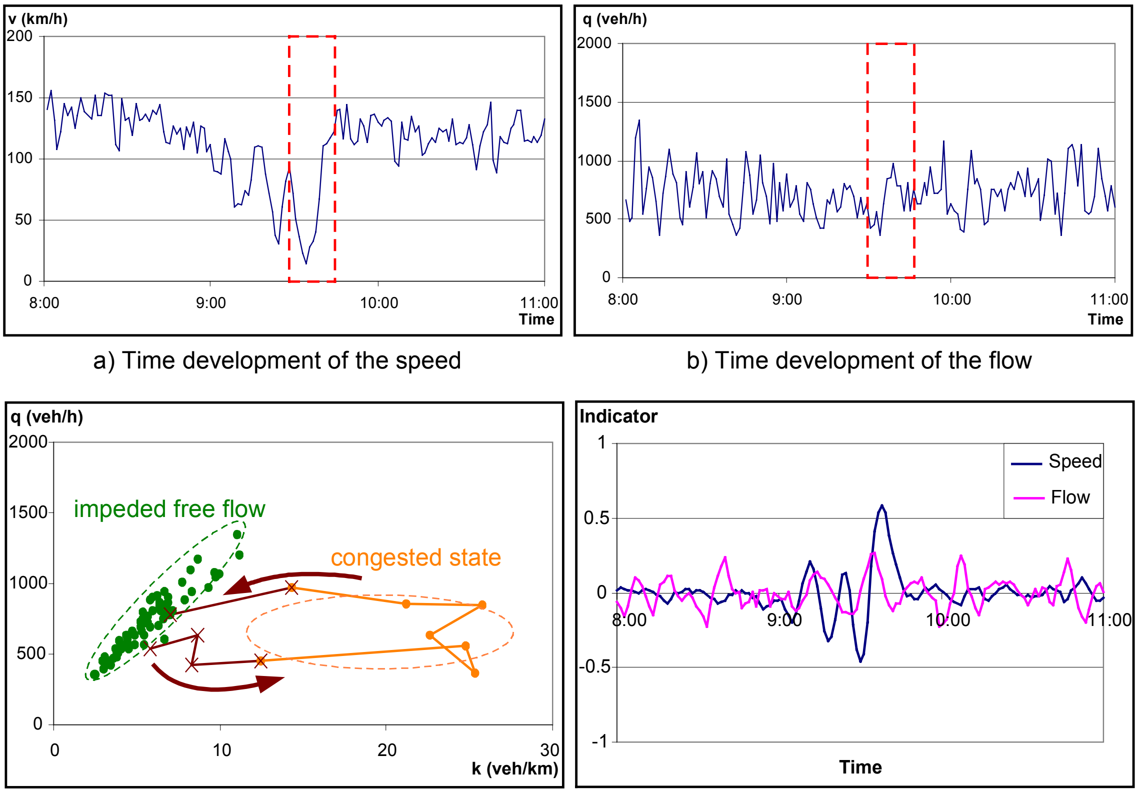


Figure 3.18: Transitions between impeded free flow and jammed state

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. After the transition to the jammed state there are disturbances which show the characteristics of the unstable state. The fluctuations of the speed and the flow are strongly correlated, which is the characteristic of the jammed state and 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.

b) Transitions between Impeded Free Flow and Congested State

In the transition between impeded free flow and congested state the changes in the speed are noticeable but the flow does not vary significantly. The indicators clearly show that the speed fluctuates wildly but the flow does not change pronouncedly during the transitions. 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 match; see Fig. 3.19.

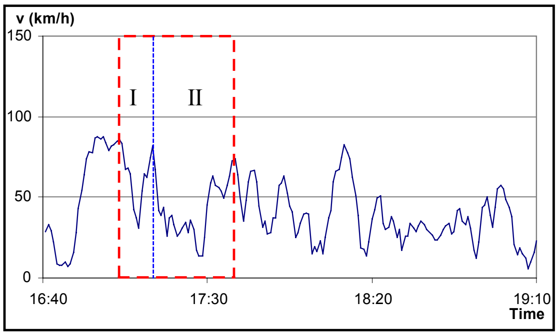


a) Time development of the speed
b) Time development of the flow
c) The flow-density relation
d) The transition indicators

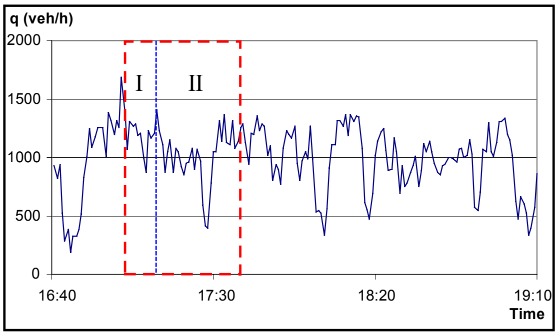
Figure 3.19: Transitions between impeded free flow and congested state

c) Repeated Transitions between Impeded Free Flow and Jammed State

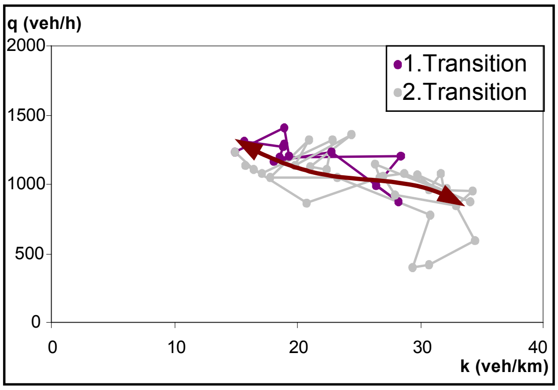
In the repeated transitions between impeded free flow and jammed state the speed fluctuates wildly and the flow follows the same tendency. The transition indicators show a strong correlation between the speed and the flow; see Fig. 3.20.



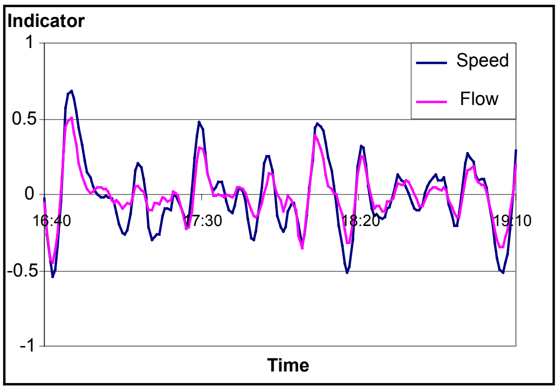
a) Time development of the speed



b) Time devlopment of the flow



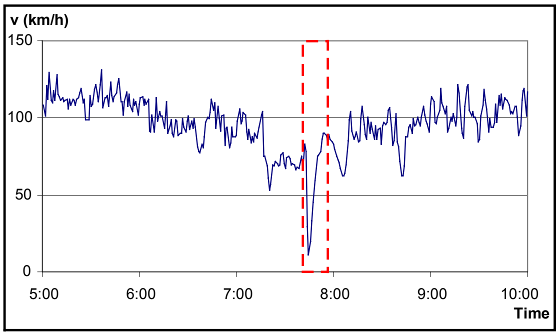
d) The flow-density relation



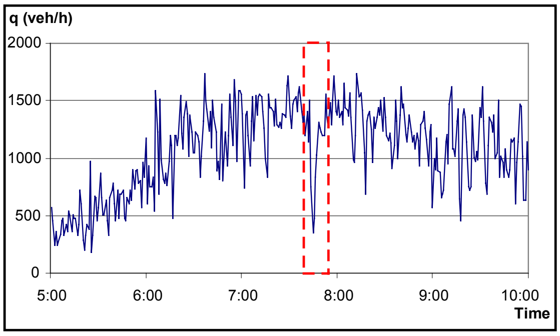
d) The transition indicators

Figure 3.20: Repeated transitions between impeded free flow and jammed state

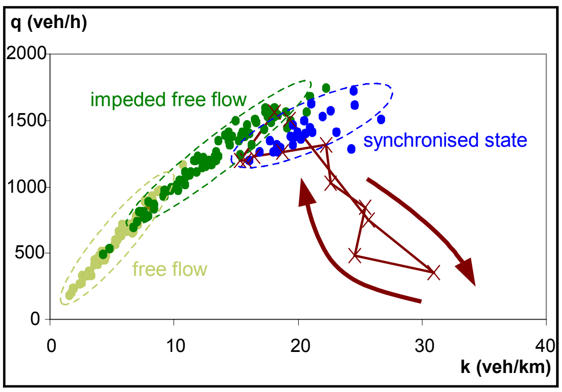
d) Transitions between Synchronised and Jammed State



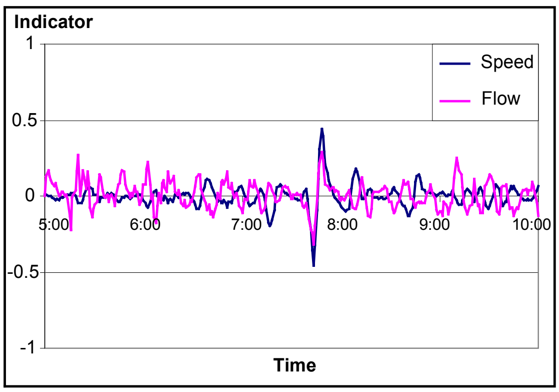
a) Time development of the speed



b) Time development of the flow



c) The flow-density relation



d) The transition indicators

Figure 3.21: Transitions between synchronised and jammed state

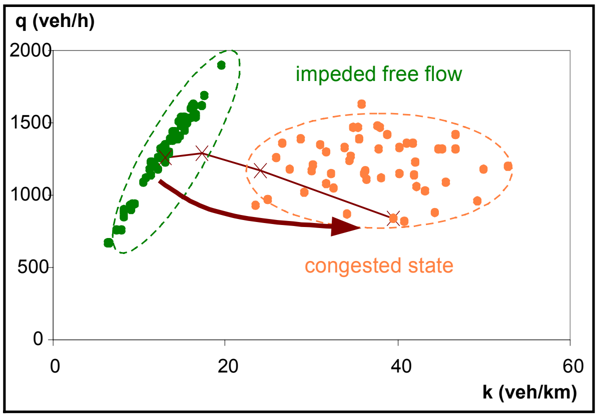
In the impeded free flow the indicators show the weak correlation between the speed and the flow. In the transition between synchronised and jammed state the indicators show the same tendencies as in the transition between impeded free flow and the jammed state. Both indicators have the minimum and maximum values simultaneously; see Fig. 3.21.

e) Consecutive Transitions between Traffic States

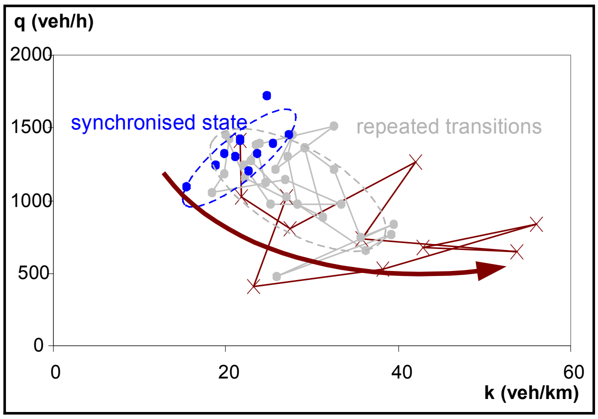
The characteristics of consecutive transitions in the flow-density relation are compared with the time development of the indicators; see Fig. 3.22.

The 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 a). 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 analysed in the flow-density relation.

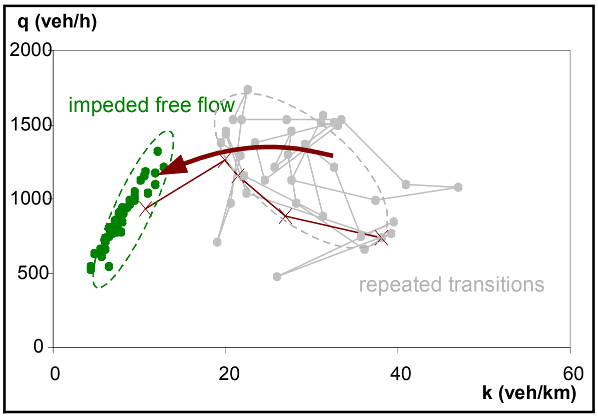
At 09:00 the synchronised traffic changes to the jammed state. The speed and the flow decrease significantly at the same time. After that, repeated transitions between the impeded free flow and the jammed state occur and the indicators shows the strong correlation between the flow and the speed after the pronounced drop of the speed and flow indicators at 09:00. This situation can be compared with the flow-density relation b).



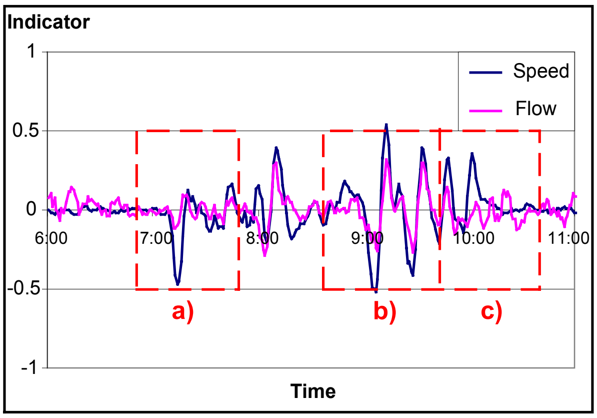
a) From impeded free flow to congested state



b) From synchronised to jammed state



c) From jammed to impeded free flow state



d) The transition indicators

Figure 3.22: Consecutive transitions between traffic states

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 c).

3.6 Summary

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

Traffic measurements at different consecutive sections on German motorways 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 synchronised, the congested and the jammed state), which are supply-oriented, i.e. caused by the downstream capacity or bottlenecks. This means that the time series of traffic measurements were analysed with respect to the behaviour of the shock waves passing the cross section of measurement either downstream or upstream through the measurement points.

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 motorway.

By means of the empirical investigation of freeway sections the traffic states and the transitions between the states are analysed and represented together in a diagram of traffic states. The states are not sharply defined against each other, but partially overlapping. The shape of the diagram of traffic states defined in this paper can be generalised and parameterised through further analysis of data which has not been often used by now.

In order to differentiate free flow (the free flow and the impeded free flow state) and congested flow (the synchronised, the congested and the jammed state) the mean and the standard deviation of the headway are calculated from individual vehicle data and the differences between the average speed of all lanes are tested. For the identification of transitions, differences between moving averages of the flow and the speed are applied.

This chapter demonstrates that traffic data collected on a section and represented in the flow-density relation can and must be interpreted under the prevailing traffic conditions occurring at the section. From results of the present investigation it can be emphasised that the traffic data (i.e. the flow and the speed) is meaningful as input values for traffic flow models only when the dynamic context of the traffic flow and the cause of the occurred congestion are analysed and considered. The existing static flow-density relations and the corresponding traffic flow models alone do not adequately describe the traffic state dynamics. As the flow-density relation is an important element of the traffic flow models the interpretation of the shape of the states diagram introduced here has a marked impact on the simple and the high order continuum models.

4 Traffic Characteristics of Bottlenecks Caused by Ramps

Bottlenecks are defined as sections that have less capability of accommodating traffic than other sections of the roadway which are linked in series with the bottleneck sections (GAZIS, 1974). Bottlenecks can be located at places where the motorway geometry changes, or move according to slow-moving obstructions. Once traffic situations worsen owing to bottlenecks, their impacts spread fast and wide and it takes a long time to recover from the poor traffic situations. Therefore, the analysis of bottlenecks is critical for traffic flow modelling and traffic control on motorways.

Bottlenecks caused by ramps are more interesting than any other bottlenecks because occurrence, propagation, and disappearance of congestion on motorways are mainly influenced by ramps. The characteristics and the modelling of traffic flow of motorway sections with ramps have been investigated empirically as well as theoretically.

BANKS (1989) empirically investigated the effect of bottlenecks derived from ramps on the speed-flow-concentration relations depending on the detection points. CREMER and MAY (1985) extended a macroscopic dynamic flow model to reproduce traffic flow of bottlenecks such as a lane drop or a merging on-ramp flow by minor modifications of terms in the speed equation of the PAYNE-CREMER model. DAGANZO (1999) theoretically explains the behaviour of multi-lane motorway traffic not only for the homogeneous motorway sections but also for motorway sections with on-ramps with a multi-class traffic flow model. MUNOZ and DAGANZO (2000a, 2000b) empirically analysed the behaviour of multi-lane motorway traffic, upstream of an oversaturated off-ramp.

On the other hand, some physicists (HELBING ET AL., 1999; LEE ET AL., 1999, 2000) investigated the traffic flow of motorway sections with an on-ramp applying the phase diagram theoretically and empirically as well. In the phase diagram various traffic states with different characteristics are represented depending on the upstream traffic demand and the on-ramp flow. Characteristics and analytical conditions of transitions between the states are investigated.

In this chapter traffic flow of motorway sections with an on-ramp and an off-ramp is analysed based on a new phase diagram. Traffic flow of motorway sections with an on-ramp and an off-ramp is analysed considering the on-ramp and off-ramp flows, the upstream traffic demand and the outflow from the bottleneck. Traffic flow in motorway sections with ramps is classified into three traffic states in the new phase diagram; free flow, congestion with propagation, congestion without propagation.

4.1 Former Investigations of Phase Diagrams for Regions of Ramps

It is widely known from one-dimensional many-body systems with short-range interactions that localised inhomogeneities can cause a variety of phenomena, including phase transitions and spontaneous symmetry breaking (HELBING ET AL., 1999). Phase diagrams are a very powerful method to characterise the parameter dependence of possible states of a system resulting in the long run (HELBING ET AL., 1999). Recently, a group of physicists have been trying to analyse the nonlinear dynamics of traffic flow applying the phase diagrams. Various traffic states and their relations to each other have been investigated theoretically and empirically in motorway sections with ramps. By systematic variations of the upstream traffic demand and the on-ramp flow, distinct traffic states and the phase transitions between them were identified and characterised (HELBING ET AL., 1999; LEE ET AL., 1999). Former investigations are reviewed in this section.

4.1.1 The Investigation of HELBING ET AL.

HELBING ET AL. (1999) simulated a motorway section with an on-ramp in the presence of a single downstream perturbation travelling upstream applying the nonlocal, gas-kinetic-based traffic flow model. The equation for the vehicle density ρ(x,t) at position x and time t is the continuity equation with a sink/source term and reads

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho V)}{\partial x}=\frac{Q_{rmp}(x,t)}{L_{rmp}}.$$

V denotes the average vehicle speed, L_{rmp} is the length of the ramp, Q_{rmp} is the flow of vehicles entering the freeway or leaving it.

The speed equation contains a convection term (due to the movement of the speed profile with speed V), a pressure term (reflecting dispersion effects due to a finite speed variance θ), a relaxation term (describing an adaptation to a desired speed V_0), and an interaction term (corresponding to braking maneuvers).

$$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}=-\frac{1}{\rho}\frac{\partial(\rho\theta)}{\partial x}+\frac{1}{\tau}(V_0-V)-PA(\rho_a)\frac{(\rho_a V_a)^2}{(1-\rho_a)^2}B(\delta_V)$$

P is a scaling factor of a cross-section and $A(\rho_a)$ represents a structure factor which determines the form of the flow-density relation in equilibrium. An index “a” indicates that the respective quantity is evaluated at the advanced interaction point rather than at the actual position (anticipative driver behaviour), which characterises the nonlocality of the model.

$$A(\rho)=0.171+0.417\{\tanh[10(\rho-0.27)]+1\}$$

$B(\delta_V)$ is represented as the following formula where the dimensionless speed difference δ_V is a Boltzmann factor arising from vehicle interactions.

$$B(\delta_V) = 2\left[\delta_V \frac{e^{-\delta_V^2/2}}{\sqrt{2\pi}} + \left(1+\delta_V^2\right)\int_{-\infty}^{\delta_V} dy \frac{e^{-y^2/2}}{\sqrt{2\pi}}\right]$$

The nonlocal, gas-kinetic-based traffic model induces different kinds of congested states depending on the upstream traffic demand (q_{in}) and the flow of onramp (q_{rmp}) respectively; see Fig. 4.1. They also give analytical conditions for the existence of these states.

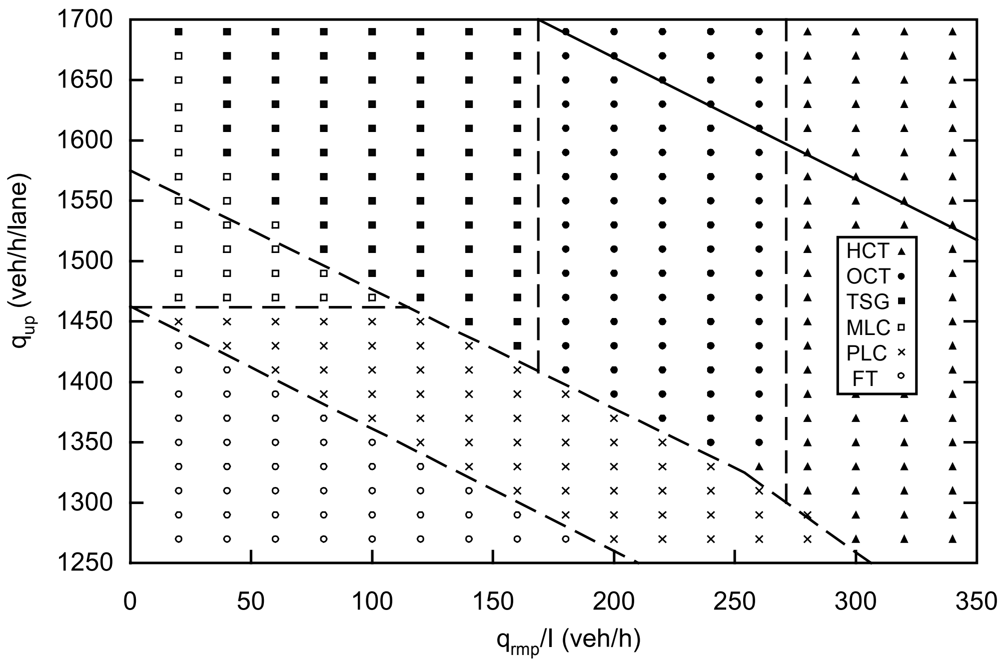


Figure 4.1: Numerically determined phase diagram (HELBING ET AL., 1999)

Various traffic states are displayed in Fig. 4.1; homogeneous congested traffic (HCT), oscillatory congested traffic (OCT), triggered stop-and-go traffic (TSG), moving localised clusters (MLC), pinned localised clusters (PLC), and free traffic (FT). The dashed lines indicate the theoretical phase boundaries. The solid line represents the condition $q_{up} + q_{rmp} = q_{max}$ that separates the region, in which a breakdown of traffic flow is caused by exceeding the theoretically possible freeway capacity q_{max} without any perturbations. The spatio-temporal dynamics of the traffic states can be found in HELBING ET AL. (1999).

4.1.2 The Investigations of LEE ET AL.

LEE ET AL. (1999) simulated various inhomogeneous but time-independent traffic states for a motorway section with an on-ramp based on a modified KERNER-KONHÄUSER model and also found nontrivial analytic solutions corresponding to the traffic states observed in numerical simulations.

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v)}{\partial x} = q_{in}(t)\varphi(x)$$

$$\rho\left(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x}\right) = \frac{\rho}{\tau}\left[V(\rho) - v\right] - c_0^2 \frac{\partial \rho}{\partial x} + \mu \frac{\partial^2 v}{\partial x^2}$$

In the system of equations $q_{in}(t)\varphi(x)$ the source term represents the flow of an on-ramp. The spatial distribution of the flow of an on-ramp, $\varphi(x)$, is localised near x = 0 (on-ramp position) and normalised so that $q_{in}(t)$ denotes the total flow of an on-ramp. The second term on the right hand side of the speed equation represents an effective "pressure" gradient on vehicles due to the anticipation driving and the speed fluctuations. The third term takes into account an intrinsic dampening effect that is required to fit the experimental data. The spatial distribution of the flow of an on-ramp is chosen as

$$\varphi(x) = \left(2\pi\sigma^2\right)^{-1/2} \exp\left(-x^2/2\sigma^2\right).$$

To obtain all possible traffic states two methods are used; one is to apply a triggering pulse to a steady state by changing the value of q_{rmp} for a short time. The other is the adiabatic sweeping method (LEE ET AL., 1999). By these methods the traffic states depending on the given system parameters q_{up} and q_{rmp} are classified; see Figure 4.2.

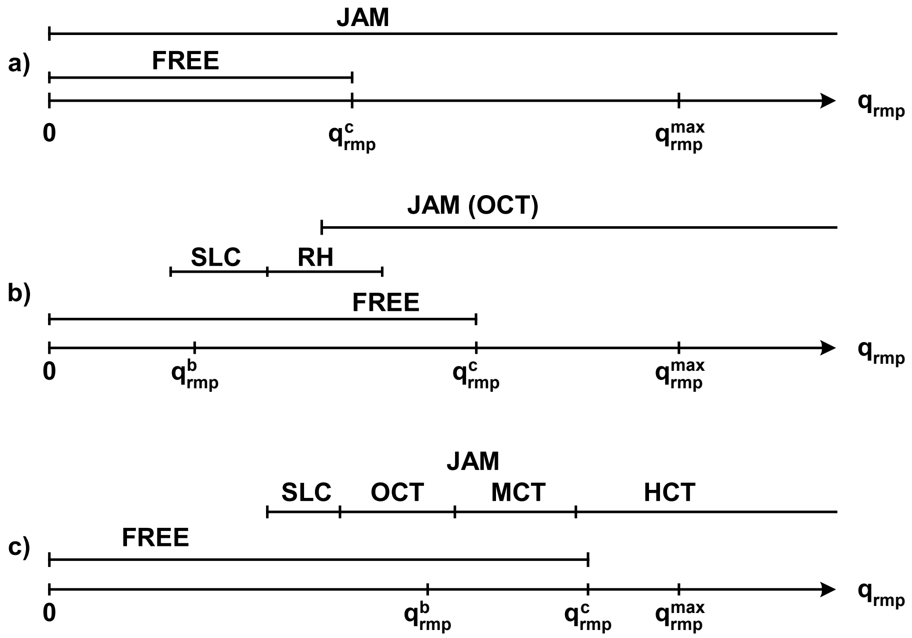


Figure 4.2: Theoretical phase diagram (LEE ET AL., 1999)

Traffic states are investigated for three representative values of $q_{up,}$ and for each of them a phase diagram for the entire range of q_{rmp} is constructed. For the determination of the value of q_{up}, the reference value q_b is chosen from the study of the homogeneous motorway section, below which the congested traffic cannot be created. The phase diagrams are produced for a) $q_{up} > q_b$, b) $q_{up} < q_b$, and c) $q_{up} \ll q_b$.

Due to the density gradient near the on-ramp, a traffic jam can occur even when the downstream density is below the critical density of the usual traffic jam formation in homogeneous motorways and its structure varies qualitatively with q_{rmp}. LEE ET AL. found the on-ramp flow is a more important factor for the formation of the traffic jam than the total flow (the on-ramp flow + the upstream traffic demand). LEE ET AL. classified the congested traffic into various traffic states; the homogeneous congested traffic (HCT), the oscillating congested traffic (OCT), the mixed congested traffic (MCT) of HCT and OCT, the standing localised cluster (SLC), and recurring humps (RH). Recurring humps represent a traffic state which becomes a spatially localised limit cycle of motorway traffic flow under the constant external inflow (q_{up} and q_{rmp}). The spatio-temporal dynamics of the traffic states can be found in LEE ET AL. (1999). Analytical conditions for the existence of these states are provided.

Both theoretical studies by HELBING ET AL. and LEE ET AL. present qualitatively similar results.

LEE ET AL. (2000) presented an empirical phase diagram of congested traffic flow measured on a motorway section with an effective on-ramp. They classified traffic flow based on two criteria, local speed variation patterns and expansion of congested regions. Three distinct congested traffic states are identified in Fig. 4.3; congested state (A) in which the congested region does not expand and the growth of speed oscillation does not appear, congested state (B) in which the congested region expands and the growth of speed oscillation does not appear, and congested state (C) in which the congested region expands and the growth of speed oscillation appears. The dashed line is an empirical estimation of the free flow state boundary below which the free flow state can remain linearly stable. The overlapping of the free flow state and the congested traffic states shows the hysteresis phenomenon in traffic flow.

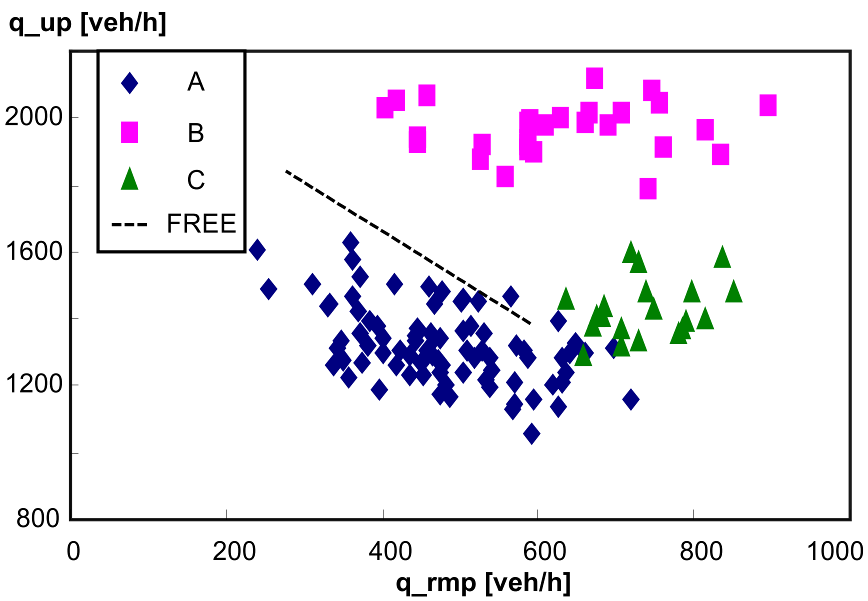


Figure 4.3: Empirical phase diagram (LEE ET AL., 2000)

The empirical analysis shows that the boundary between state (B) and state (C) is better described by f_{up} = const, while the theoretical investigation predicts the vertical line Q_{rmp}/I = const as the phase boundary between the corresponding HCT (homogeneous congested traffic) and OCT (oscillatory congested traffic) states (HELBING ET AL., 1999).

LEE ET AL. (2000) explained that the expansion rate of congestion is proportional to the degree of the flux mismatch $f_{up} + f_{rmp} - f_{down}$, which is a reasonable criterion for the congestion expansion but does not consider the off-ramp flow.

4.1.3 The Investigation of TREIBER ET AL.

TREIBER ET AL. (2000) simulated the general inhomogeneities caused by various types of bottlenecks such as lane closings, intersections, and uphill gradients applying a single lane microscopic model (intelligent driver model) using empirical boundary conditions.

The acceleration assumed in the intelligent driver model is a continuous function of the speed v_α, the clearance $s_\alpha = d_\alpha - l_{\alpha-1}$, and the speed difference Δv_α of vehicle α to the leading vehicle:

$$\dot{v}_\alpha = a_\alpha \left[1 - \left(\frac{v_\alpha}{v_\alpha^0} \right)^\delta - \left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha} \right)^2 \right].$$

This expression is a superposition of the acceleration tendency on a free road and the deceleration tendency describing the interactions with other vehicles. The deceleration term depends on the ratio between the "desired clearance" s_α^* and the actual clearance s_α. The desired clearance is dynamically varying with the speed v_α and the approaching rate Δv_α.

$$s_\alpha^*(v_\alpha, \Delta v_\alpha) = s'_\alpha + s''_\alpha \sqrt{\frac{v_\alpha}{v_\alpha^0}} + T_\alpha v_\alpha + \frac{v_\alpha \Delta v_\alpha}{2\sqrt{a_\alpha b_\alpha}}$$

The parameters of the chosen vehicle α are the desired speed v_α^0, the safe time clearance T_α, the maximum acceleration a_α, the comfortable deceleration b_α, the jam distances s'_α and s''_α.

The fundamental diagram for the model can be derived from the acceleration equation and has a triangular shape.

$$Q_e(\rho) = \min(\rho v_0, [1 - \rho(l + s')]/T)$$

The fundamental diagram is calibrated with v_0 (low density), δ (transition region), T (high density), s'_α and s''_α (jammed traffic).

Various traffic states are reproduced by the simulation applying this model. Bottleneck inhomogeneities are implemented microscopically by locally increasing the safe time clearance (T) which is one of the model parameters.

TREIBER ET AL. (2000) presented a refined phase diagram of HELBING ET AL. (1999). They introduced the following general definition of the bottleneck strength.

$$\Delta q := q_{rmp} / I + q_{out} - q'_{out}$$

In this equation, q_{out} is the outflow from the congestion at the motorway section with the largest capacity and q'_{out} is the outflow at the respective bottleneck.

The phase diagram resulting from the intelligent driver model with a bottleneck is shown in Fig. 4.4. The control parameters are the flow q_{in} and the bottleneck strength Δq. The solid thick lines separate the congested traffic states TSG, OCT, HCT, PLC, MLC and free traffic (FT) as they appear after adiabatically increasing the inflow q_{in} and applying a large perturbation.

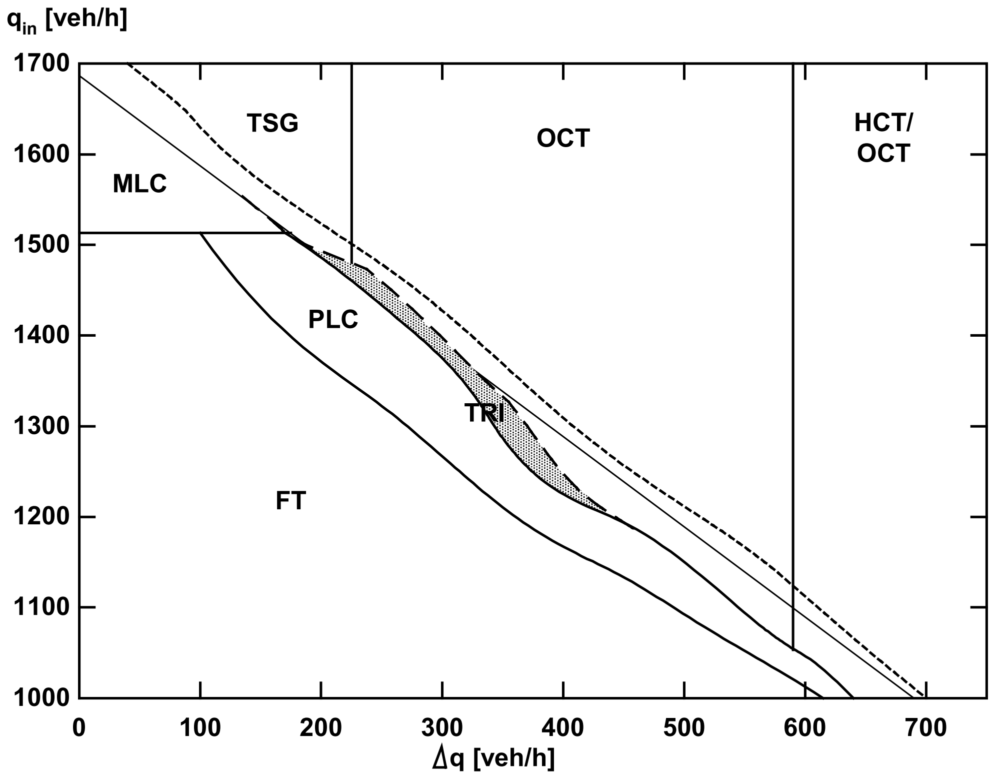


Figure 4.4: Phase diagram resulting from the simulation (TREIBER ET AL., 2000)

4.2 New Phase Diagram

The phase diagram is a very efficient method to classify the traffic states and to analyse the dependence of the states. There are, however, some difficulties in using the existing phase diagrams in practice. In this section the problems of the existing phase diagrams are investigated and the new phase diagram is developed, which can overcome the problems and be applied to traffic control systems.

4.2.1 Shortcomings of Former Investigations

The theoretical phase diagrams were produced using macroscopic or microscopic traffic flow models and compared with empirical phase diagrams. There are, however, some difficulties in using the theoretical phase diagrams in practice, which are obtained by simulations with traffic flow models.

- Macroscopic traffic flow models used to produce the phase diagrams are composed of the continuity equation and the momentum equation for the speed. There is the fundamental diagram in the speed equation of the KERNER-KONHÄUSER model, which mainly characterises the stability and the behaviour of the model. Functions $A(\rho_a)$ and $B(\delta_v)$ in the nonlocal gas-kinetic based traffic model play the same role as the fundamental diagram in the KERNER-KONHÄUSER model. The results of the intelligent driver model are also very sensitive to the shape of the fundamental diagram. The produced traffic states and transitions in the phase diagram are influenced significantly by the fundamental diagram and the stability of the model. From the same traffic flow model, different traffic states and transitions can be produced by modifying the fundamental diagram.

- In the theoretical phase diagrams the off-ramp flow was not considered though the effect of the off-ramp flow is not negligible in motorway sections with ramps. The effect of off-ramp flow cannot be correctly simulated only by the continuity equation of the traffic flow model. The off-ramp flow always decreases the density and the congestion in the model. The exiting vehicles, however, change lanes and cause interaction with the through traffic flow, which deteriorates the traffic situations. Data analyses show that the off-ramp flow and congestion have a positive correlation. If the upstream traffic demand increases and the O/D composition does not change the off-ramp flow increases. The increased off-ramp flow causes more interaction with the through traffic in the traffic flow with higher density. Apart from the direct interaction effects, the vehicles in all motorway lanes in the motorway section with ramps decrease their speeds in the presence of exit queues (CASSIDY, 2001). Therefore, the off-ramp flow and the congestion are thought to be positively correlated. In the German Highway Capacity Manual, HBS (BRILON ET AL., 2001) the off-ramp flow is considered to evaluate the level of service in the motorway section with an off-ramp. Depending on the traffic situations caused by the on-ramp and off-ramp flows the flow-density relation should be adjusted.

- The classification of congestion in the theoretical phase diagrams is too elaborate. It is very difficult to identify such elaborate classification with the observed traffic data and to apply it to the on-line traffic flow model. As shown above, LEE ET AL. (2000) classified the traffic states roughly into three traffic states with traffic data. They also showed that the characteristics and the boundaries of the traffic states in the theoretical phase diagrams do not coincide with those in the empirical phase diagram.

4.2.2 Indicator for Propagation of Congestion

A new empirical phase diagram is developed to overcome the drawbacks mentioned above, the consideration of the off-ramp flow and a simple classification of traffic flow which can be applied to on-line traffic flow models. The new phase diagram is represented based on the upstream traffic demand and **interaction strength** which indicates the interaction between the flows of ramps and the through traffic flow.

$$q_{\text{int}} := q_{up} + q_{in} - (a)q_{out} - q_{down}$$

The interaction strength q_{int} is composed of the upstream traffic demand (q_{up}), the on-ramp flow (q_{in}), the downstream flow (q_{down}), and the off-ramp flow (q_{out}) which is not considered in the bottleneck strength of TREIBER ET AL. (2000) and the flux mismatch of LEE ET AL. (2000).

The capacity of bottlenecks is influenced by the interaction between the flows of ramps and the through traffic flow. There are many reasons for the generation of congestion and it is not easy to predict when a congestion forms. But if a congestion builds up the propagation of the congestion can be predicted applying the interaction strength.

The effect of the off-ramp flow on the traffic condition of the main stream is related with O/D composition, and the value of constant (a) can be determined according to the magnitude of the effect. In this analysis (a) is replaced by –1 just because of the positive relation between the off-ramp flow and congestion. The dependence of the queue discharge rate and O/D composition was observed also in the empirical investigation by MUNOZ and DAGANZO (2000). The relation between queue discharge rate and O/D composition is, however, not fully identified yet.

4.3 Empirical Investigations

In the last section the shortcomings of the existing phase diagrams are analysed and a new phase diagram is proposed. The new empirical phase diagram is produced based on the observed traffic data on the German motorway A9.

4.3.1 Test Field

For the empirical investigation the traffic data on a section of the German motorway A9 direction Munich is analysed. This section is composed of 3 lanes and the distances between the ramps are about 2 km. There is a motorway junction (AK München-Nord) downstream AS Garching-Süd; see Fig. 4.5. AK (Autobahnkreuzung) represents the motorway interchange and AS (Anschlussstelle) represents the region of ramps.

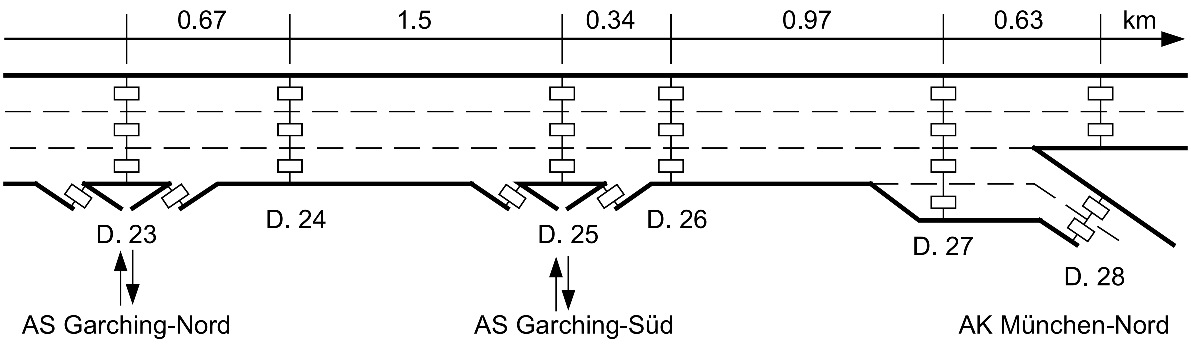


Figure 4.5: Schematic configuration of the section of the German motorway A9

This section shows recurrent daily congestion patterns during the morning and afternoon peak hours. Congestion is caused mainly by the motorway junction of AK München-Nord and sometimes by the ramps of AS Garching-Süd.

The objective of this research is to analyse the conditions of the generation and the propagation of congestion in the motorway section with ramps. Therefore, the traffic data which is not influenced by the congestion generated from the motorway junction is selected and analysed. The traffic data was collected for 6 months from April, 1997 to September, 1997.

For the calculation of the interaction strength q_{int} the data of detector 24 and detector 26 are used as the upstream and the downstream data, and the traffic data of the on-ramp and off-ramp (AS Garching-Süd) are used.

4.3.2 Results

In this investigation traffic states are classified into three states based on the upstream traffic demand and the interaction strength; free flow, congestion with propagation, and congestion without propagation; see Figure 4.6. It is desirable for online application that the traffic flow should be simply classified into traffic states with consistent characteristics.

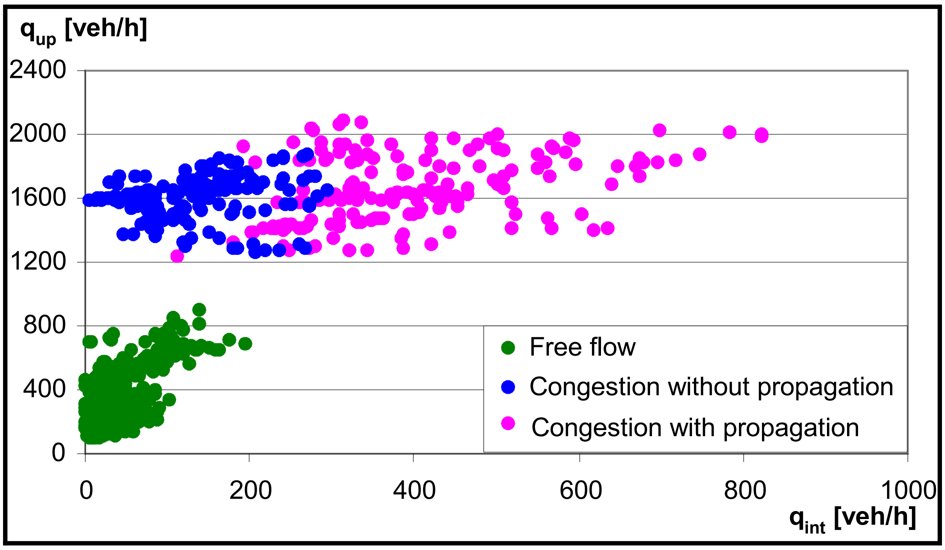


Figure 4.6: A new empirical phase diagram

In **free flow** the flows of main stream and ramps are very low. The values of the interaction strength q_{int} are low as well. In free flow the traffic flows of ramps have little effect on the through traffic flow, and both traffic flows have little interaction. In free flow disturbances seldom happen, and if ever, they do not develop to congestion.

As the flows of main stream and ramps increase, the lane changing effect and the interaction between the through traffic flow and the ramp traffic flows increases. **Congestion without propagation** is observed. In this traffic state the flows of main stream and ramps are much higher than those in free flow. The values of the interaction strength q_{int} are not significantly higher than in free flow. The total flow of the main stream and on-ramp do not reach the capacity of the bottleneck (which can change depending on the interaction strength) and the outflow from the bottleneck does not decrease significantly. The congestion generated does not propagate upstream and the traffic volume accumulated in the bottleneck by disturbances can still be contained in the bottleneck until the capacity of the bottleneck is reached. This can be considered as one of the generating processes of the congested traffic which normally occurs in motorway sections with ramps. This traffic state shows the characteristics of the congested traffic that the speed is low but the flow is not so low and the density is rather high.

When the upstream demand of the main stream is as high as in the congestion without propagation but the flows of ramps and the interaction strength q_{int} is higher than in the congestion without propagation, **congestion with propagation** is observed. The increased interaction strength decreases the capacity of the bottleneck. The total flow of the ramps and the main stream reaches the decreased capacity of the bottleneck. The outflow from the bottleneck decreases significantly. The congestion generated propagates upstream in the form of shock waves and the traffic volume accumulated in the bottleneck by disturbances cannot be contained in the bottleneck. If the density or the interaction strength q_{int} is beyond thresholds the breakdown of the traffic flow occurs spontaneously and it can be considered as a self-organisation effect. The process of the congestion generation has not been exactly identified yet. In this state the traffic flow of the on-ramp can also be influenced by the traffic situation of the main stream. If the traffic situation of the main stream is improved and the flow increases, the on-ramp flow also increases. If the traffic situation of the main stream deteriorates and the flow of the main stream decreases, the on-ramp flow also decreases.

The time development of the speed at the detectors and the interaction strength (q_{int}) are analysed in the case of congestion with propagation and congestion without propagation. This analysis is compared with the flow-density relation at detector 25; see Fig. 4.7. In the time development of the speed at detector 27 it is shown that no congestion was observed by detector 27.

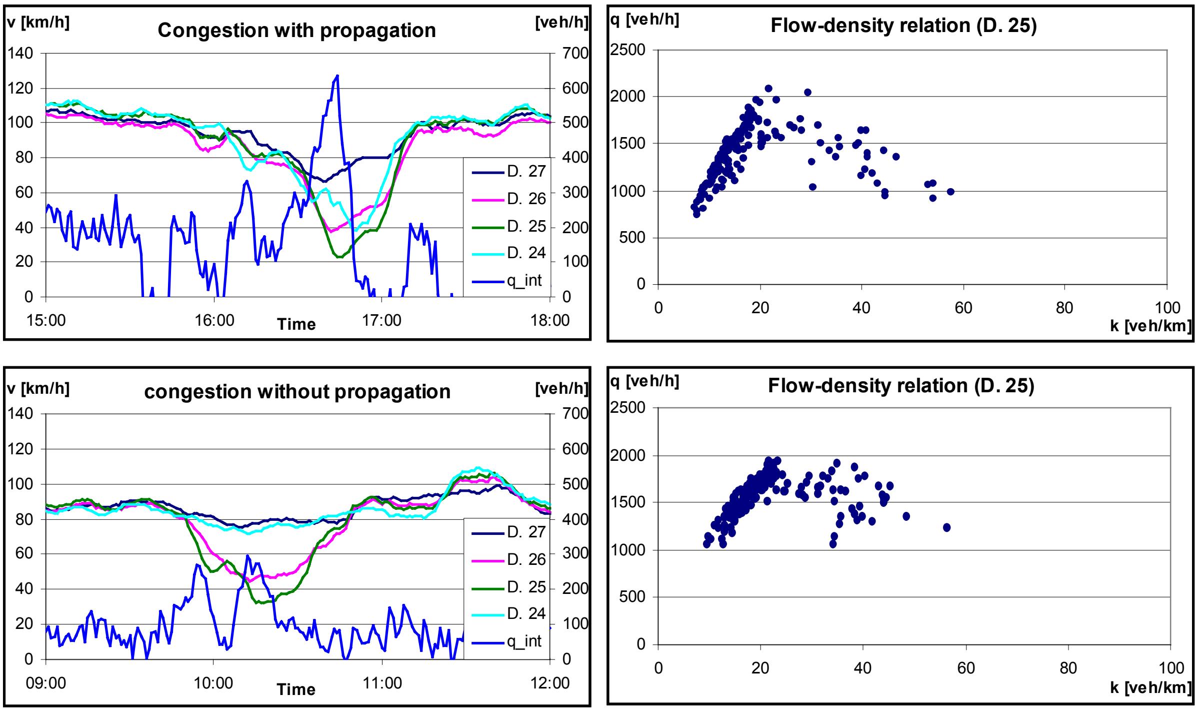


Figure 4.7: Congestion propagation and the flow-density relation

The data of congestion with propagation was observed on 15 July 1997. The speed of detector 25 first decreases followed by a reduction in the speed at detector 24. In this traffic state the interaction strength q_{int} shows a very high value. The interaction strength has a maximum value just before the congestion arrives at detector 24 and the speed of detector 24 has very low values. The data of congestion without propagation was observed on 30 July 1997. The speed of detector 25 is low but the speed of detector 24 remains high. The interaction strength is not very high.

The interaction strength shows noticeable differences in two cases though there are no significant differences in the flow-density relations. The interaction strength can be used as an indicator for the congestion propagation. In the next chapter the interaction strength and the upstream traffic demand are applied to the determination of the dynamic flow-density relation in motorway sections with ramps.

4.4 Summary

Even though traffic characteristics of motorway sections with ramps are very important to traffic flow modelling and traffic control of motorway networks, they are not identified yet because of the intangible properties of traffic behaviour in motorway sections with ramps.

In this research the propagation of congestion generated by the ramps is analysed applying the new phase diagram which was produced based on the upstream traffic demand and the interaction strength. The new phase diagram overcomes the drawbacks of the existing phase diagrams and can be applied to real time traffic flow modelling and traffic control systems.

The generation process of congestion remains unsolved. In order to investigate the congestion generation the traffic behaviour should be described in more detail considering the interaction between the traffic flow of the main stream and the ramp.

5 Online Situational Hydrodynamic Model

This chapter presents a new approach to online traffic flow modelling on motorways based on the continuum theory and an online process to adapt the flow-density relations dynamically to the site-dependent changes in the traffic context.

Macroscopic traffic flow models are very effective for the description of the current traffic state but they are based on a static function for the flow-density relation. This static relation is proposed only for a stable and stationary traffic state and should be understood as a long-time average relationship. The static relation is not capable of reacting satisfactorily to unexpected changes in the prevailing traffic states, which is very important for the real time traffic control.

To study the dynamic behaviour of the traffic flow on motorways, the flow-density relation should be analysed based on short detection intervals (like 1-minute) considering the upstream and downstream traffic conditions observed along a motorway. This analysis leads to an empirical classification of different traffic states, characterised by consecutive phases of traffic bringing about hysteresis phenomena in the states diagram.

As explained before, the high order refinements of the simple continuum model do not improve the deficiencies in a proper way and the high order models have more parameters to calibrate, which is critical for the online traffic flow description. Therefore, for the purpose of online 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 which are updated at each time interval during the online simulation, based on the shock wave theory depending on upstream and downstream traffic data (the model is named '*situational cell-transmission model*' in this research). For the determination of the dynamic sending and receiving functions, traffic states classification and fuzzy logic are employed.

The situational cell-transmission model is extended to describe the propagation of the congestion in motorway sections with ramps applying observed empirical phenomena in traffic flow.

5.1 Structure of the Situational Cell-Transmission Model

The cell-transmission model of DAGANZO is extended by the modification of the sending/receiving functions, the classification of the cells and the application of the determination strategy for the flow-density relation in the cells. In the implementation of the macroscopic traffic flow model unreasonable results (negative or illogically high density) can occur. These unreasonable results are alleviated by applying buffer cells. The mathematical proof of the role of buffer cells is presented. The model is also extended to simulate the traffic flow in motorway sections with ramps.

5.1.1 Modification of Sending/Receiving Function

In the research of DAGANZO (1994, 1999a) the static sending and receiving functions are used which are determined beforehand and do not vary during the traffic flow simulation. With these static functions complicated traffic dynamics generated by various downstream and upstream traffic situations cannot be described in real time. In this research dynamic sending and receiving functions are therefore proposed which vary depending on the observed downstream and upstream traffic data.

For the computer implementation linear sending and receiving functions as well as the maximum flow of cells are used, as in the former research of DAGANZO (1994); see Fig. 5.1. It is assumed in this paper that every traffic data fits to a branch (either sending or receiving function) in the flow-density relation.

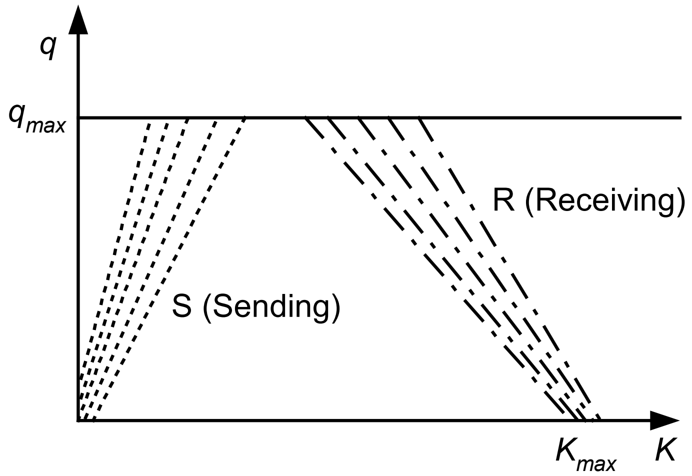


Figure 5.1: Modified dynamic sending and receiving functions

In the modified flow-density relation the maximum flow q_{max} is a constant given as a parameter. Each traffic data fits a sending or receiving function in the flow-density relations 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 the traffic states classified in chapter 3. The sending and receiving functions are updated in each interval.

The shock wave speed is determined by the fuzzy solver with the current traffic data. 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. The sending function can have a positive or negative intersection with the flow axis depending on traffic data, which is different from the sending function in DAGANZO (1994) which always passes the origin. The intersection is determined by the tangent of the sending function and a pivot which is the averaged traffic data (the density and the flow) for a certain detection interval.

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 this case the intersection of the sending function with the flow axis is assumed to be 0. The maximum density of the receiving function (the intersection with the density axis) is determined analogously as described above for the determination of the intersection with the flow axis. Contrary to the fixed jam density in DAGANZO (1994), the maximum density varies depending on the traffic data. There are no constraints on the maximum density in order to represent the characteristics of the current traffic states suitably (i.e. the tangent of congested traffic can be nearly 0).

From the flow-density relation determined in this way, the negative flow value can be produced in the model, although such a case happens seldom with real traffic data. The negative flow values are corrected by introducing non-negative constraints on the flow.

Even though the shock wave speed is updated with the current traffic data in each minute interval, the values of the shock wave speed do not fluctuate so wildly owing to tolerant characteristics of the fuzzy controller. By using moving averages of traffic data with longer detection intervals more stable values of the shock wave speed can be obtained.

5.1.2 Classification of Cells

In the situational cell-transmission model a motorway link is divided into various cells with different characteristics; see Fig. 5.2. The ordinary cells have a certain length (d) and follow the updating scheme of the density and the flow described by the continuity equation and the flow equation.

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

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

The input and output cells have no length and obtain their flow and density values directly from the detector at the beginning (input) and the end (output) of the link and therefore have no calculation processes.

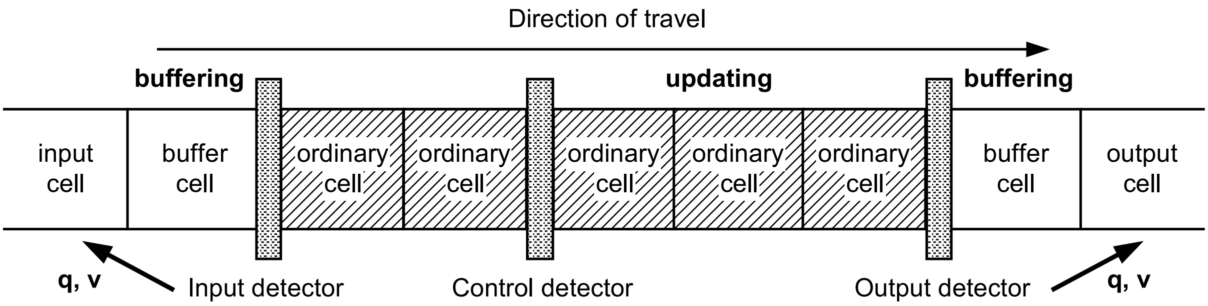


Figure 5.2: Presentation of a motorway section in the model

The buffer cells have no length like the input and output cells and absorb the difference between traffic data and the traffic flow model. Most continuum traffic flow models assume that input and output data follow a given flow-density relationship, and the traffic dynamics is described in the models depending on the input and output data. In reality input and output data, however, deviate from the given flow-density relationship and can change unexpectedly. Most traffic flow models do not rapidly react to changes in traffic data. Sudden changes make most models unstable and induce unreasonable results, i.e. negative density or illogically high density values. In particular, because the updating interval in the cell-transmission model is very short the deviations of traffic data from the flow-density relationship have a very serious effect on the simulation. To avoid this side effect the buffer cells are included.

The updating scheme of the density 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 updated density in the buffer cells, whose associated flow value is chosen in the flow equation above, instead of using the continuity equation as in the ordinary cells. A mathematical proof of the effectiveness of the buffer cell approach with the dynamic flow-density relation determination strategy is presented in section 5.1.4.

5.1.3 Determination Strategy for the Flow-Density Relation in the Cells

Contrary to the models of DAGANZO (1994 and 1999a) using the same flow-density relation over the whole simulation, dynamic flow-density relations are used in the situational cell-transmission model according to a 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 output cell have the flow-density relation determined by the input or output data, respectively. The ordinary cells have the flow-density relation determined by the input or output traffic data based on the shock wave theory. If the shock wave has a positive speed the current flow-density relation in the ordinary cells will be influenced by the upstream traffic situation. If the shock wave has a negative speed the flow-density relation in the ordinary cells will be influenced by the downstream traffic situation.

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

Table 5.1: A flow-density relation determination strategy in the ordinary cells

The traffic situations are simplified as the four cases in table 5.1. In this strategy it is assumed that the speed is a monotone decreasing function of the density. If the upstream speed is higher than the downstream speed, $v_{up} > v_{down}$, it means that the upstream density is lower than the downstream density, $k_{up} < k_{down}$.

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. With this strategy the propagation of the congestion generated upstream as well as downstream can be described satisfactorily for the purpose of traffic control.

[1] Speed at upstream detector

In motorway sections with ramps the flow-density relations are influenced by the interactions between the flows of the main stream and the ramps. The interactions cause the capacity reduction of the motorway sections with ramps. This effect is discussed in section 5.1.5.

Finer determination strategies for the flow-density relation can be developed considering the upstream and downstream traffic situations as well as the motorway geometry.

5.1.4 Buffer Cells

Since traffic data used as boundary conditions deviates from the given flow-density relation, unreasonable results of the model (negative density or illogically high density values) may occur in the first and last cells of the traffic flow model. In this section the generation of the unreasonable results is discussed and the role of buffer cells to alleviate the results is proved mathematically.

5.1.4.1 The Needs for Buffer Cells

The unreasonable results of the model may occur in free flow as well as in congested flow conditions. The simulated traffic situation of the boundary cell between the output cell and ordinary cells in the free flow condition (Fig. 5.3 a)) and the simulated traffic situation of the boundary cell between the input cell and ordinary cells in the congested flow condition (Fig. 5.3. b)) are shown as examples.

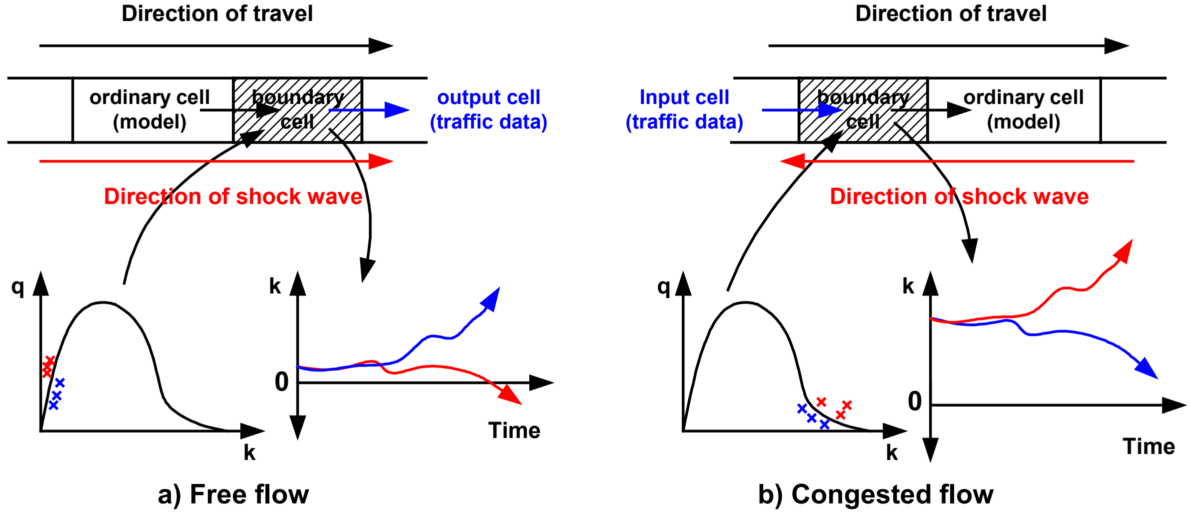


Figure 5.3: Unreasonable simulation results in the boundary cells

The propagation of perturbations in the traffic flow model is represented as the direction of shock wave. In the free flow condition the changes in the density always propagate downstream and in the congested flow condition the changes in the density always propagate upstream. Therefore, the boundary cells of both cases are influenced by the ordinary cells and the ordinary cells are not influenced by the boundary cells, i.e. the density of ordinary cells is determined exclusively by the model (more specifically by the given flow-density relation). Unless there were discrepancies between the given flow-density relation and traffic data, the traffic situations of the boundary cells would be the same as those of the ordinary cells next to the boundary cells and remain in the stable state with low or high density values.

In **free flow**, if the traffic data contains lower flow values than those of the given flow-density relation with the same density values for a certain time interval (blue points in Fig. 5.3a)) the inflow to the boundary cell is higher than the outflow from the boundary cell and the density of the boundary cell becomes higher until the speed of shock wave has a negative value and the ordinary cells are influenced by the boundary cell. If the observed flow values are higher than those of the given flow-density relation for a certain time interval (red points in Fig. 5.3a)) the inflow to the boundary cell is lower than the outflow from the boundary cell and the density of the boundary cell becomes lower with no limit.

In **congested flow**, if the observed flow values are lower than those of the given flow-density relation for a certain time interval (blue points in Fig 5.3b)) the inflow to the boundary cell is lower than the outflow from the boundary cell and the density of the boundary cell becomes lower until the speed of shock wave has a positive value and the ordinary cells are influenced by the boundary cell. If the observed flow values are higher than those of the given flow-density relation for a certain time interval (red points in Fig. 5.3b)) the inflow to the boundary cell is higher than the outflow from the boundary cell and the density of the boundary cell becomes higher with no limit.

Depending on the flow calculation schemes of the model (i.e. $q_i = v_i \times k_i$, $q_i = v_{i+1} \times k_{i+1,}$ $q_i = (\alpha)v_i \times k_i + (1\text{-}\alpha)\ v_{i+1} \times k_{i+1}$ or $q_i = k_i \times v_{i+1}$) the unreasonable results occur in different situations but are not entirely eliminated.

In order to solve the problems, the imaginary cells which are similar to the buffer cells in this research or constraints on the density have been applied to the implementation of the macroscopic traffic flow models. However, the application of the imaginary cells without suitable strategies for adjustments of traffic data to the traffic flow model is not effective. The application of the constraints can alleviate the negative or too high density values but it takes a long time for boundary cells to recover normal states from weird states once they break away from the normal states.

5.1.4.2 Stability Analysis

The unreasonable results caused by the discrepancies between traffic flow model (ideal situation) and traffic data (real situation) can be alleviated by employing buffer cells. The role of the buffer cells are proved mathematically. For the proof, the motorway section is represented schematically; see Figure 5.4.

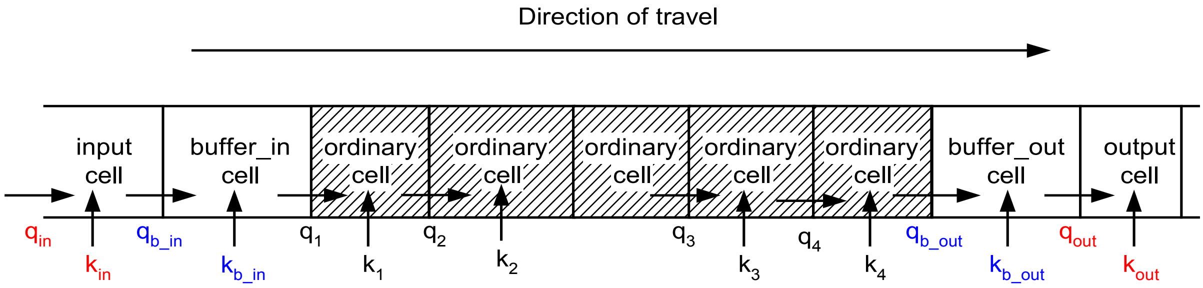


Figure 5.4: Schematic representation of the motorway section

The updating scheme of the buffer cells in the situational cell-transmission model is represented as follows,

the density: buffer_in: if $S_{in}(k_{in}) < R(k_1)$, then $k_{b\_in} = k_{in}$.
if $Sin(k_{in}) > R(k_1)$, then $k_{b\_in} = k_1$.

buffer_out: if $S(k_4) < R_{out}(k_{out})$, then $k_{b\_out} = k_4$.
if $S(k_4) > R_{out}(k_{out})$, then $k_{b\_out} = k_{out}$.

the flow: buffer_in: if $S_{in}(k_{in}) < R(k_1)$, then $q_{b\_in} = S_{in}(k_{in})$.
if $S_{in}(k_{in}) > R(k_1)$, then $q_{b\_in} = R(k_1)$.

buffer_out: if $S(k_4) < R_{out}(k_{out})$, then $q_{b\_out} = S(k_4)$.
if $S(k_4) > R_{out}(k_{out})$, then $q_{b\_out} = R_{out}(k_{out})$.

The following two assumptions for the proof can be generally accepted.

- The simple continuum model is stable over the whole range of the density, i.e. within the model the illogical results do not occur.
- The sending and receiving functions are decided by the determination strategy of the flow-density relation.

Input cell	Output cell	q-k relation of ordinary cells	Buffer_in	Case	Buffer_out	Case
Free flow	Free flow	By input data	$S_{in}(k_{in}) < R_{in}(k_1)$	1	$S_{in}(k_4) < R_{out}(k_{out})$	5
			$S_{in}(k_{in}) > R_{in}(k_1)$	2	$S_{in}(k_4) > R_{out}(k_{out})$	6
Free flow	Jammed flow	By input data	$S_{in}(k_{in}) < R_{in}(k_1)$	1	$S_{in}(k_4) < R_{out}(k_{out})$	5
			$S_{in}(k_{in}) > R_{in}(k_1)$	2	$S_{in}(k_4) > R_{out}(k_{out})$	6
		By output data	$S_{in}(k_{in}) < R_{out}(k_1)$	3	$S_{out}(k_4) < R_{out}(k_{out})$	7
			$S_{in}(k_{in}) > R_{out}(k_1)$	4	$S_{out}(k_4) > R_{out}(k_{out})$	8
Jammed flow	Jammed flow	By output data	$S_{in}(k_{in}) < R_{out}(k_1)$	3	$S_{out}(k_4) < R_{out}(k_{out})$	7
			$S_{in}(k_{in}) > R_{out}(k_1)$	4	$S_{out}(k_4) > R_{out}(k_{out})$	8
Jammed flow	Free flow	By input data	$S_{in}(k_{in}) < R_{in}(k_1)$	1	$S_{in}(k_4) < R_{out}(k_{out})$	5
			$S_{in}(k_{in}) > R_{in}(k_1)$	2	$S_{in}(k_4) > R_{out}(k_{out})$	6
		By output data	$S_{in}(k_{in}) < R_{out}(k_1)$	3	$S_{out}(k_4) < R_{out}(k_{out})$	7
			$S_{in}(k_{in}) > R_{out}(k_1)$	4	$S_{out}(k_4) > R_{out}(k_{out})$	8

Table 5.2: The classification of the traffic states

According to the flow-density relation decision strategy and the first assumption that the simple continuum model is stable, the traffic situations are classified into eight cases and each of them is examined. The traffic states of input and output cells are used only as a means to understand the traffic situations. The role of the buffer cells are proved independent of the traffic situations at the input and output cells.

Case 1:
The flow-density relation of the ordinary cells is determined by input data. Since S_{in} (k_{in}) < R_{in} (k_1), $k_{b\_in} = k_{in}$ and $q_{b\_in} = S_{in}$ (k_{in}).

$$\frac{k_1(t+\Delta t)-k_1(t)}{\Delta t}+\frac{q_2-q_1}{\Delta x}=0$$
$$\frac{k_1(t+\Delta t)-k_1(t)}{\Delta t}=\frac{q_1-q_2}{\Delta x}$$

$$q_1=\min\{S_{in}(k_{b\_in}),q_{\max},R_{in}(k_1)\}$$
$$q_2=\min\{S_{in}(k_1),q_{\max},R_{in}(k_2)\}$$

If $q_1 > q_2$, then $k_1(t)$ is an increasing function of time until the condition S_{in} (k_{in}) < R_{in} (k_1) holds. If the condition becomes S_{in} (k_{in}) > R_{in} (k_1) then it becomes case 2.

If $q_1 < q_2$, then $k_1(t)$ is a decreasing function of time. As the k_1 gets smaller, q_1 becomes S_{in} (k_{b_in}) = S_{in} (k_{in}) and q_2 becomes S_{in} (k_1).

$$\frac{k_1(t+\Delta t)-k_1(t)}{\Delta t}=\frac{S_{in}(k_{in})-S_{in}(k_1)}{\Delta x}$$

If we set S_{in} (k) = a·k + b (a > 0) without loss of generality. then

$$\frac{k_1(t+\Delta t)-k_1(t)}{\Delta t}=\frac{a\cdot(k_{in}-k_1)}{\Delta x}$$

If $k_{in} > k_1$, $k_1(t)$ is an increasing function. If $k_{in} < k_1$, $k_1(t)$ is a decreasing function. The function $k_1(t)$ is stable around the value of k_{in}.

Case 2:
The flow-density relation of the ordinary cells is determined by input data. Since S_{in} (k_{in}) > R_{in} (k_1), $k_{b\_in} = k_1$ and $q_{b\_in} = R_{in}$ (k_1).

$$q_1=\min\{S_{in}(k_{b\_in}),q_{\max},R_{in}(k_1)\}=\min\{S_{in}(k_1),q_{\max},R_{in}(k_1)\}$$

The illogical results do not occur under the first aussumption that the simple continuum model is stable within the model.

Case 3:
The flow-density relation of the ordinary cells is determined by output data. Since S_{in} (k_{in}) < R_{out} (k_1), $k_{b\_in} = k_{in}$ and $q_{b\_in} = S_{in}$ (k_{in}).

$$\frac{k_1(t+\Delta t)-k_1(t)}{\Delta t}+\frac{q_2-q_1}{\Delta x}=0$$
$$\frac{k_1(t+\Delta t)-k_1(t)}{\Delta t}=\frac{q_1-q_2}{\Delta x}$$

$$q_1 = \min\{S_{in}(k_{b\_in}), q_{\max}, R_{out}(k_1)\}$$
$$q_2 = \min\{S_{out}(k_1), q_{\max}, R_{out}(k_2)\}$$

If $q_1 > q_2$, then $k_1(t)$ is an increasing function of time until the condition $S_{in}(k_{in}) < R_{out}(k_1)$ holds. If the condition becomes $S_{in}(k_{in}) > R_{out}(k_1)$ then it becomes case 4.

If $q_1 < q_2$, then $k_1(t)$ is a decreasing function of time. As the k_1 gets smaller, q_1 becomes $S_{in}(k_{b\_in}) = S_{in}(k_{in})$ and q_2 becomes $S_{out}(k_1)$.

$$\frac{k_1(t+\Delta t) - k_1(t)}{\Delta t} = \frac{S_{in}(k_{in}) - S_{out}(k_1)}{\Delta x}$$

$k_1(t)$ is a decreasing function until the value of the function $S_{in}(k_{in})$ is smaller than that of the function $S_{out}(k_1)$. If the value of $S_{in}(k_{in})$ is greater than that of $S_{out}(k_1)$, $k_1(t)$ is an increasing function. For this case a constraint $S_{in}(k_{in}) > C$ is added in the implementation.

Case 4:
The flow-density relation of the ordinary cell is determined by output data. Since $S_{in}(k_{in}) > R_{out}(k_1)$, $k_{b\_in} = k_1$ and $q_{b\_in} = R_{out}(k_1)$.

$$\frac{k_1(t+\Delta t) - k_1(t)}{\Delta t} + \frac{q_2 - q_1}{\Delta x} = 0$$

$$q_1 = \min\{S_{in}(k_1), q_{\max}, R_{out}(k_1)\}$$
$$q_2 = \min\{S_{out}(k_1), q_{\max}, R_{out}(k_2)\}$$

If $q_2 > q_1$, $k_1(t)$ is an increasing function of time. q_1 becomes $R_{out}(k_1)$ and q_2 becomes $R_{out}(k_2)$.

$$\frac{k_1(t+\Delta t) - k_1(t)}{\Delta t} = \frac{R_{out}(k_1) - R_{out}(k_2)}{\Delta x}$$

If we set $R_{out}(k) = c \cdot k + d$ $(c<0)$ without loss of generality, then

$$\frac{k_1(t+\Delta t) - k_1(t)}{\Delta t} = \frac{c \cdot (k_1 - k_2)}{\Delta x}.$$

If $k_1 > k_2$, $k_1(t)$ is a decreasing function. If $k_1 < k_2$, $k_1(t)$ is an increasing function. $k_1(t)$ is stable around the value of k_2.

If $q_1 > q_2$, $k_1(t)$ is a decreasing function until the condition $S_{in}(k_{in}) > R_{out}(k_1)$ holds.

Case 5:
The flow-density relation of the ordinary cells is determined by input data. Since $S_{in}(k_4) < R_{out}(k_{out})$, $k_{b\_out} = k_4$ and $q_{b\_out} = S_{in}(k_4)$.

$$\frac{k_4(t+\Delta t) - k_4(t)}{\Delta t} = \frac{q_4 - q_{b\_out}}{\Delta x} = \frac{q_4 - S_{in}(k_4)}{\Delta x}$$

$$q_4 = \min\{S_{in}(k_3), q_{\max}, R_{in}(k_4)\}$$

If $q_4 > S_{in}(k_4)$, $k_4(t)$ is an increasing function until $S_{in}(k_4) < R_{out}(k_{out})$ holds.
If $q_4 < S_{in}(k_4)$, $k_4(t)$ is a decreasing function and q_4 becomes $S_{in}(k_3)$.

$$\frac{k_4(t+\Delta t) - k_4(t)}{\Delta t} = \frac{S_{in}(k_3) - S_{in}(k_4)}{\Delta x}$$

If we set $S_{in}(k) = a \cdot k + b$ $(a > 0)$ without loss of generality. then

$$\frac{k_4(t+\Delta t) - k_4(t)}{\Delta t} = \frac{a \cdot (k_3 - k_4)}{\Delta x}$$

If $k_3 > k_4$, k_4 is an increasing function. If $k_3 < k_4$, k_4 is a decreasing function. $k_4(t)$ is stable around the value k_3.

Case 6:
The flow-density relation of the ordinary cells is determined by input data. Since $S_{in}(k_4) > R_{out}(k_{out})$, $k_{b\_out} = k_{out}$ and $q_{b\_out} = R_{out}(k_{out})$.

$$\frac{k_4(t+\Delta t) - k_4(t)}{\Delta t} + \frac{q_{b\_out} - q_4}{\Delta x} = 0$$
$$\frac{k_4(t+\Delta t) - k_4(t)}{\Delta t} = \frac{q_4 - R_{out}(k_{out})}{\Delta x}$$

$$q_4 = \min\{S_{in}(k_3), q_{\max}, R_{in}(k_4)\}$$

If $q_4 > R_{out}(k_{out})$, then $k_4(t)$ is an increasing function of time and q_4 becomes $R_{in}(k_4)$ and

$$\frac{k_4(t+\Delta t) - k_4(t)}{\Delta t} = \frac{R_{in}(k_4) - R_{out}(k_{out})}{\Delta x}$$

$k_4(t)$ is an increasing function of time until $R_{in}(k_4)$ is greater than $R_{out}(k_{out})$. If $R_{in}(k_4)$ is smaller than $R_{out}(k_{out})$ then $k_4(t)$ is a decreasing function of time. For this case a constraint $R_{out}(k_{out}) > C$ is added in the implementation.

If $q_4 < R_{out}(k_{out})$, then $k_4(t)$ is a decreasing function of time until the condition $S_{in}(k_4) > R_{out}(k_{out})$ holds. If $S_{in}(k_4) < R_{out}(k_{out})$, then it is case 5.

Case 7:
The flow-density relation of the ordinary cells is determined by output data. Since $S_{out}(k_4) < R_{out}(k_{out})$, $k_{b\_out} = k_4$ and $q_{b\_out} = S_{out}(k_4)$.

$$\frac{k_4(t+\Delta t) - k_4(t)}{\Delta t} = \frac{q_4 - S_{out}(k_4)}{\Delta x}$$

$$q_4 = \min\{S_{out}(k_3), q_{\max}, R_{out}(k_4)\}$$

If $q_4 > S_{out}(k_4)$, $k_4(t)$ is an increasing function until the condition $S_{out}(k_4) < R_{out}(k_{out})$ holds.

If $q_4 < S_{out}(k_4)$, $k_4(t)$ is a decreasing function and q_4 becomes $S_{out}(k_3)$.

$$\frac{k_4(t+\Delta t)-k_4(t)}{\Delta t}=\frac{S_{out}(k_3)-S_{out}(k_4)}{\Delta x}$$

If we set $S_{out}(k) = a \cdot k + b$ $(a > 0)$ without loss of generality. then

$$\frac{k_4(t+\Delta t)-k_4(t)}{\Delta t}=\frac{a\cdot(k_3-k_4)}{\Delta x}$$

If $k_3 > k_4$, k_4 is an increasing function. If $k_3 < k_4$, k_4 is a decreasing function. $k_4(t)$ is stable around the value of k_3.

Case 8:
The flow-density relation of the ordinary cells is determined by output data. Since $S_{out}(k_4) > R_{out}(k_{out})$, $k_{b\_out} = k_{out}$ and $q_{b\_out} = R_{out}(k_{out})$.

$$\frac{k_4(t+\Delta t)-k_4(t)}{\Delta t}+\frac{q_{b\_out}-q_4}{\Delta x}=0$$
$$\frac{k_4(t+\Delta t)-k_4(t)}{\Delta t}=\frac{q_4-R_{out}(k_{out})}{\Delta x}$$

$$q_4=\min\{S_{out}(k_3),q_{\max},R_{out}(k_4)\}$$

If $q_4 > R_{out}(k_{out})$, then $k_4(t)$ is an increasing function of time and q_4 becomes $R_{out}(k_4)$ and

$$\frac{k_4(t+\Delta t)-k_4(t)}{\Delta t}=\frac{R_{out}(k_4)-R_{out}(k_{out})}{\Delta x}$$

If we set $R_{out}(k) = c \cdot k + d$ $(c < 0)$ without loss of generality. Then

$$\frac{k_4(t+\Delta t)-k_4(t)}{\Delta t}=\frac{c\cdot(k_4-k_{out})}{\Delta x}$$

If $k_4 > k_{out}$, $k_4(t)$ is a decreasing function. If $k_4 < k_{out}$, $k_4(t)$ is an increasing function. The function $k_4(t)$ is stable around k_{out}.

If $q_4 < R_{out}(k_{out})$, then $k_4(t)$ is a decreasing function of time until the condition $S_{out}(k_4) > R_{out}(k_{out})$ holds. If the condition becomes $S_{out}(k_4) < R_{out}(k_{out})$ then it is case 7.

The traffic situation is classified into eight cases and the stability of the model is proved in each case.

5.1.5 Extension of the Model for Motorway Sections with Ramps

The traffic dynamics of motorway sections with ramps is more complicated than that of homogeneous motorway sections because of the intangible effects of exiting and entering vehicles. A group of researchers have been investigating the traffic characteristics of motorway sections with ramps and trying to develop traffic flow models which can describe the complicated traffic dynamics macroscopically or microscopically. However, the traffic dynamics has not been fully identified yet.

The objective of this research is to obtain simple but useful information of traffic characteristics in motorway sections with ramps for the real time traffic control, even though the traffic dynamics cannot be exactly described. Therefore, in this research the bottleneck system is abstracted as a simple input-output system with a capacity and the propagation of congestion is simulated by the situational cell-transmission model extended for motorway sections with ramps.

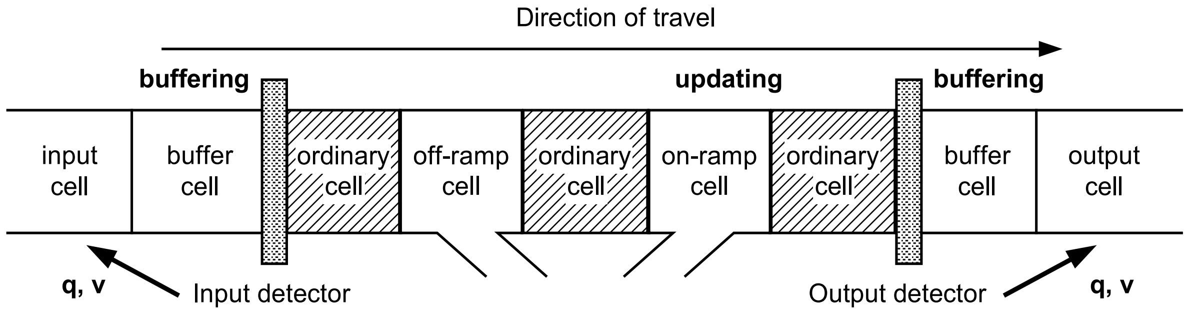


Figure 5.5: The motorway section with ramps

The motorway section with ramps is separated from homogeneous sections and limited to a minimum length to minimise the unpredictable section of the motorway; see Fig. 5.5. The on-ramp and off-ramp cells have the same length as the ordinary cells.

The situational cell-transmission model is extended by adding the on-ramp and off-ramp flow terms ($q_{on}(t)$, $q_{off}(t)$) to the continuity equation and by adjusting the flow-density relation for the motorway section with ramps. The other processes are the same as those of homogenous sections.

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

The flow-density relation is a temporal description of traffic flow at a detection point. The flow-density relation of the section with ramps is different from the neighbouring homogeneous sections. In homogeneous motorway sections, the temporal changes in traffic flow at a detection point are influenced by the upstream and downstream traffic situations (spatial changes in the traffic flow) and represented differently depending on both traffic situations. This relation between the spatial and temporal changes becomes more complicated if the traffic flow is influenced by exogenous situations like on-ramp and off-ramp traffic flows or bottlenecks.

In homogeneous motorway sections the flow-density relation was determined by a simple strategy based on the shock wave theory. In motorway sections with ramps the flow-density relation, however, should be determined considering the on-ramp and off-ramp flows. The on-ramp and off-ramp flows influence not only the changes in the density in motorway sections but also induce the interaction which causes complicated traffic dynamics in motorway sections with ramps.

As shown in chapter 4, the on-ramp and the off-ramp flows cause the reduction of the capacity in the motorway section, which is a very important and useful characteristic for modelling the propagation of congestion. If the flows of ramps and main stream are low and the interaction between them remains weak there is no capacity reduction. If the flows increase and the interaction becomes strong the capacity of the bottleneck will be reduced. In this situation the congestion propagates upstream more often. The propagation of congestion depends mainly on the capacity of the motorway section.

Traffic flow in the motorway section with ramps is classified into three traffic states depending on the upstream traffic demand and the interaction strength; free flow, congestion without propagation, and congestion with propagation. The capacity of the motorway section is reduced differently depending on the traffic state. The capacity reduction can be considered explicitly in the dynamic flow-density relation. If the flow-density relation is described by a triangle or a composite of the linear functions (e.g. the capacity of motorway sections, sending and receiving functions) the capacity reduction is represented by the reduction of the jam density k_{max}. If the flow-density relation, however, is described by a parabolic curve more parameters must be adjusted for the reduction of the capacity.

The thresholds for the classification of the traffic state are not clear and fuzzy logic is applied to the determination of the traffic states. Fuzzy logic combines the traffic state and the capacity reduction, which is explained in the next section.

5.2 Determination of the Dynamic Flow-Density Relation with Fuzzy Logic

Traffic flow is generally classified into two traffic states (free flow and congested flow). This general classification of traffic flow is, however, not sufficient to describe the changes in the prevailing traffic state in practical traffic control systems, because available traffic data used for real time traffic control is limited and the current traffic state must be identified with the limited data. A detailed classification of traffic flow based on shorter detection intervals is required so that the prevailing traffic state can be identified and considered in the traffic flow models. With the shorter detection intervals the states diagram has a different shape from the flow-density relation suggested for the steady states.

As shown in chapter 3, the traffic states in the states diagram are empirically classified into six states; free flow, impeded free flow, synchronised, congested, jammed, stopped states. From the detailed classification of traffic states a dynamic flow-density relation which represents the current traffic state at a detection point can be inferred. However, the thresholds for the classification of these states are not clear. In this research fuzzy logic is applied to classify the traffic states and to determine the shape of the dynamic flow-density relation.

For the classification of traffic states and the determination of the dynamic flow-density relation for the situational cell-transmission model three macroscopic traffic variables (the speed, the flow, and the density) are used as input values and the respective free-flow speed or shock wave speed is inferred as the output. The maximum density of the receiving function and the intersection with the flow axis of the sending function in the flow-density relations are determined from the averaged traffic data in a certain interval.

5.2.1 Fuzzy Logic

The term fuzzy logic has been used in two different senses. In a narrow sense, fuzzy logic refers to a logical system that generalises classical two-valued logic for reasoning under uncertainty. In a broad sense, fuzzy logic refers to all of the theories and technologies that employ fuzzy sets whose boundaries are unsharp.

Since the idea of fuzzy sets was born in July 1964 fuzzy logic has been applied to a wide variety of areas, e.g. consumer products, robotics, manufacturing, process control, medical imaging, and financial trading and distinguished performances of fuzzy logic have been verified. Nowadays, fuzzy logic is also applied to traffic control systems and shows good results (BOGENBERGER and KELLER, 2001; KERNER ET AL., 2001).

Fuzzy logic was motivated by two objectives. First, it aims to alleviate difficulties in developing and analysing complex systems encountered by conventional mathematical tools. Second, it is motivated by observing that human reasoning can utilise concepts and knowledge that do not have well-defined, sharp boundaries (i.e. vague concepts). The former motivation requires fuzzy logic to work in quantitative and numeric domains, while the latter motivation enables fuzzy logic to have a descriptive and qualitative form because vague concepts are often described qualitatively by words. These two motivations together not only make fuzzy logic unique and different from other technologies that focus on only one of these goals but also enable fuzzy logic to be a natural bridge between the quantitative world and qualitative world. This unique characteristic of fuzzy logic allows this technology to offer an important benefit; it not only provides a cost-effective way to model complex systems involving numeric variables but also offers a qualitative description of the system that is easy to comprehend.

Fuzzy logic is based on four basic concepts: (1) fuzzy sets, (2) linguistic variables, (3) possibility distribution, and (4) fuzzy if-then rules.

5.2.1.1 Fuzzy Sets

A fuzzy set is a set with a smooth boundary. The fuzzy set theory generalises classical set theory to allow partial membership. A set in the classical set theory always has a sharp boundary because membership in a set is a black-and-white concept; an objet either belongs to the set completely or does not belong to the set at all. Even though some sets have sharp boundaries many others do not. Fuzzy set theory directly addresses this limitation by allowing membership in a set to be a matter of degree.

The degree of membership in a set is expressed by a value between 0 and 1. A fuzzy set is thus defined by a function that maps objects in a domain of concern to their membership value in the set. Such a function is called 'membership function' and is usually denoted by the Greek symbol μ; see Fig. 5.6. The membership function provides a gradual transition from regions completely outside a set to regions completely within the set. Even though membership functions of arbitrary shape can be defined theoretically, the use of parameterisable functions is strongly recommended, which can be defined by a small number of parameters. The parameterisable membership functions most commonly used in practice are the triangular membership function and the trapezoid membership function.

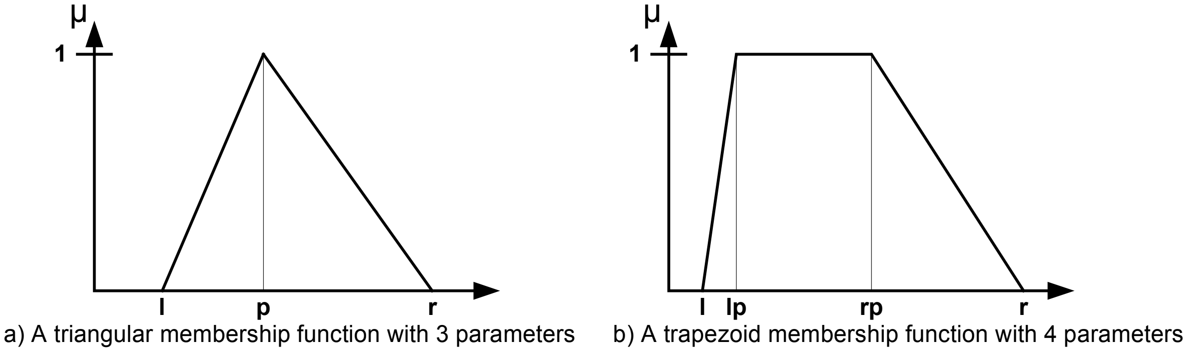


Figure 5.6: Most commonly used membership functions

In addition to membership functions, a fuzzy set is also associated with a linguistically meaningful term, e.g. High and Low or Good and Poor. Associating a fuzzy set to a linguistic term offers two important benefits. First, the association makes it easier for human experts to express their knowledge using the linguistic terms. Second, the knowledge expressed using linguistic terms is easily comprehensible.

Since membership in a fuzzy set is a matter of degree, set operations of the classical set theory should be generalised accordingly. The union of two fuzzy sets is defined by the maximum of the two fuzzy sets.

$$\mu_{A \cup B}(x) = \max\{\mu_A(x), \mu_B(x)\}$$

The intersection of two fuzzy sets is defined by the minimum of the two fuzzy sets.

$$\mu_{A \cap B}(x) = \min\{\mu_A(x), \mu_B(x)\}$$

The complement of a fuzzy set A is defined by the difference between 1 and the membership degree in A.

$$\mu_{A^C}(x) = 1 - \mu_A(x)$$

5.2.1.2 Linguistic Variables

A linguistic variable enables its value to be described both qualitatively by a linguistic term (i.e. a symbol serving as the name of a fuzzy set) and quantitatively by a corresponding membership function (which expresses the meaning of the fuzzy set). The linguistic term is used to express concepts and knowledge in human communication, whereas the membership function is useful for processing numeric input data. Using the notion of the linguistic variable to combine these two kinds of variables into a uniform framework is, in fact, one of the main reasons that fuzzy logic has been successful in offering intelligent approaches in various areas that deal with continuous problem domains.

5.2.1.3 Possibility Distributions

Assigning a fuzzy set to a linguistic variable constrains the value of the variable, just as a crisp set does. The difference between the two, however, is that the notion of possible versus impossible values becomes a matter of degree. For situations where a sharp boundary is undesirable, fuzzy logic offers an appealing alternative; it generalises the binary distinction between possible vs. impossible to a matter of degree called possibility. In general, when a fuzzy set A is assigned to a variable X, the assignment results in a possibility distribution of X, which is defined by A's membership function:

$$\Pi_X(x) = \mu_A(x)$$

5.2.1.4 Fuzzy If-Then Rules

Fuzzy if-then rules are a knowledge representation scheme for describing a functional mapping or logical formula that generalises an implication in two-valued logic. They allow their inferred conclusion to be modified by the degree to which the antecedent is satisfied.

Mathematically, fuzzy rule-based inference can be viewed as an interpolation scheme because it enables the fusion of multiple fuzzy rules when their conditions are all satisfied to a degree. The degree to which each rule is satisfied determines the weight of the rule's conclusion. Using these weights, fuzzy rule-based inference combines the conclusion of multiple fuzzy rules similar to linear interpolation. The algorithm of fuzzy rule-based inference consists of four steps; fuzzy matching, inference, combination, and defuzzification.

Fuzzy Matching

The fuzzy matching step calculates the degree to which the input data matches the condition of the fuzzy rules. When a rule has multiple conditions combined using AND (conjunction), a fuzzy conjunction operator is used to combine the matching degree of each condition. The most commonly used fuzzy conjunction operator is the min operator; see Fig. 5.7. If the antecedent of a rule includes conditions connected by OR (disjunction), then a fuzzy disjunction operator (e.g. max operator) to combine matching degrees is the max operator.

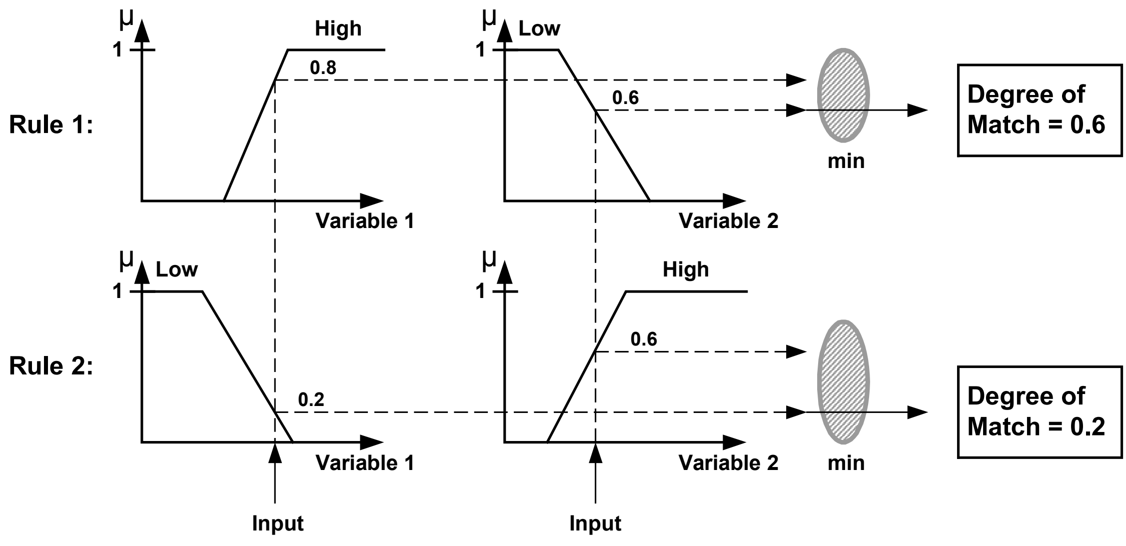


Figure 5.7: Fuzzy matching for conjunctive conditions

Inference

After the fuzzy matching step, a fuzzy inference step is invoked for each of the relevant rules to produce a conclusion based on their matching degree. There are two methods to produce the conclusion: the clipping method and the scaling method. Both methods generate an inferred conclusion by suppressing the membership function of the consequences. The clipping method cuts off the top of the membership function whose value is higher than the matching degree. The scaling method scales down the membership function in proportion to the matching degree; see Fig. 5.8.

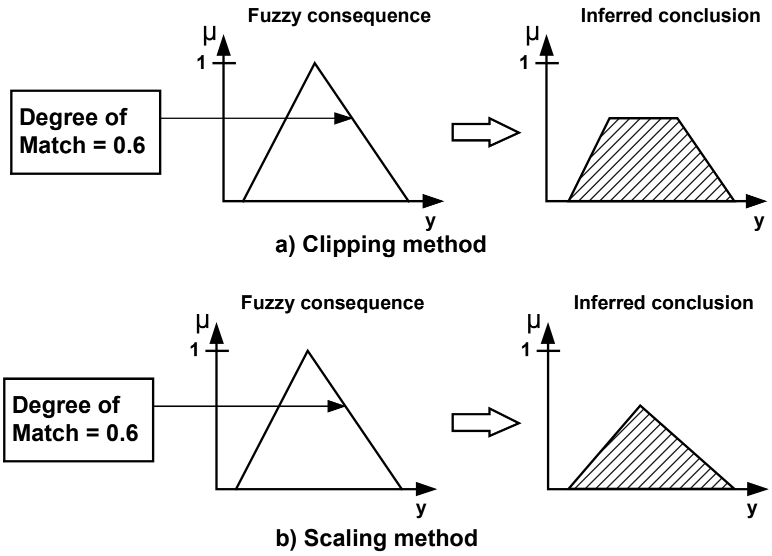


Figure 5.8: Fuzzy inference methods

Combining Fuzzy Conclusions

Because a fuzzy rule-based system consists of a set of fuzzy rules with partially overlapping conditions, a particular input to the system often induces multiple fuzzy rules (i.e. more than one rule will match the input to a nonzero degree).

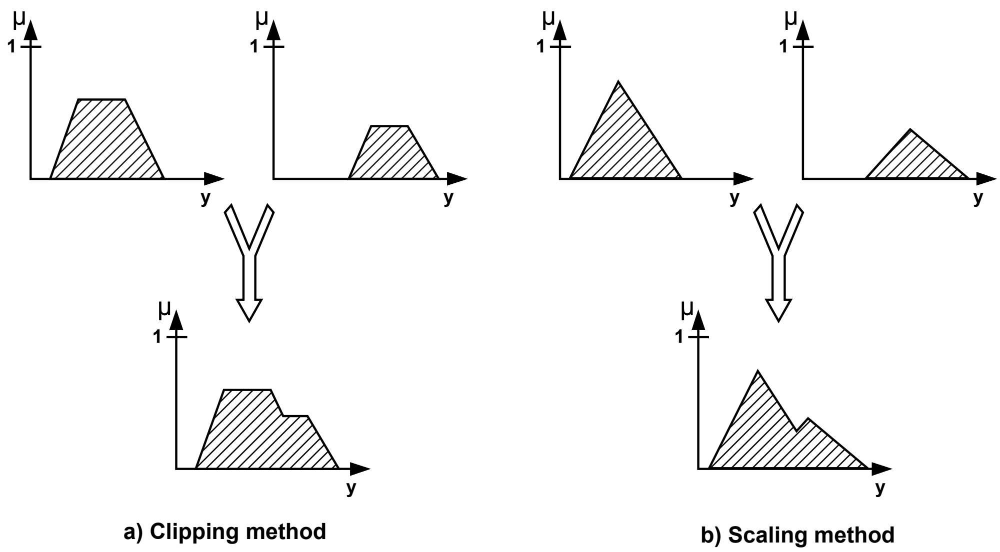


Figure 5.9: The maximum method

Therefore, the third step is needed to combine the inference results of these rules. The most common combining methods are the maximum, algebraic sum, and the sum method. The maximum method of rule deduction accomplished by superimposing all fuzzy conclusions about a variable. Combining fuzzy conclusions through superimposition is based on applying the max fuzzy disjunction operator to multiple possibility distributions of the output variable; see Fig. 5.9. The algebraic sum method calculates the algebraic sum of the two outputs, and the sum method adds the two output degrees

Defuzzification

For a fuzzy system whose final output needs to be in a crisp (non-fuzzy) form, defuzzification step is needed to convert the final combined fuzzy conclusion into a crisp one. There are two major defuzzification techniques: the mean of maximum (MOM) method and the centre of area (COA).

The mean of maximum defuzzification calculates the average of all variable values with maximum membership degrees. The MOM defuzzification method can be expressed using the following formula:

$$MOM(A) = \frac{\sum_{y^* \in P} y^*}{|P|}$$

where P(A) is the set of the output value y with the highest membership degree in A, i.e.,

$$P = \left\{ y^* \mid \mu_A(y^*) = \sup_y \mu_A(y) \right\}.$$

The centre of area defuzzification method calculates the weighted average of a fuzzy set. The COA defuzzification method can be expressed using the following formula:

$$y = \frac{\sum_i \mu_A(y_i) \times y_i}{\sum_i \mu_A(y_i)}$$

The mean of maximum (MOM) method and the centre of area (COA) are shown in Fig. 5.10.

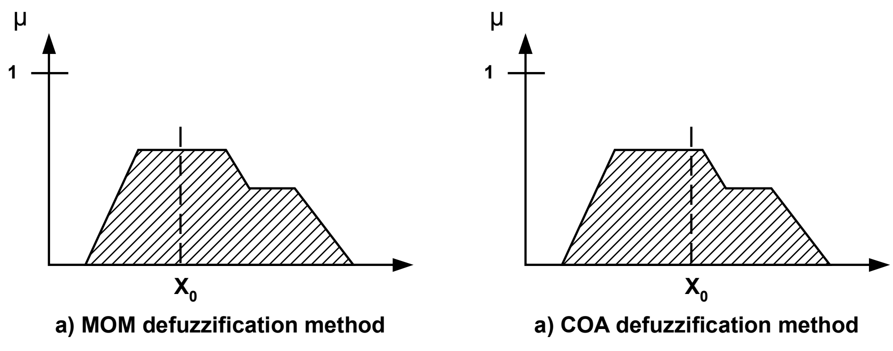


Figure 5.10: Defuzzification methods

5.2.2 Relation between Traffic Flow and Fuzzy Logic

Traffic flow is a very complicated non-linear system which is composed of many self-driven particles. Traffic flow has been analysed based on various approaches from physics but still remains not clearly identified in a mathematical way. For practical traffic control systems, even online traffic flow modelling is required which is much more difficult than offline analysis.

In this research an online modelling approach of traffic flow was proposed applying the dynamic flow-density relation. The flow-density relation is a basic requirement for the macroscopic traffic flow models and represents traffic flow behaviour under different flow and density conditions. The dynamic flow-density relation represents the changes in traffic flow behaviour depending on the related traffic conditions, which are difficult to describe in a mathematical way.

For the dynamic flow-density relation traffic flow is classified into different traffic states; free flow, impeded free flow, synchronised, congested, jammed, and stopped state. For the classification the mean and the variance of headway are calculated from the individual traffic data and the differences between the average speed of all lanes are tested. These methods are, however, not efficient for online applications, therefore, a classification method using the macroscopic variables (the speed, the density, the flow) is proposed. But the objective criteria for the classification applying the macroscopic traffic variables are very difficult to find and the thresholds are not clear.

The difficulties of the online traffic flow modelling can be alleviated by applying fuzzy logic whose motivations are to alleviate difficulties in developing and analysing complex systems encountered by conventional mathematical tools and to utilise concepts and knowledge that do not have well-defined, sharp boundaries. The similarities or the relation between fuzzy logic and the traffic flow is explained by two traffic situations; homogeneous motorway section and motorway sections with ramps.

5.2.2.1 Homogeneous Motorway Sections

The traffic states of homogeneous motorway sections are classified into the 5 traffic states in the states diagram in chapter 3 based on the macroscopic traffic variables. The speed, the flow and the density are used as input values and the respective free-flow speed or shock wave speed is inferred as the output.

The traffic states of the states diagram as well as linguistic description about the traffic variables such as “High”, “Medium” and “Low” have no sharp boundaries to which traffic data fits. The traffic states and the linguistic variables are **fuzzy sets** and are represented as degrees of membership functions in the sets.

The membership functions for the traffic variables and the shock wave speed are presented in Fig. 5.11. The threshold values of the membership functions are manually adjusted to the states diagram. These threshold values are, however, not as sensitive as the parameters in the static flow-density relations. These threshold values are tested by traffic data of various German motorways.

The values of **linguistic variables** are described both qualitatively and quantitatively by fuzzy sets. The traffic variables (linguistic variables), e.g. speed, flow and density are described by linguistic terms (fuzzy sets) “High”, “Medium” and “Low” and modifiers “Very”.

The **possibility distribution** of fuzzy sets “Very Low and Low” of a linguistic variable “speed” is represented as the red line of the maximum of both membership functions; see Fig. 5.11.

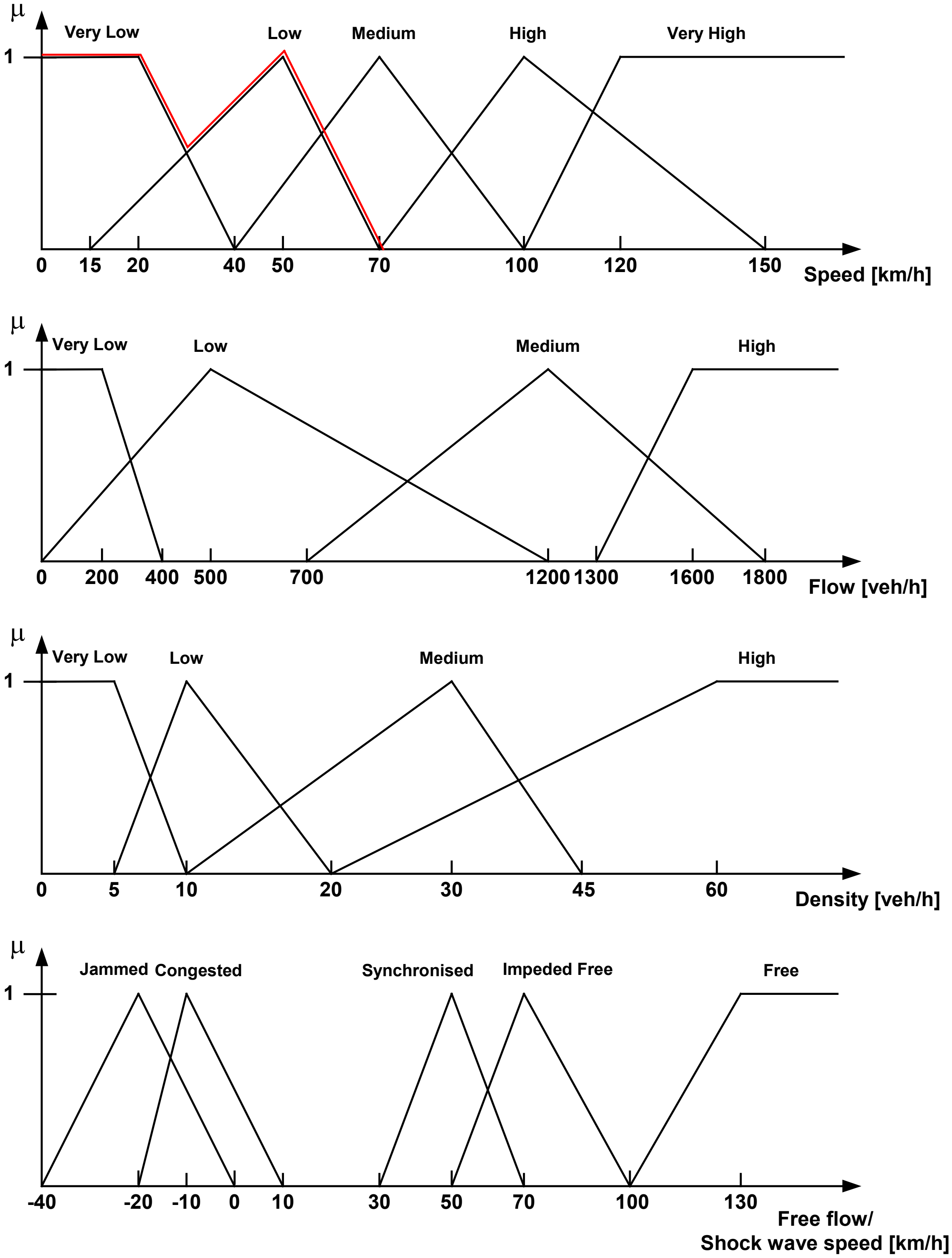


Figure 5.11: Membership functions of the input and output variables

Fuzzy if-then rules represent the relation between the fuzzy sets of traffic variables and the traffic states; see table 5.3.

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	Synchronised
8	Medium	Medium	Medium	Synchronised
9	Medium	Low	Low	Synchronised
10	Low	Medium	High	Congested
11	Very Low	Low	High	Jammed

Table 5.3: Fuzzy if-then rules

A states diagram of traffic flow is reconstructed with fuzzy logic and represented in Figure 5.12. The states diagram shows traffic states to which each density/flow value fits. The shapes of the traffic states are simplified to ellipses and the degrees of the membership in the traffic states are not shown in this diagram.

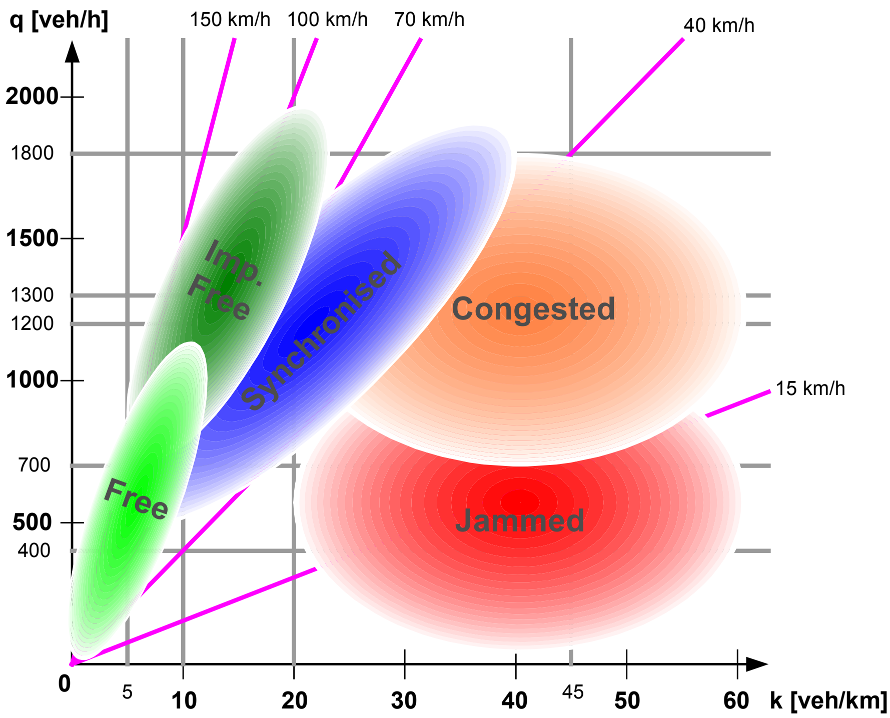


Figure 5.12: States-diagram of traffic flow reproduced by fuzzy logic

Not the entire area of the density-flow relation is covered by this diagram. Traffic data not included in this diagram is difficult to interpret and not suitable to use for the determination of the dynamic fundamental diagram. This data causes unreasonable results of the traffic flow model. It is assumed in this investigation that such data comes from the malfunction of data collection.

The states diagram in chapter 3 and this diagram are identical except for the synchronised traffic state. The area of synchronised traffic of this diagram is a little larger than that in chapter 3 where the synchronised traffic has a small variance in flow value. The characteristic of the synchronised traffic is observed in the traffic data used in this chapter, too. Even though the synchronised traffic has a small variance in a phase transition the location of the synchronised traffic is different depending on motorways and the phase transitions. For the on-line implementation of the traffic flow model the states diagram has a large region of synchronised traffic.

5.2.2.2 Motorway Sections with Ramps

The dynamic flow-density relation in motorway sections with ramps is determined based on the classification of the traffic states in the homogeneous sections and the capacity reduction determined by another fuzzy logic based on the upstream traffic demand and the interaction strength defined in chapter 3.

The determination of the flow-density relation in motorway sections with ramps can be divided into two cases depending on traffic data determining the sending/receiving functions.

Case 1: By the current traffic data the sending function is determined.
Case 2: By the current traffic data the receiving function is determined.

Case 1:
The sending function is determined by the same scheme as in homogenous motorway sections and the receiving function is determined by the shock wave speed given beforehand as a parameter and the jam density determined by applying fuzzy logic. The input data for the determination of the jam density in the receiving function is the upstream traffic demand and the interaction strength. Membership functions for the variables and the fuzzy if-then rules are shown in Fig. 5.13 and table 5.4. The threshold values of membership functions are determined manually.

Rule	Input		Output
	q_{up}	q_{int}	
1	Low	Low	Free flow
2	High	Low	Congestion without propagation
3	High	High	Congestion with propagation

Table 5.4: Fuzzy if-then rules in case 1

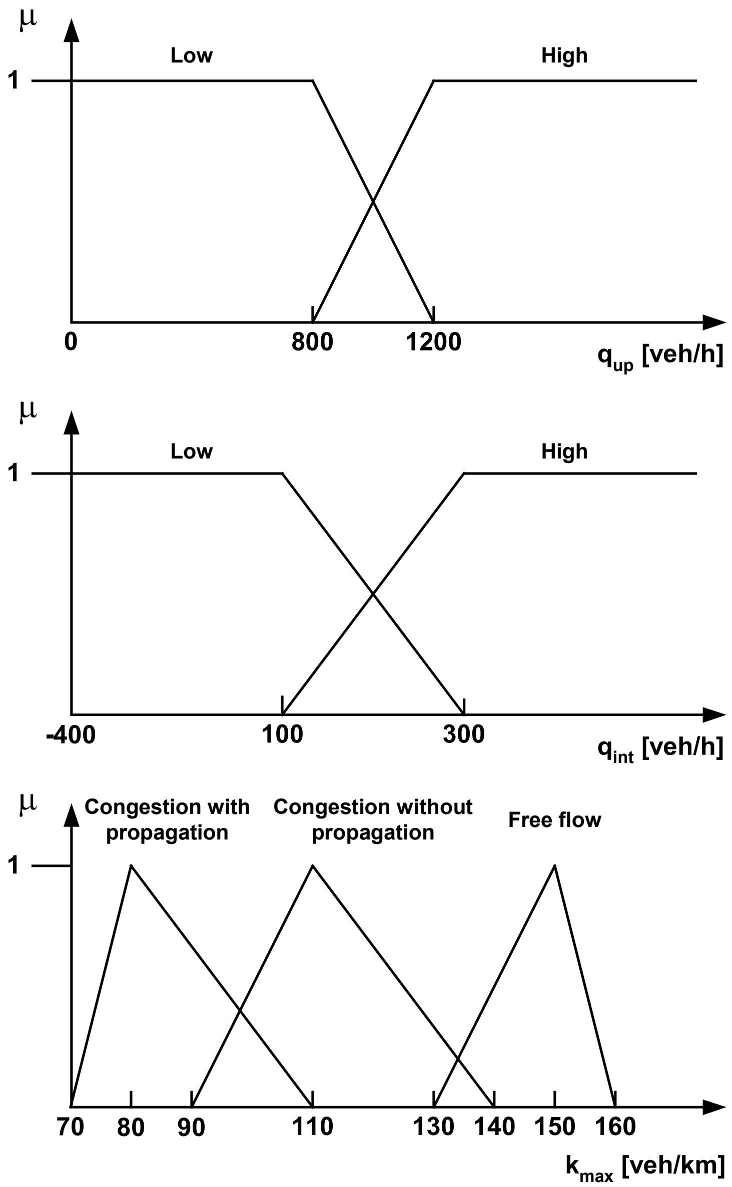


Figure 5.13: Membership functions in case 1

Case 2:
The sending function is determined by the free flow speed given beforehand as a parameter and the receiving function is determined by the same scheme as for homogenous motorway sections (KIM and KELLER, 2001) but with the jam density reduction determined by applying fuzzy logic. The input values for the determination of the jam density reduction are the upstream traffic demand and the interaction strength. Membership functions for the variables and the fuzzy if-then rules are shown in Fig. 5.14 and table 5.5. The threshold values of membership functions are determined manually.

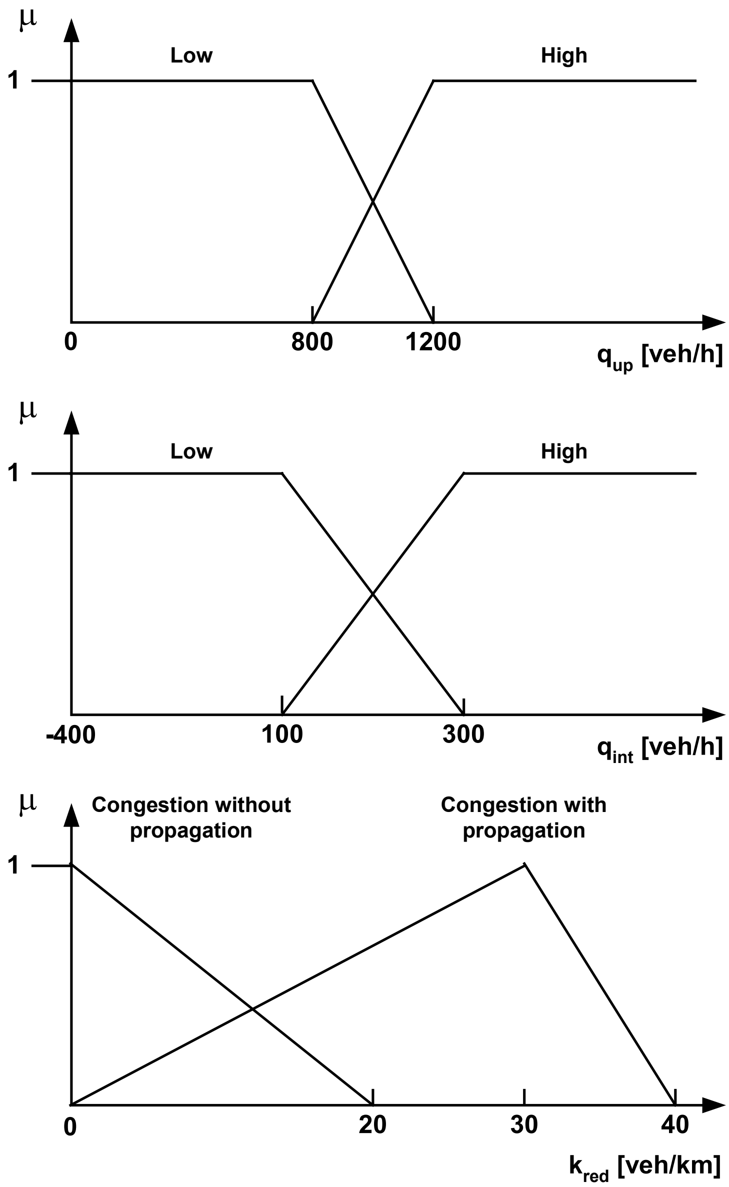


Figure 5.14: Membership functions in case 2

Rule	Input		Output
	q_{up}	q_{int}	
1	High	Low	Congestion without propagation
2	High	High	Congestion with propagation

Table 5.5: Fuzzy if-then rules in case 2

5.3 Implementation of the Situational Cell-Transmission Model

To test and evaluate the new approach to online traffic flow modelling on motorways the situational cell-transmission model and the fuzzy controller were written in Microsoft Visual

C++ 6.0. In this section values of the parameter in the model and the specific method of fuzzy logic are discussed.

5.3.1 Updating Interval and Length of Cells

For the numerical implementation of the continuity equation the stability restriction must be satisfied.

$$\left|\frac{C \cdot \varepsilon}{d}\right| \leq 1$$

In the stability restriction 'C' is the maximum shock wave speed, 'ε' is the time updating interval and 'd' is the length of the cells in the continuity equation,

$$\frac{k(t+\varepsilon, x) - k(t, x)}{\varepsilon} + C \cdot \frac{k\left(t, x + \frac{d}{2}\right) - k\left(t, x - \frac{d}{2}\right)}{d} = 0.$$

In the simulation of the homogeneous section the ordinary cells are 250 m long and the updating interval is 6 sec, and in the simulation of the motorway sections with ramps the ordinary cells are 50m long and the updating interval is 1 sec, and the shock wave speed determined by applying fuzzy logic has a range from – 40 km/h to 130 km/h. With these parameter values the stability restriction is always satisfied and this discretisation scheme of the partial differential equation is stable.

5.3.2 Determination Strategy for the Flow-Density Relation in Cells

One branch of the flow-density relation is determined by traffic data and the other branch is determined by given parameters. The parameter values for the shock wave speed and the maximum density of the receiving function are –20 km/h and 150 veh/km. The parameter value for the free flow speed of the sending function is 130 km/h. The maximum density and the intersection of the sending function with the flow axis in the flow-density relations are determined by the tangent of the sending/receiving function and a pivot which is the averaged traffic data (the density and the flow) in the last 5-min. interval.

Case	Speed relation	Flow relation	Determination of flow-density relation
1	$v_{up} > v_{down}$	$q_{up} + \alpha > q_{down}$	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

Table 5.6: Implementation of a flow-density relation determination strategy

Since traffic data is collected in a short time interval the noise (high frequent component) is not filtered and remains in the traffic data, which causes inconsistencies in the direction of the shock wave between traffic data and the model, in particular, during the transitions. To alleviate the logical fault generated by the stochastic characteristics of traffic data, constants α and β are added in the determination strategy. By using high values of α and β the ordinary cells are more influenced by the downstream detector. In this research 100 and 0 are used for α and β; see table 5.6.

5.3.3 Fuzzy Controller

The fuzzy controller performs the logical operations of the fuzzy inference process. All the elements of fuzzy control, fuzzyfication, inference, fuzzy sets and parameters, and the if-then rules are included and the computational work is done.

Several different methods are available for each step of the calculation. For the accumulation it is possible to define the maximum method and the algebraic sum method. The fuzzy combining methods are the clipping method or the scaling method. For the defuzzyfication it is possible to define the centre of gravity method or the mean of maximum method. It is also possible to define a weighting factor for each rule. The membership function can either be a triangle or a polygon (BOGENBERGER, 2001; VUKANOVIC ET AL., 2001). This fuzzy controller communicates with the situational cell-transmission model.

The fuzzy controller in this research uses the maximum method for the fuzzy combining method, the clipping method for the fuzzy inference method, and the centre of gravity method for defuzzyfication.

5.4 Summary

In this chapter a new online modelling approach of traffic flow is presented. In the new approach the cell-transmission model of DAGANZO is extended by the classification of the cells, the modification of the static flow-density relation, and the application of the determination strategy for the flow-density relation in the cells.

In the situational cell-transmission model a motorway link is divided into ordinary cells, buffer cells, and input/output cells depending on the characteristics of cells. By applying the buffer cells between traffic data and traffic flow model, unreasonable results (negative or illogically high density) occurring in the implementation of the model are alleviated. In the stability analysis the role of the buffer cells is also proved mathematically.

The dynamic flow-density relation is determined based on the classification of the traffic states by employing fuzzy logic and the shock wave theory. By applying the dynamic flow-density relation traffic dynamics generated by various downstream and upstream traffic situations can be considered in the model in real time.

The situational cell-transmission model is extended to describe the propagation of the congestion in motorway sections with ramps. For the determination of the dynamic flow-density relation in motorway sections with ramps the capacity reduction caused by the interaction between the traffic flows of the mainstream and the ramps is considered.

6 Test and Performance Evaluation of the Model

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

6.1 Homogeneous Motorway Sections

6.1.1 Test Fields

The situational cell-transmission model is tested for various homogeneous German motorway sections A5, A9, and A3 which have 3 lanes in each direction. The test motorway sections show daily recurrent congestion patterns during peak hours.

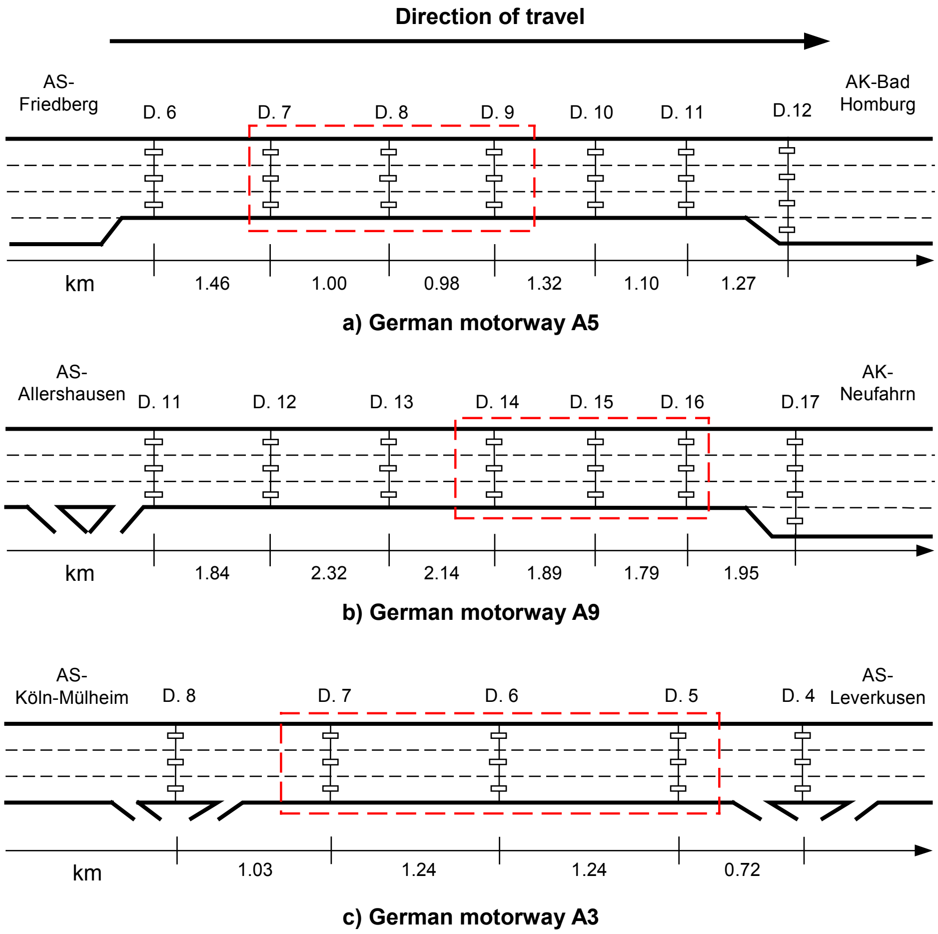


Figure 6.1: Schematic presentation of homogeneous motorway sections

The traffic data is collected at 1-min. intervals and averaged over the 3 lanes. The red lines indicate the test motorway sections; see Figure 6.1. The lengths of the test motorway sections are about 2.0 km (A5), 3.7 km (A9), and 2.5 km (A3).

The traffic data observed at three sets of detectors is used for the traffic flow modelling and for the performance evaluation of the model in the homogeneous motorway sections. The traffic data of the upstream and downstream detectors is used as the boundary condition of the model and that of all detectors is compared with the simulation results by the model for the performance evaluation of the model.

Since the flow-density relation determination strategy of the situational cell-transmission model is based on the assumption that the traffic situations in the motorway sections are determined satisfactorily by the upstream and downstream traffic conditions, the length of the motorway sections should be limited. Therefore, the simulation is spatially limited to motorway sections with three detectors. If a motorway section is too long the traffic flow in the motorway section is not influenced directly by the upstream and downstream traffic conditions and is difficult to describe.

6.1.2 Performance Evaluation

The performance evaluation is based on moving averages of the 5-min intervals for the simulation results and the traffic data. The correlation coefficients for the simulation results and the traffic data of the detectors are used as the performance indices.

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 in chapter 5, the existing macroscopic modelling 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 is compared with those of high order continuum model, a modified CREMER-PAYNE model (POSCHINGER, 1999) with a static flow-density relation in order to emphasise the importance of the parameter calibration for the traffic flow model. The static flow-density relation of the modified CREMER-PAYNE model is calibrated beforehand to optimise the simulation results of the German motorway section A5 and the static flow-density relation is used to simulate the other German motorway section A9 and A3. The detailed structure of the modified CREMER-PAYNE model and the implementation scheme is shown later.

A set of simulation results and the flow-density relation of the downstream traffic situation (detector 9) of the German motorway section A5 are shown in Fig. 6.2 because the flow-density relation of the downstream traffic situation has a pronounced impact on the macroscopic traffic flow models.

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 motorway 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 and with the modified CREMER-PAYNE model very good simulation results are obtained, too. The correlation coefficients for the traffic data of detector 7 and the simulation results by the situational cell-transmission simulation model and the modified CREMER-PAYNE model are 0.931 and 0.929, for the traffic data of detector 8 are 0.984 and 0.933, and for the traffic data of detector 9 are 0.922 and 0.932. The simulation results for the traffic data of detector 9 are actually not worse than the others. However, the time shift between the simulation results and the traffic data decreases the correlation coefficient values. The flow-density relation used in the modified CREMER-PAYNE model is calibrated to fit the observed traffic data.

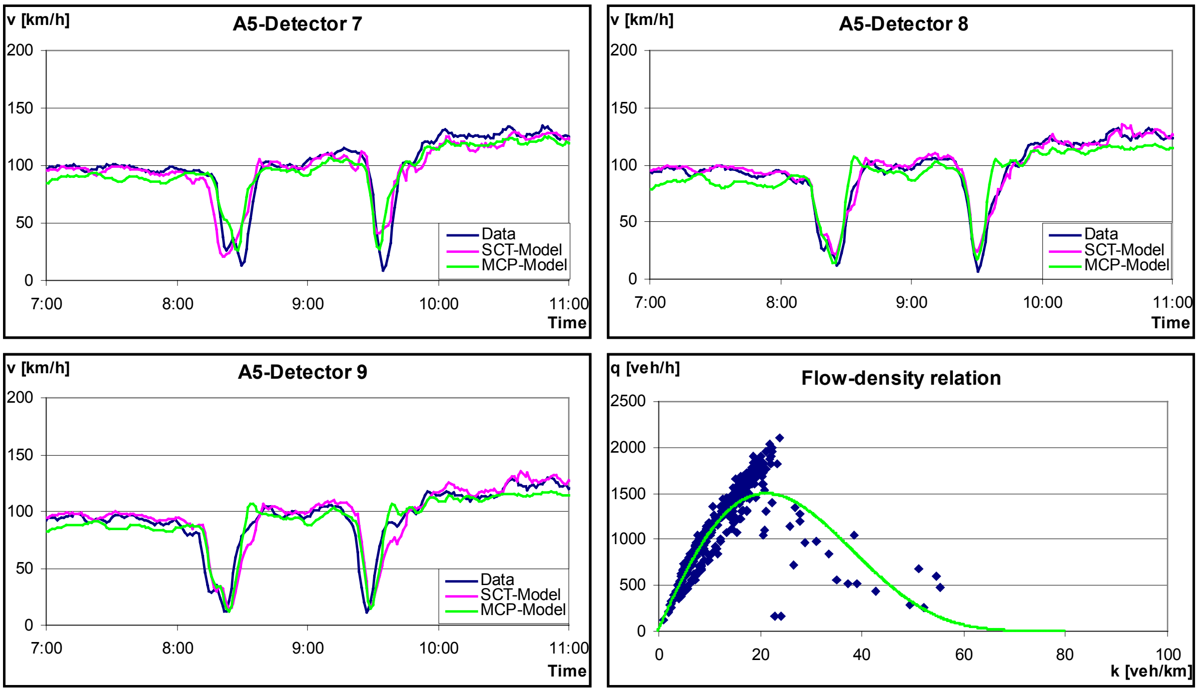


Figure 6.2: Results of German motorway A5

A set of simulation results and the flow-density relation of the downstream traffic situation (detector 16) of the German motorway section A9 are shown in Fig. 6.3. In this traffic data congestion is observed for about one hour. The congestion has a minor change in shapes during the propagation through the motorway section.

The simulation with the situational cell-transmission model gives very good results but the simulation results with the modified CREMER-PAYNE model with the static flow-density relation are not quite satisfactory. The correlation coefficient for the traffic data of detector 14 and the situational cell-transmission model is 0.916, for the traffic data of detector 15 is 0.966 and for the traffic data of detector 16 is 0.947. The correlation coefficient for the traffic data of detector 14 and the modified CREMER-PAYNE model is 0.892, for the traffic data of detector 15 is 0.632 and for the traffic data of detector 16 is 0.815. As can be seen in Fig. 6.3, 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.

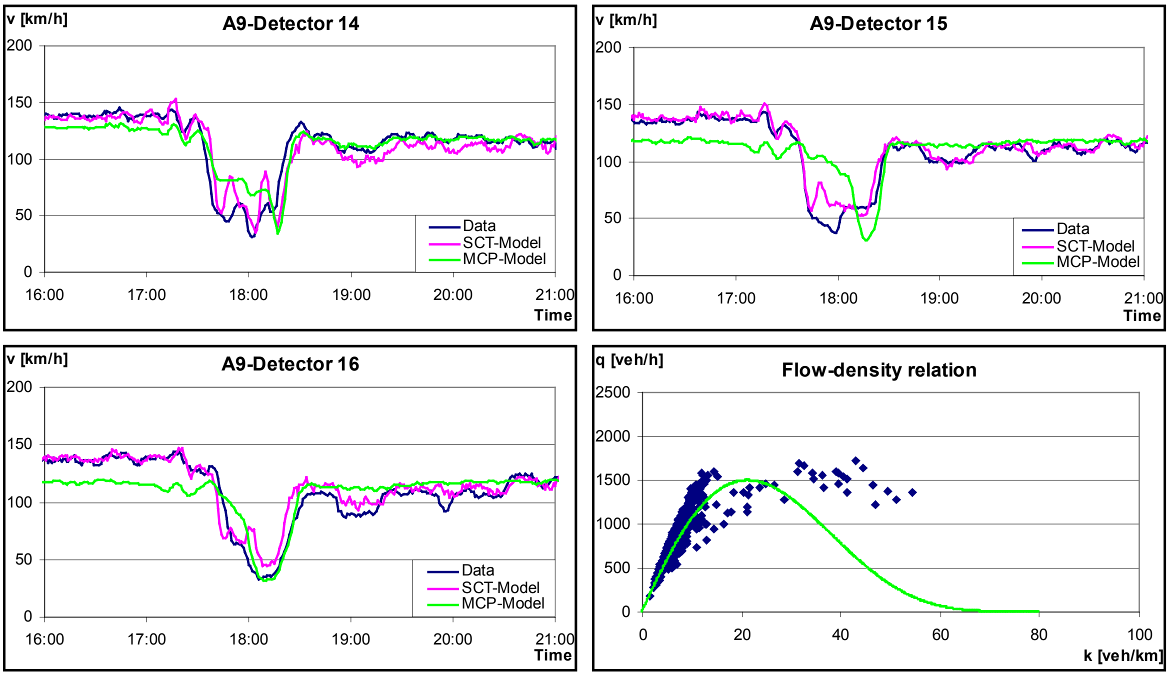


Figure 6.3: Results of German motorway A9

A set of simulation results and the flow-density relation of the downstream traffic situation (detector 5) of the German motorway section A3 are shown in Fig. 6.4. In this traffic data congestion is observed for about one hour. The congestion has a significant change in shapes during the propagation through the motorway section.

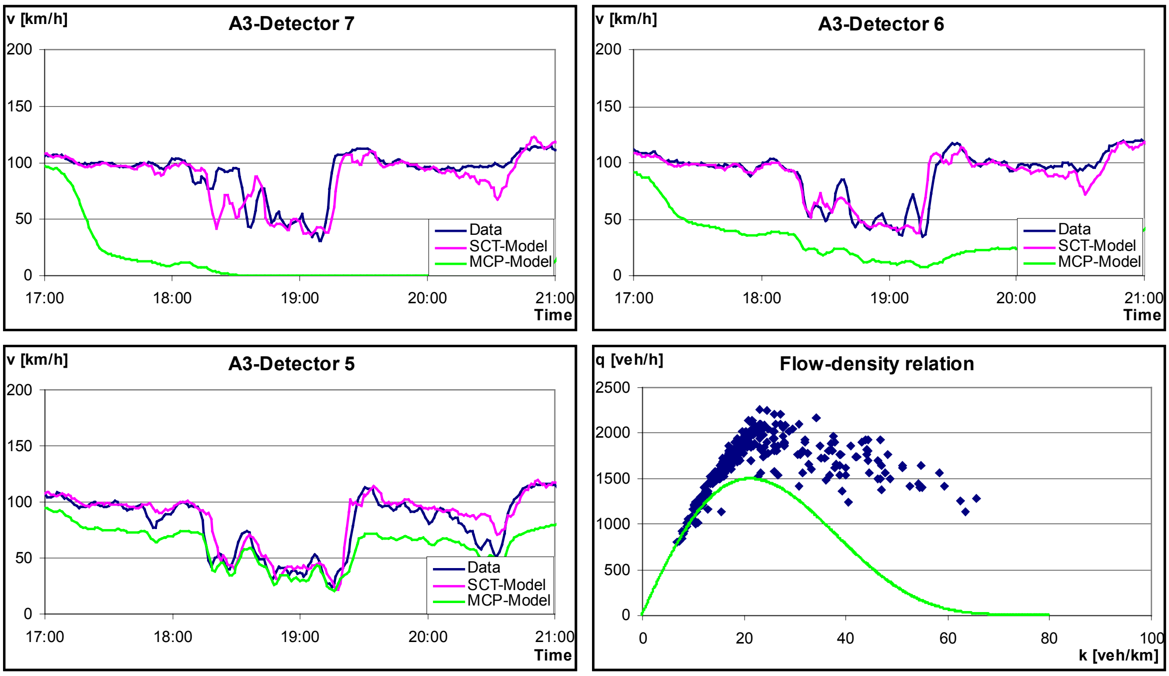


Figure 6.4: Results of German motorway A3

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. The upstream traffic situation is not consistent with the downstream traffic situation. 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 motorway section is 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 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. The correlation coefficient for the traffic data of detector 7 and the simulation results by the situational cell-transmission model is 0.843, for the traffic data of detector 6 is 0.928 and for the traffic data of detector 5 is 0.928.

Since the static flow-density relation does not match the traffic data the modified CREMER-PAYNE model cannot describe the traffic dynamics of this motorway 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 correlation coefficient for the traffic data of detector 7 and the simulation results by the modified CREMER-PAYNE model with the static flow-density relation is 0.238, for the traffic data of detector 6 is 0.475 and for the traffic data of detector 5 is 0.942.

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. The correlation coefficients for the simulation results and the traffic data show this tendency very well; see table 6.1.

Motorway	Upstream	Intermediate	Downstream
A5	0.931	0.984	0.922
A9	0.916	0.966	0.947
A3	0.843	0.928	0.928

Table 6.1: Correlation coefficients for traffic data and the situational cell-transmission model

Motorway	Upstream	Intermediate	Downstream
A5	0.929	0.933	0.932
A9	0.892	0.632	0.815
A3	0.238	0.475	0.942

Table 6.2: Correlation coefficients for traffic data and the modified CREMER-PAYNE model

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 Fig. 6.5. In the whole simulation of this research, the situational cell-transmission model applied the same parameters and no additional adjustments were needed, which is very important for the online application of the traffic flow model.

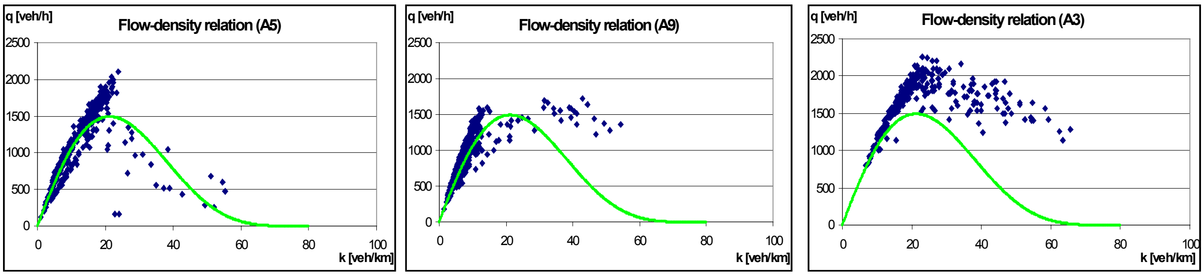


Figure 6.5: The flow-density relations

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 overcome the critical problem, i.e. transferability and the post-prediction problem, which enables the on-line simulation.

6.2 Motorway Section with Ramps

The detailed traffic behaviour in motorway sections with ramps is very difficult to explain and simulate because of the complicated interaction between the main stream traffic flow and the ramp traffic flows, which has not been fully identified yet. For the online modelling of traffic flow including motorway sections with ramps, the traffic behaviour in these sections should be simplified and the basic traffic pattern should be abstracted and simulated.

Since the propagation of congestion caused by the ramp traffic flows has a pronounced effect on the traffic situations of the whole motorway section, traffic flow of motorway sections with ramps is classified into free traffic, congestion without propagation and congestion with propagation. The propagation of congestion is analysed by the new methods mentioned in chapter 4, and simulated based on the upstream and downstream traffic situations and the on-ramp and off-ramp flows.

6.2.1 Test Field

Traffic flow in a motorway section with ramps is simulated in the German motorway section A9. As in the homogeneous motorway sections above, the test motorway section with ramps consists of 3 lanes in each direction and the recurrent congestion pattern is observed during peak hours. The traffic data analysed in this research is collected on two working days (Monday and Tuesday) in July and is influenced also by holiday traffic.

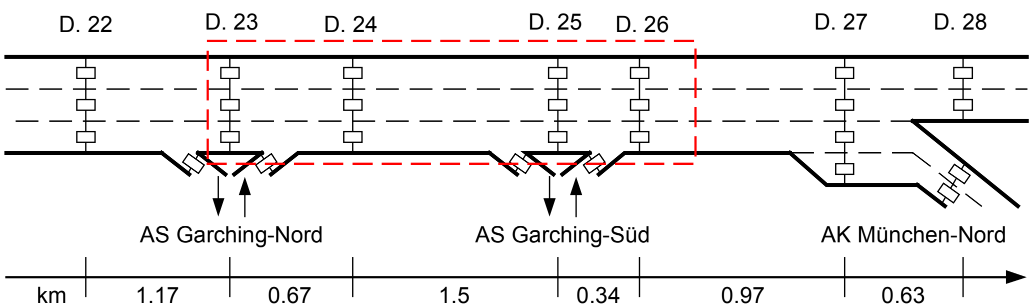


Figure 6.6: Schematic presentation of non-homogeneous motorway sections

The traffic data of detectors 23 and 26 is used as the boundary condition of the model; see Fig. 6.6. The traffic data of all detectors is compared with the simulation results of the model. For the calculation of the interaction strength q_{int} the data of detectors 24 and 26 are used as the upstream and the downstream data as well as the data of the on-ramp and off-ramp (AS Garching-Süd). The on-ramp flow of the AS Garching-Nord is negligibly small, therefore this on-ramp flow is not considered in this modelling.

6.2.2 Performance Evaluation

In this simulation the same parameters as in the simulation of homogeneous motorway sections are used. The new determination strategy of the flow-density relation for motorway sections with ramps in chapter 5 is applied. In this strategy the jam density of a motorway section is adjusted depending on the traffic situations of the motorway section with ramps.

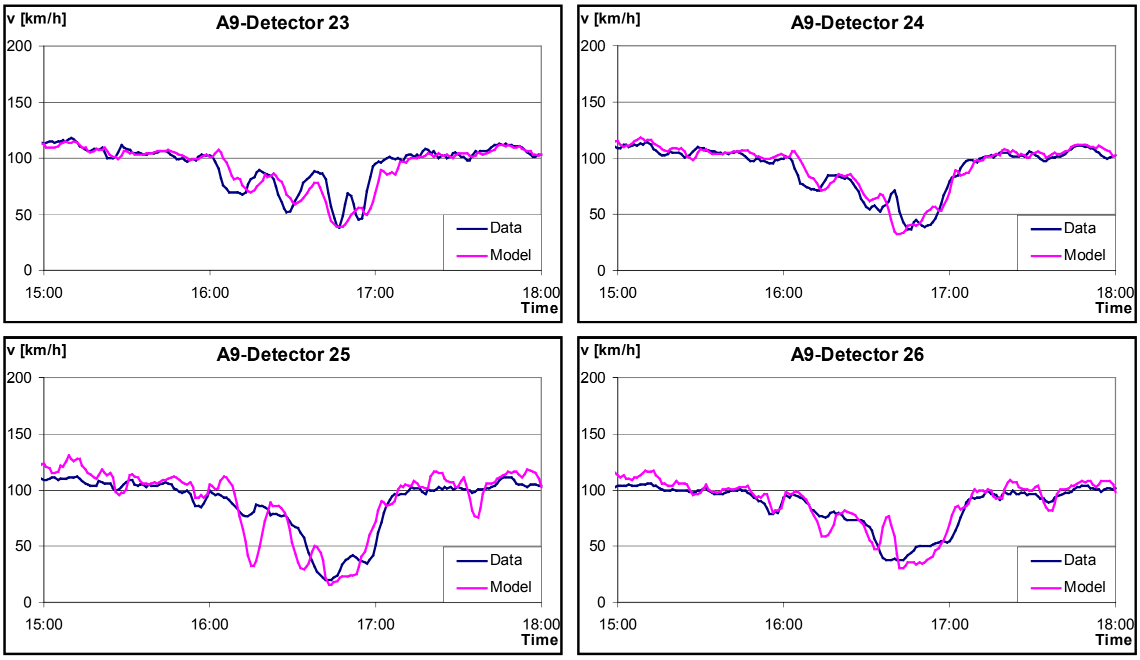


Figure 6.7: Congestion with propagation

The situational cell-transmission model applying the new phase diagram described the congestion propagation very well. Traffic dynamics generated by the on-ramp and off-ramp flows is not exactly described and the observed and modelled speeds show discrepancies at detector 25; see Fig. 6.7 and Fig. 6.8. The fluctuations of the simulation results are caused by the stochastic characteristics of the on-ramp flow. The congestion propagation, however, is simulated satisfactorily. The modelled and observed speed match very well at detector 24.

It is not easy to simulate traffic dynamics of motorway sections with ramps with macroscopic models, because there are no rules to describe the interaction and the lane changing effects in the macroscopic model. The exogenous conditions of the congestion propagation can, however, be defined and the congestion propagation can be simulated based on the conditions. If traffic dynamics is to be suitably described more sophisticated traffic flow models are needed which describe lane changing effects and interaction satisfactorily. DAGANZO (1999) tried to describe lane changing effects and interaction with a multi-class traffic flow model.

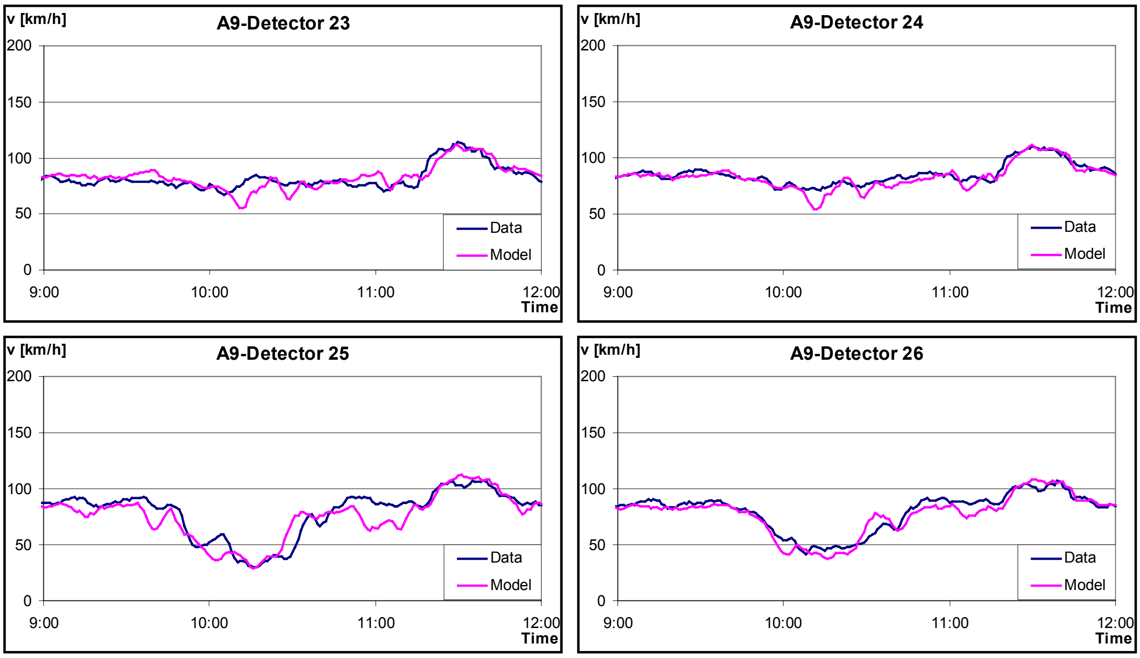


Figure 6.8: Congestion without propagation

The correlation coefficients for the simulation results and the traffic data show satisfying results. As in the simulation of the homogeneous motorway sections the correlation coefficients for the upstream traffic data and the simulation results show lower values than others.

Case	D. 23	D. 24	D. 25	D.26
Congestion with propagation	0.896	0.943	0.906	0.924
Congestion without propagation	0.808	0.925	0.886	0.952

Table 6.3: Correlation coefficients for traffic data and the situational cell-transmission model

6.3 Modified CREMER-PAYNE Model

The speed equation and the flow equation of the CREMER-PAYNE model was modified in order to obtain a robust model which works with real traffic data.

The speed equation of the CREMER-PAYNE model is replaced by the following equation.

$$v_j(k+1) = v_j(k) + \frac{T}{\Delta_j} \cdot v_j(k) \cdot \left(v_{j-1}(k) - v_j(k)\right) \cdot con + \frac{T}{\tau} \cdot f \cdot \left(V\left(\rho_j\right) - v_j\right)(k) + \frac{T}{\tau} \cdot (1-f) \cdot \left(V\left(\rho_{j+1}\right) - v_j\right)(k)$$

$$f = \frac{1}{2} \cdot \left[\frac{\rho_{max} - \rho_{j+1}}{\rho_{max}} + \frac{l_j - l_{min}}{l_{max} - l_{min}}\right] \quad if \quad k_j \le k_{max}$$

$$f = \frac{l_j - l_{min}}{l_{max} - l_{min}} \quad else$$

The extension of the relaxation and anticipation terms are investigated by CREMER and PUTENSEN (1992). In the speed equation ρ_{max}, l_{max} and l_{min} represent the maximum density, the maximum cell length, and the minimum cell length. The convection term is weighted with a constant (*con* = 0.5).

The flow equation of the CREMER-PAYNE model is replaced by the scheme of HILLIGES (1994).

$$q_j(k) = \rho_j(k) \cdot v_{j+1}(k)$$

The flow-density relation of GAZIS ET AL. (1961) is used in this model.

$$V(\rho) = V_f \cdot \left(1 - \left(\frac{\rho}{\rho_{\max}}\right)^a\right)^b$$

The flow-density relation is calibrated with parameters V_f = 122.4, ρ_{max} = 80, a =1.8 and b = 5.

In the simulation of the modified CREMER-PAYNE model the cells are 500 m long and the updating time interval of the simulation is 10 sec.

6.4 Summary

A new procedure for on-line traffic flow modelling based on a cell-transmission model and dynamic flow-density relations was tested in homogeneous motorway sections and in a motorway section with ramps. In the motorway section with ramps the basic traffic pattern is simulated applying the new phase diagram developed in this research.

The performance of the situational cell-transmission model shows very good results based on real traffic data on German motorways. The comparison of the simulation results of the situational cell-transmission model and the modified CREMER-PAYNE model emphasises that the new macroscopic modelling approach can overcome the transferability and post prediction problems stemming from the static flow-density relation and describe the basic traffic dynamics caused by prevailing traffic demand and supply conditions.

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 are spatially limited and some discrepancies between the upstream traffic data and the simulation results are observed. To alleviate these problems finer determination strategies of the flow-density relation should be developed and applied to the model.

7 Conclusions and Future Research

This dissertation describes a new approach of online traffic flow modelling based on the hydrodynamic traffic flow model and an online process to adapt the flow-density relation dynamically. The new modelling approach was tested based on the real traffic situations in various homogeneous motorway sections and a motorway section with ramps and gave encouraging simulation results.

Traffic flow models have been developed employing various off-line modelling 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 the characteristics of traffic flow. Sound traffic flow models are a decisive component for the performances of traffic control systems.

Traffic flow models developed until now cannot be satisfactorily applied to practical traffic control systems because of the transferability and post-prediction problems caused by the calibration of parameters. The parameters of traffic flow models have dominant effects on the simulation 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 dissertation a new modelling approach was developed which can alleviate the calibration problems of the current traffic flow models. It was shown by the model evaluation based on real traffic data that the new model works using various traffic data sets with no additional calibration necessary and gives satisfying accuracy for online traffic control systems.

This work is composed of two parts: first the analysis of traffic flow characteristics and second the development of the new online traffic flow model applying these characteristics.

For homogeneous motorway sections traffic flow is classified into six different traffic states with different characteristics. Discrimination criteria were developed to define these states. The hysteresis phenomena were analysed during the transitions between these traffic states. The traffic states and the transitions are represented on a states diagram with the flow axis and the density axis. For motorway sections with ramps the complicated traffic flow is simplified and classified into three traffic states depending on the propagation of congestion. The traffic states are represented in a phase diagram with the upstream demand axis and the interaction strength axis which was defined in this research. The states diagram and the phase diagram provide a basis for the development of the dynamic flow-density relation.

The first-order hydrodynamic traffic flow model was programmed according to the cell-transmission scheme extended by the modification of flow dependent sending/receiving functions, the classification of cells and the determination strategy for the flow-density relation in the cells. The unreasonable results of macroscopic traffic flow models, which may occur in the first and last cells in certain conditions are alleviated by applying buffer cells between the traffic data and the model. The sending/receiving functions of the cells are determined dynamically based on the classification of the traffic states by employing fuzzy logic and the shock wave theory. The model is extended to describe also the propagation of congestion in the motorway sections with ramps by considering the capacity reduction caused by the interaction between the traffic flows of the mainstream and the ramps.

The contribution of this research to the traffic flow theory lies in the following points:

- The time series analysis of the flow-density relation based on short data collection intervals shows the different traffic states and the various hysteresis phenomena during the transitions between them, which are not observed during the long intervals. This traffic state classification is used for the determination of the dynamic flow-density relation employed in the online traffic flow model.

- The congestion propagation of motorway sections with ramps is analysed based on the interaction between the mainstream flow and the on-ramp and off-ramp flows. A new indicator, interaction strength was defined to quantify the interaction of the flows between the main stream and the ramps in the motorway sections. Capacity reduction in the bottleneck caused by the interaction is represented based on the new phase diagram and applied to the adjustment of the dynamic flow-density relation.

- A sound traffic flow model which can be applied to online traffic control systems is developed. Unreasonable results occuring in the first and last segments of macroscopic traffic flow models can be alleviated by the application of the buffer cells. With no additional calibration of the parameters the model gives satisfying results for the online application.

This research represents the potential of the macroscopic traffic flow models for the application to online traffic control systems by applying the dynamic flow-density relation. The new modelling approach alleviates a critical problem, i.e. the parameter calibration problem, of existing traffic flow models. However, this approach still has some drawbacks which are proposed as topics of future research:

- The performance of the new model in this research was evaluated under limited conditions. The model should be tested with more traffic data collected under various conditions considering even more congestion types, geometric and weather conditions.

- The length of the simulated motorway sections is limited due to the flow-density relation determination strategy used in this research. Various flow-density relation determination strategies can be developed and tested, which can increase the spatial range of the simulation.

- In this research the traffic flow in motorway sections with ramps is simplified and the basic characteristics are simulated. For a more detailed simulation of traffic flow in non-homogeneous motorway sections a more differentiated traffic behaviour should be considered, i.e. the lane changing effects, the interaction caused by the origin-destination composition.

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