

CELLULAR AUTOMATA FOR HIGHWAY TRAFFIC FLOW SIMULATION

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ABSTRACT

A Cellular Automaton is an extremely simplified program for the simulation of complex transportation systems, where the performance velocity is more important than the detailed model accuracy. In a Cellular Automaton, space and time are divided into discrete cells and steps. A cell exchanges only transported units with the neighboring cells directly within one time step. A Cellular Automaton model is specified by the rules which control these exchanges.

The first application of the Cellular Automaton for simulation of traffic flows on streets and highways was introduced by Nagel and Schreckenberg (1992). The basic Cellular Automaton model from Nagel-Schreckenberg has been checked against measurements of realistic traffic flow on urban streets and motorways in Germany. It was found that the measured capacities on German motorways cannot be reproduced very well. On urban streets, however, it was very well possible to represent traffic patterns at intersections.

The paper describes a completely new concept for the cellular automaton principle to model highway traffic flow. This model uses a time-oriented car-following model. This model accounts for the real driving behavior more precisely than the model from Nagel and Schreckenberg. The properties of discrete time and space are maintained. Also the updating process can be done for each vehicle independently from each other. Tests showed that this model achieves rather good correspondence with the observed real traffic flow.

This paper shows that a Cellular Automaton is generally applicable for simulation of traffic flows. The degree of correspondence with reality depends on the applied car-following model. The new model concept combines realistic modeling with fast computational performance.

1 INTRODUCTION

Over the past decades, the total demand for transportation volume in the developed countries is increasing, especially within the highway networks. Traditionally more and wider motorways are supplied to cope with increasing demand. This option, however, is no longer available due to environmental and budget restrictions. Thus, more intelligent methods to enhance the capacities of highways are desired. Computer simulations may help in the task of planning more complex transport systems.

A Cellular Automaton (CA) is an extremely simplified program for the simulation of complex transportation systems, where the performance velocity is more important than the detailed model accuracy. The philosophy of the CA is to endeavor the maximum possible performance velocity of the simulation for an acceptable calculation accuracy. In a CA, space and time are divided into discrete cells and steps. A cell exchanges transported units only with the neighboring cells directly within one time step. A CA model is specified by the rules which control these exchanges. The CA is broadly applied in modern physics, astronomy, meteorology and microbiology for simulating large-scaled networks and space-time continuums.

The first application of the CA for simulation of traffic flows on streets and highways was introduced by Nagel and Schreckenberg (1992). In their basic model of CA (standard CA, STCA) there are just four rules for describing the dynamics between the vehicles travelling along a highway. These four rules represent each individual vehicle's car-following behavior. Because of the discrete division of time and space within the CA, the simulation can be implemented in a computer at the level of single bits. Due to the independent updating procedure, the model is also very favorable for parallel processing in Super Computers or by using connected computer networks. Both properties contribute to a very fast computational processing. Thus the German motorway network with more than 11 000 km could be simulated on an individual vehicle basis on a normal workstation in real time (Nagel, 1995). Because of the immense speed capability of the model, it can even be used for a dynamic vehicle-by-vehicle traffic assignment or traffic forecasting purposes. In combination with the algorithm of neural networks, even the routing behavior of the individual vehicle can be learned through day-by-day simulations.

The STCA model from Nagel-Schreckenberg has been checked against measurements of realistic traffic flow on motorways in Germany and against the results from traffic flow theory regarding macroscopic parameters, for instance, speed and capacity. It turned out that this model could not represent a realistic speed-flow relationship of the traffic flow on motorways. For example, the measured capacities on German motorways cannot be reproduced very well. On urban streets, however, it was very well able to represent traffic patterns at intersections with sufficient quality. Because of the extreme simplicity, this model can be calibrated very easily, especially for urban intersections. Useful parameters to represent German traffic flow patterns are given.

This paper describes another completely new concept for the principle of CA to model highway traffic flow. Still four rules are necessary to describe the vehicle dynamics within a traffic flow. This model uses a time-oriented car-following model (TOCA). This model accounts for the real driving behavior more precisely than the STCA model from Nagel-Schreckenberg. The properties of discrete time and space are maintained. Also the updating process can be done for each vehicle independently from each other. Thus also this model is running very fast and it can be operated on parallel computers. Also the calibration of this model is rather simple. Tests showed that this model achieves very good correspondence with the observed real traffic flow. Also the transition between flowing and congested traffic are modeled in a realistic way.

Both models are calibrated and validated by data from measurements in real traffic flow. The model parameters are given for different types of streets and highways, intersections and for different traffic conditions.

The reasons why the models do agree with the reality more or less are also discussed based on a more fundamental model theory concept. These insights could also contribute to better understanding of other model concepts for traffic flow.

This paper shows that a CA is generally applicable for simulation of traffic flows. The degree of correspondence with reality depends on the applied car-following models. By a suitable car-following model, a CA can be calibrated to become a realistic and fast tool to model also motorway traffic under high degree of saturation. It can be expected that in future the CA will become a powerful tool for research and also for practice of traffic science and traffic engineering.

2 THE STANDARD CELLULAR AUTOMATON (STCA)

2.1 The Model and its rules

Designing a simulation model as simple as possible, the most radical way is to use integer variables for space, time and speed. Such a simulation model is called a cellular automaton (Wolfram, 1986). The space is divided into cells that can contain a vehicle or can be empty. The length of a cell is given by the minimum space headway between vehicles in jam. It is the reciprocal of the jam density k_j and is set to be 7.5 m ($k_j = 133$ veh/km). The update time-step Δt is rather arbitrary, one usually uses the driver reaction time that lies between 0.6 and 1.2 s. Thus, also Δt can be considered as a parameter to be calibrated. The speed ranges from 0 to $v_{\max} = 6$ cells/ Δt that corresponds to a speed of 162 km/h for $\Delta t = 1$ s. The STCA uses a simple philosophy that approximately describes the dynamic of driving (car-following): go as fast as you wish and as the vehicle in front allows you and decelerate if you have to avoid a rear end collision (Nagel and Schreckenberg, 1992; Nagel, 1995).

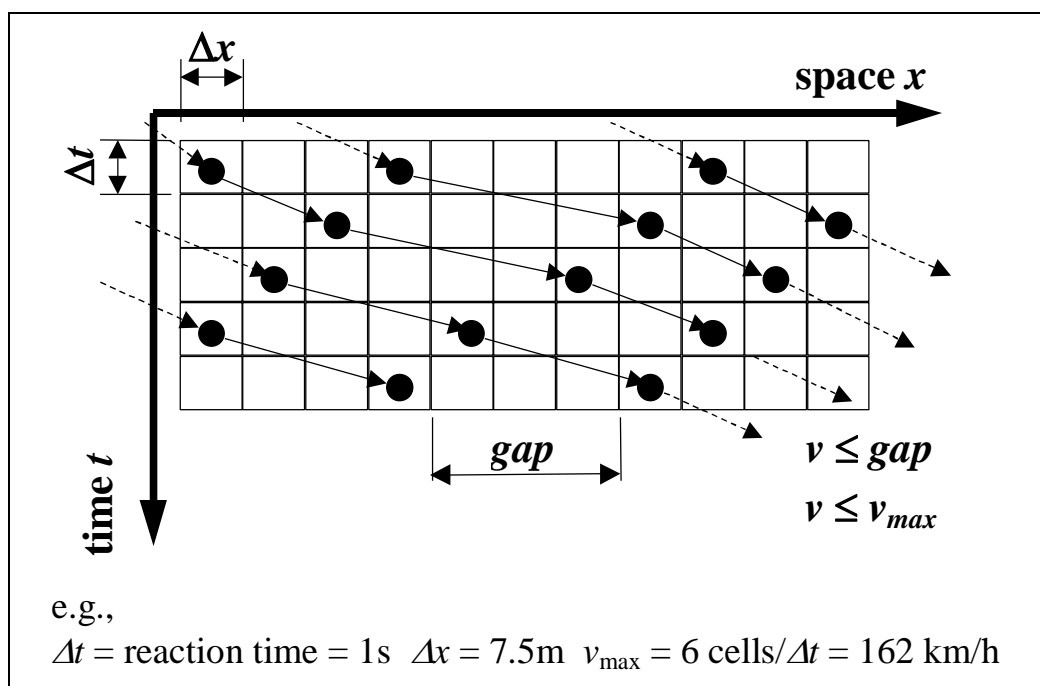


Fig. 1 – Principle of a Cellular Automaton

This philosophy is represented by the following four rules in the STCA. Denoting *gap* as the number of free sites in the front of a vehicle, x the actual position and v the actual speed of the vehicle, one obtains (cf. Fig. 1) the pseudo-code for the rules:

- (1) if ($v < v_{\max}$) then $v = v + 1$ (if the present speed is smaller than the desired maximum speed, the vehicle is accelerated)
 The desired speed v_{\max} can be assumed to be distributed by a statistical distribution function where the values of v_{\max} are only allowed to be 1, 2, ..., 6 cell/ Δt .
- (2) if ($v > \text{gap}$) then $v = \text{gap}$ (if the present speed is larger than the gap in the front, set $v = \text{gap}$)
 This rule avoids rear end collisions between vehicles. Note that here a very unrealistic braking rule allowing for arbitrarily large decelerations is involved. This rule forces a minimum time headway of Δt s.
- (3) if ($v > 0$) then $v = v - 1$ with p_{brake} (the present speed is reduced by 1 with the probability p_{brake})
 This rule introduces a random element into the model. This randomness models the uncertainties of driver behavior, such as acceleration noise, inability to hold a fixed distance to the vehicle ahead, fluctuations in maximal speed, and assigns different acceleration values to different vehicles. This rule has no theoretical background and is introduced quite heuristically. The most of the shortcomings of the STCA are due to this unrealistic rule.
- (4) $x = x + v$ (the present position on the road is moved forward by v)

According to these rules the speed and the acceleration/deceleration ratio of a vehicle are independent of speed of other vehicles at any time. They are only functions of the gap in the front. Thus, these rules can be updated in parallel for any vehicle. However, the acceleration and deceleration ratio can take infinite large value if a vehicle changes its speed according to these rules. The average deceleration ratio over the driver population is p_{brake} . The average acceleration ratio over the driver population yields $1 - p_{\text{brake}}$. Despite its extreme simplicity, this model shows many features which agree with the real-world traffic. Especially, the distribution of time headways and the distribution of arrivals within a time interval can be somewhat satisfactorily reproduced. The STCA of Nagel-Schreckenberg uses a minimal set of rules that under certain conditions yield desired macroscopic behavior. For describing queuing systems, e.g., intersections of two urban streets, the STCA delivers very good results compared with the real-world traffic conditions (Brilon and Wu, 1997).

2.2 Application of STCA for urban streets

For streets in urban traffic networks, intersections (with or without traffic signals) are always the bottlenecks of the total system. The capacity of the intersections are therefore decisive for the total network.

At intersections with traffic signals, the capacity of the intersections can be reproduced very well with STCA by varying the parameter p_{brake} . Fig. 2 shows the shape of the capacity curves at intersections with traffic signals as function of the parameter p_{brake} . The curves are organized according to the desired speed (v_{\max}) at the intersection. These curves indicate the simulated discharge capacity of a queue by STCA. With this curves, the saturation flow during green

time (Q_s) at an intersection with traffic signals can be easily reproduced by choosing a occasional parameter p_{brake} . For instance, by using a $p_{\text{brake}} = 0.2$, a saturation flow of about $Q_s = 1700$ veh/h can be obtained for $v_{\text{max}} = 2$ cell/ Δt (corresponds to $V=54$ km/h). In other words, if a saturation flow of $Q_s = 1700$ veh/h for $v_{\text{max}}=2$ cell/ Δt is needed, a parameter $p_{\text{brake}} = 0.2$ should be applied in STCA.

From these curves of capacities, also the move-up times t_f at intersections without traffic signals (i.e., priority-controlled intersections) can be calculated. The move-up time t_f represents the average time headway between two vehicles departing at the stop line in succession. It is the reciprocal of the capacity at the stop line. Therefore, one obtains $t_f = 1/Q_s$.

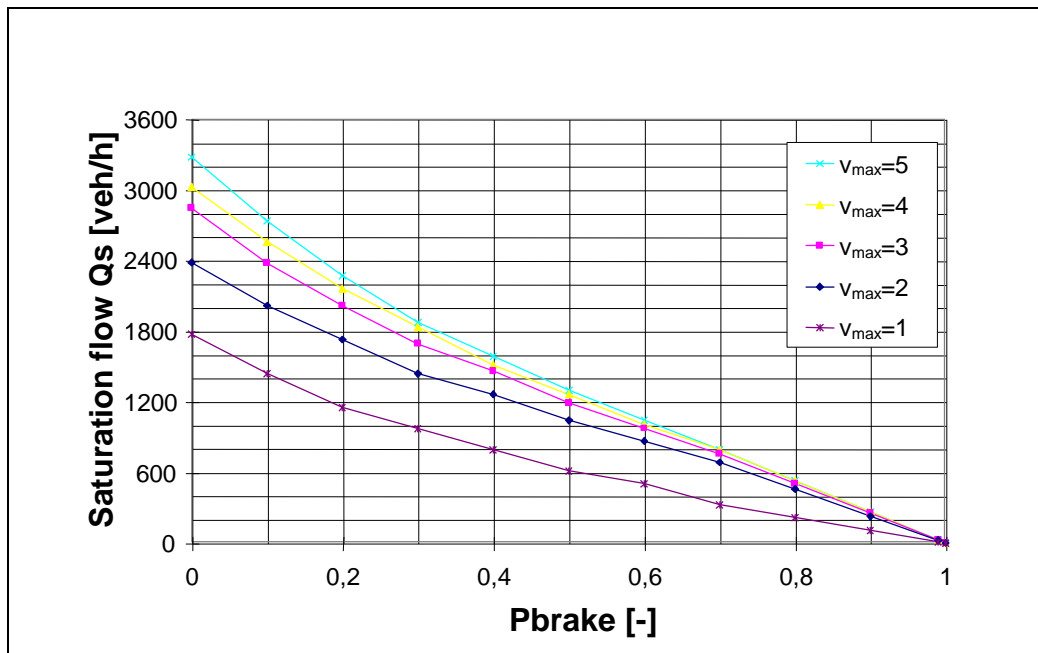


Fig. 2 – Saturation flow Q_s from STCA at signalized intersections

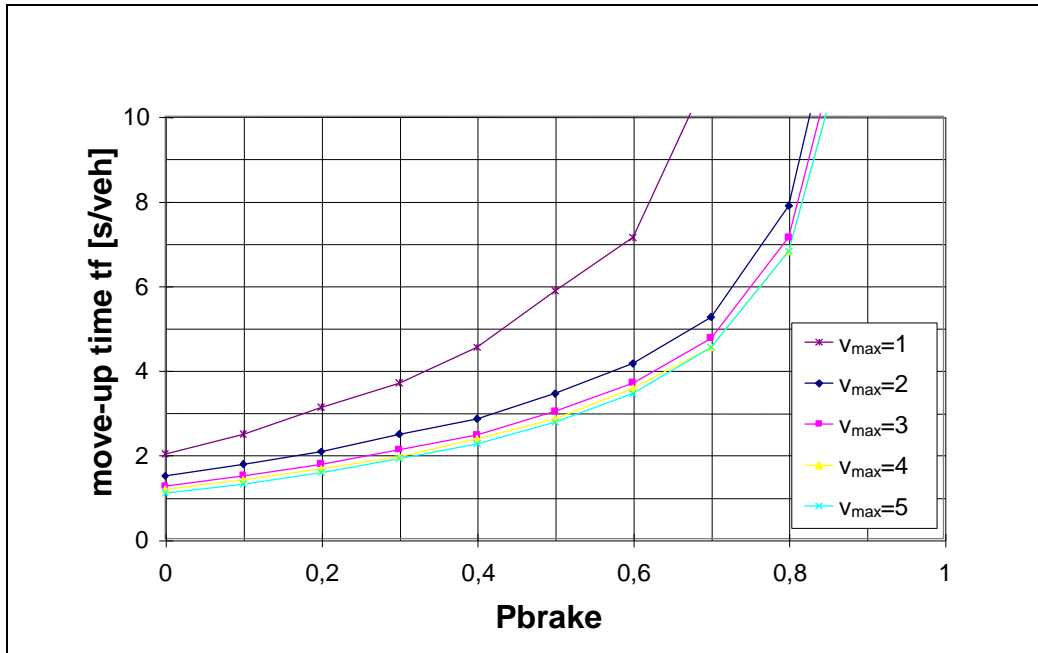
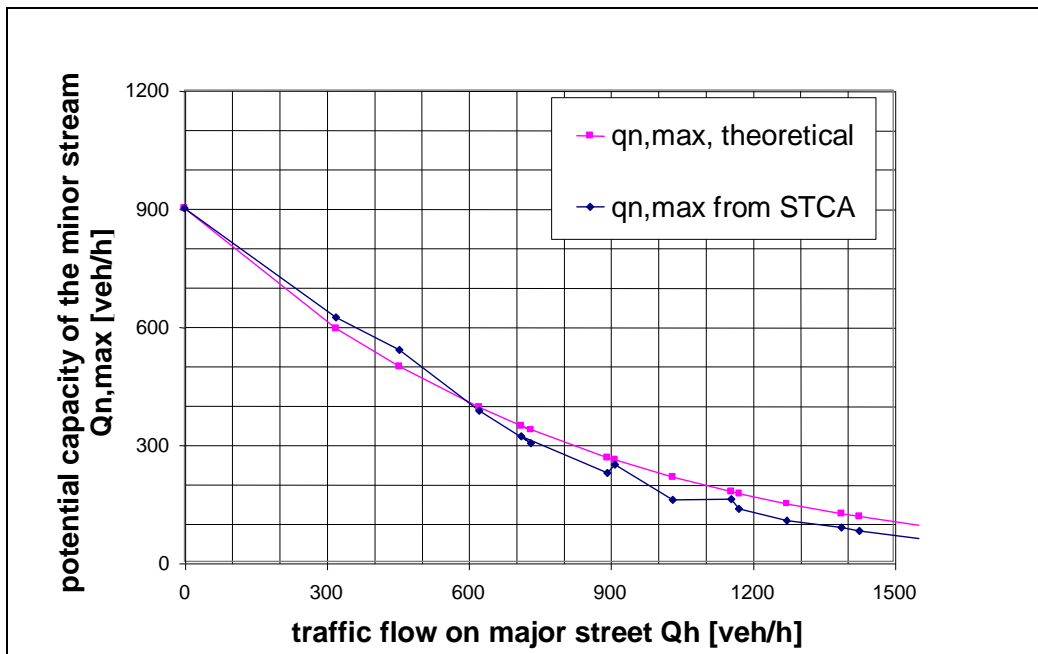


Fig. 3 – Move-up times t_f from STCA at unsignalized intersections

According to this relationship the curves for the move-up times t_f can also be obtained from the Fig. 2. The curves for t_f are directly shown in Fig. 3. The move-up times t_f are functions only of the parameter p_{brake} for the subject minor street.



a)

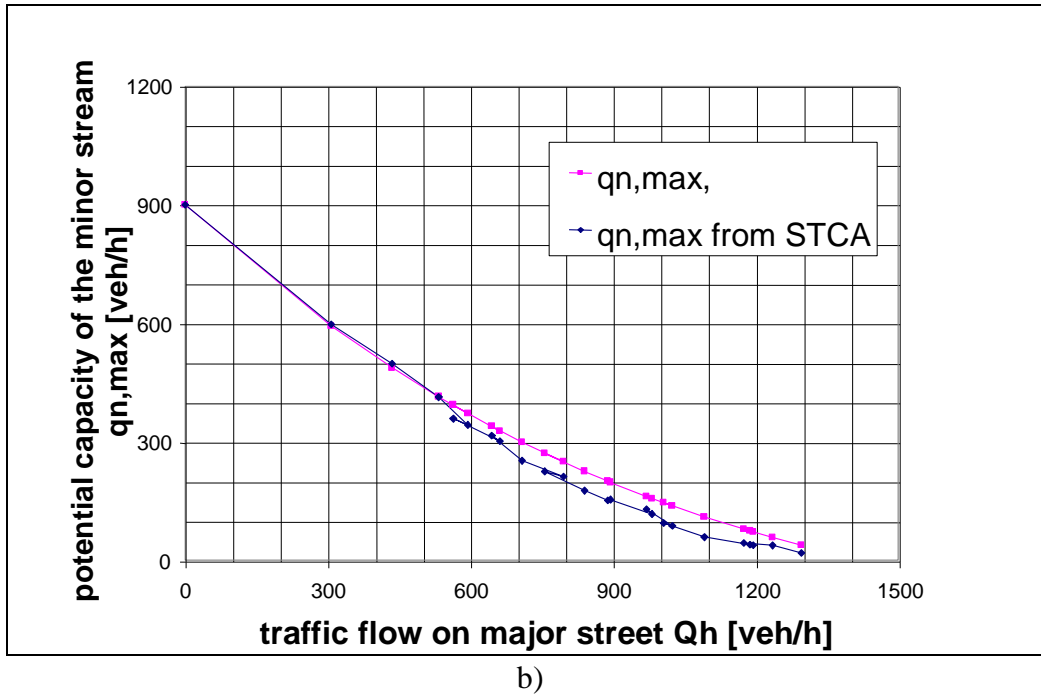


Fig. 4 – Potential capacities from STCA at unsignalized intersection
a) potential capacity for single-lane major-streets
b) potential capacity for multi-lane major-streets

The critical gaps t_g at intersections without traffic signals can be considered as a function of the number T of cells which have to be checked by the vehicle waiting at the intersection, the desired speed $v_{max,h}$ and the parameter $p_{brake,h}$ for the major street. The following relationship can be stated: $T = t_g \cdot (v_{max,h} - p_{brake,h}) - 1$. For instance, if a critical gap $t_g = 5$ s, a desired speed on the major street $v_{max,h} = 2$ cells/ Δt (corresponds to $V=54$ km/h), and a parameter $p_{brake,h} = 0.2$ for the major street are used, one has to apply $T = 5 \cdot (2 - 0.2) - 1 = 8$ cells in STCA.

Thus, according to the procedure: a) setting the parameter $p_{brake} = f(t_f)$ for the minor street (cf. Fig. 3), b) setting the parameter $T = t_g \cdot (v_{max,h} - p_{brake,h}) - 1$ for the major street, and c) simulating the capacity $Q_{n,max} = f(t_f, t_g)$ using p_{brake} and T , the potential capacity of the minor street at intersections without traffic signals can be obtained by STCA.

The potential capacity simulated with this approach by STCA at intersections without traffic signals agrees very well with the theoretical results (cf. Fig. 4) obtained from gap acceptance theory.

Therefore, the using this approach STCA can be recommended for simulating large scale urban street networks. Here the intersections always represent the bottlenecks of the system whereas the traffic flow on links is not decisive. Thus the simple model is sufficient for moving the vehicles along the links of the networks to represent real world conditions.

2.3 Application of STCA for freeways

On the other hand, as a result of the extreme simple configuration of the STCA, the characteristics of traffic flow in motion (no queuing) can not be described by STCA with

satisfying performance. The simulated traffic flow on motorways, especially on European motorways, cannot represent the realistic speed-flow relationships. Analyzing the STCA in details one finds the following unrealistic features on the microscopic level:

1. The acceleration and deceleration ratios are unrealistic because of their infinite value and dependence on each other (acceleration ratio $=1-p_{\text{brake}}$, deceleration ratio $=p_{\text{brake}}$).
2. The acceleration ratio ($=1-p_{\text{brake}}$) is larger than the deceleration ratio ($=p_{\text{brake}}$) (for the common case of $p_{\text{brake}} > 0.5$).
3. The speed of a vehicle is not dependent on the speed of other vehicles ahead.
4. The minimum time headway between two vehicles cannot obtain values smaller than Δt .
5. The driver reaction time is always equal to Δt .
6. The speeds are classified in discrete classes (i.e. with steps 27 km/h).
7. The threshold (time interval to the vehicle ahead) for changing (adjusting) speed is always equal to Δt .

These microscopic properties of the STCA lead to the following macroscopic disagreements compared to real traffic flow on motorways:

1. The maximum flow ratio in the opening (depressive) phase C_{open} is larger than the maximum flow ratio in the closing (compressive) phase C_{close} , whereas in reality just the opposite occurs.
2. No capacity drops exist.
3. The convoy dynamics is always stable.
4. No breakdowns in an open pipeline system.

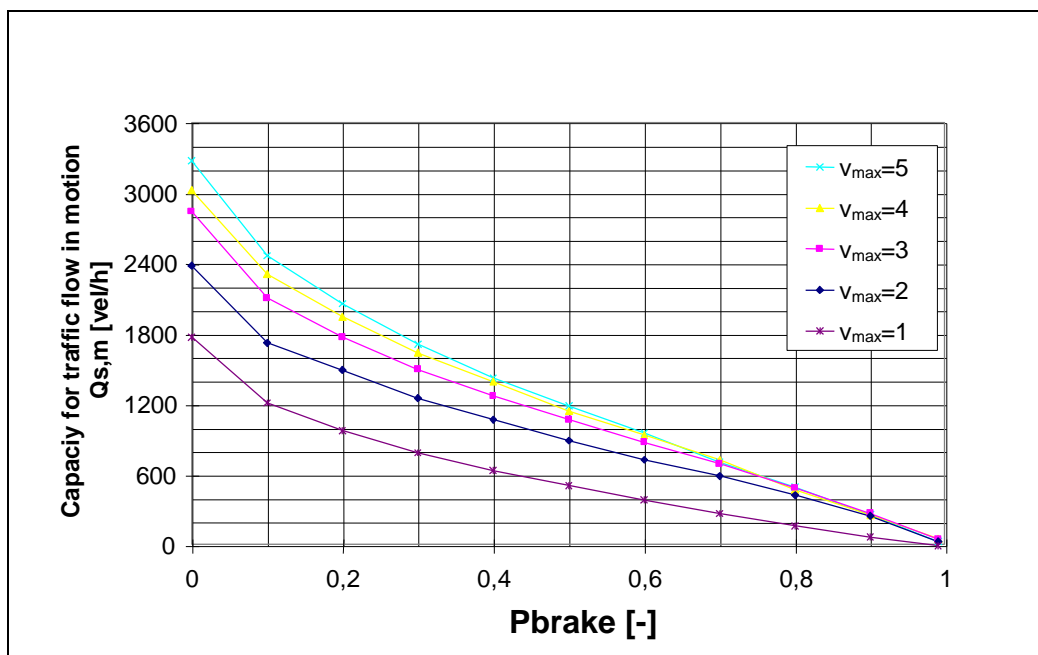


Fig. 5 – Capacity $Q_{s,m}$ from STCA for traffic flow in motion

Fig. 5 shows the curves of capacities $Q_{s,m}$ simulated by STCA for traffic flow in motion. Comparing the queue discharge capacities (saturation flow Q_s) for queuing systems (Fig. 2), it can be recognized that the capacities for traffic flow in motions are always smaller than the queue discharge capacities. This is the main reason why in the car-following model of STCA

the maximum flow ratio in the opening phase C_{open} is larger than the maximum flow ratio in the closing phase C_{close} and why no capacity drops and breakdowns occur.

For simulation traffic flow on freeways, configurations with more than one lane should be taken into account. In order to simulate multi-lane traffic an additional set of rules for lane-changing is needed. These rules are updated before the speed update is done. They are divided into two parts representing the desire and the possibility of changing lane without hindering the other vehicles. Also, the reason of changing from left to right is different from the reason of changing from right to left (Wagner, 1995; Wagner, et al., 1996; Nagel, et al., 1996). Because of the so-called "mandatory driving on the right lane and the prohibition of overtaking on the right" (MDR) on motorways in most of the European countries the lane-usage between different lanes is non-homogeneous (on US motorways the lanes are used more or less homogeneously under heavy traffic volume due to the rule "keep in lane"). The pseudo-code of these rules in STCA for changing lane in case of MDR are (cf. Fig. 6):

- (1) if ($gap < v_{max}$) and ($gap_{left} \geq gap$) then desire-from-right-to-left
- (2) if ($gap > v_{max} + v_{offset}$) and ($gap_{right} > v_{max} + v_{offset}$) then desire-from-left-to-right
- (3) if ($gap_{back} \geq v_{back}$) then possibility-of-changing-lane

Here, v_{offset} is a parameter which is used to represent the asymmetric driving and distance behavior on different traffic lanes. This parameter then significantly affects lane split of traffic flow on motorways. In addition, a ban on passing on right is implemented. This can be written as

- (4) if ($v_{right} > gap_{left}$) then $v_{right} = gap_{left}$ (prohibition of passing on right)

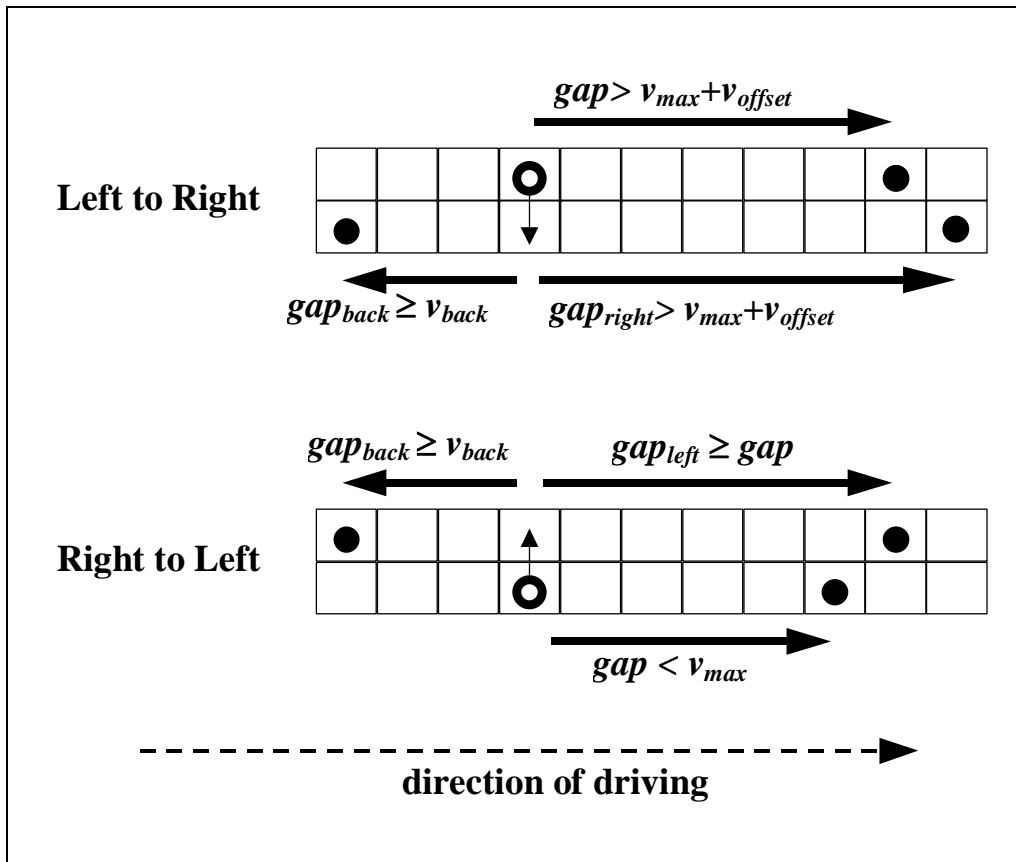


Fig. 6 – Principle of lane-changing in STCA

This set of rules is somewhat too restrictive. For very large densities the most vehicles remain on the left lane, whereas the right one is relatively empty. This can be remedied by introducing another set of rules that includes a certain probability for lane changing to the right if there is more room there. This set of rules is executed with a small probability p_{12r} . The probability that a vehicle is changing from right to left, regardless of approaching vehicles on the left, is described by the parameter p_{r2l} .

Table 1 - Performance speeds of STCA at different computers for real-time simulation

| Type of computer | Number of CPNs | Scale of the network | Number of vehicles |
|---------------------|----------------|---|--------------------|
| SUN ULTRASPARC | 1 CPN | 1 000 km Freeway | 100 000 veh |
| SGI POWER CHALLENGE | 16 CPNs | 11 000 km Autobahn 75 000 km rural highway | 1 000 000 veh |
| iPSC | 32 CPNs | 260 000 km*lane | 3 500 000 veh |
| GCel-3 | 1024 CPNs | 900 000 km*lane | 12 000 000 veh |

(Source: Nagel, 1995)

The STCA model can be implemented with enormous efficiency on modern computers. Even on a workstation it is possible to simulate large street networks in real time. Approximately 1000 km of a two-lane (per direction) motorway network containing 10^5 vehicles can be simulated in real-time on a SUN ULTRASPARC. Even larger networks can be simulated by using parallel computing, e.g. the German motorway network (11 000 km, 75 000 km lane, 10^6 vehicles) can be done in real-time on a SGI POWER CHALLENGER with 16 CPN (cf. Table 1). However, all this speed is useless, if the model does not agree with the real-world traffic conditions. Therefore, how the model compares to reality has to be discussed.

Since the model allows unrealistic microscopic values compared to real-world data, the calibration and validation of STCA is only possible at the macroscopic level.

2.4 Comparison with field data on German freeway

The field data for comparison were collected on a Germany motorway near the city of Muenster. All data were recorded as 1-minute-averages. The measured speed-flow relationship of these data is given in Fig. 7.

Calibrating the model to realistic distribution of traffic by lanes we obtained for the parameter $p_{12r} = 0.05$, $v_{offset} = 8$ cells, and $p_{r2l} = 0.2$. applying these parameters for a pattern of volume over time like the field data, the simulation results are presented as a speed-flow diagram in Fig. 8. The macroscopic speed-flow relationships differ from the field data (cf. Fig. 7) in three major points:

1. The maximal traffic volumes are too low.
2. The speeds for volumes above 2500 veh/h are too high.
3. No breakdowns into congested conditions occur.

The points 1 and 2 are two characteristics of STCA affected by the parameter p_{brake} . Both of the characteristics decrease with increasing p_{brake} . This leads to a dilemma for validating the STCA: if the model is validated according to the maximum traffic flow, the speed is always too high; if the model is validated according to speed, the maximum traffic flow is always too low. Point 3 is the result of the stable convoy system modeled by STCA on the background that the capacity in the opening phase C_{open} is larger than the capacity in the closing phase C_{close} . In this stable convoy system the oscillating motion of a vehicle in car-following cannot be considered.

Nevertheless, the simulation results from STCA represent a shape of speed-flow diagram like the real data. Regardless of the speed of the traffic flow, the maximum traffic flow (capacity) of STCA can still be calibrated. Here, three speed classes ($v_{\text{max}}=4, 5, \text{ and } 6$) for cars and one speed class ($v_{\text{max}}=3$) for trucks are used.

In Table 2, the parameters for different types of freeways in Germany under ideal traffic conditions are listed together. Table 3 shows the corresponding capacities of these freeways with the truck portions of 5%, 10%, and 15%. Also for other traffic and weather conditions (light/dark; wet/dry) the parameters were obtained by calibrations (cf. Brilon, Wu 1997).

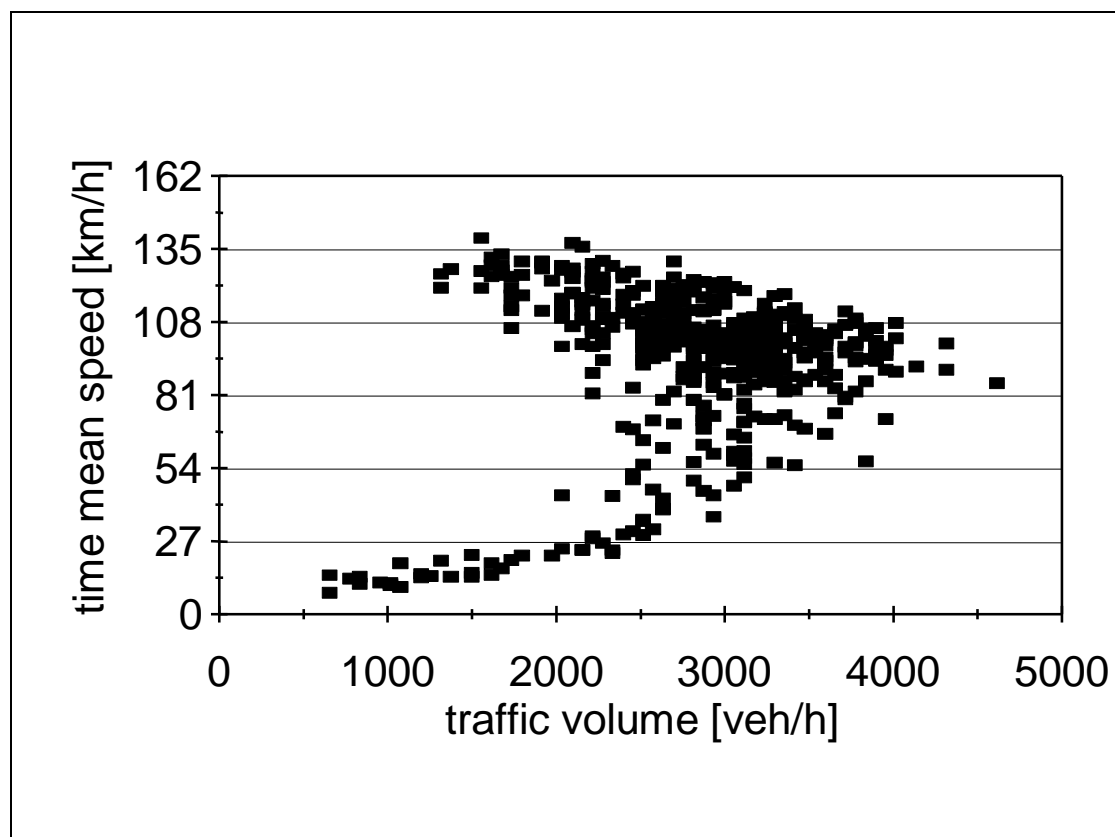


Fig. 7 – Example of speed-flow relationship from measurements on a 2-lane directional roadway of a motorway in Germany

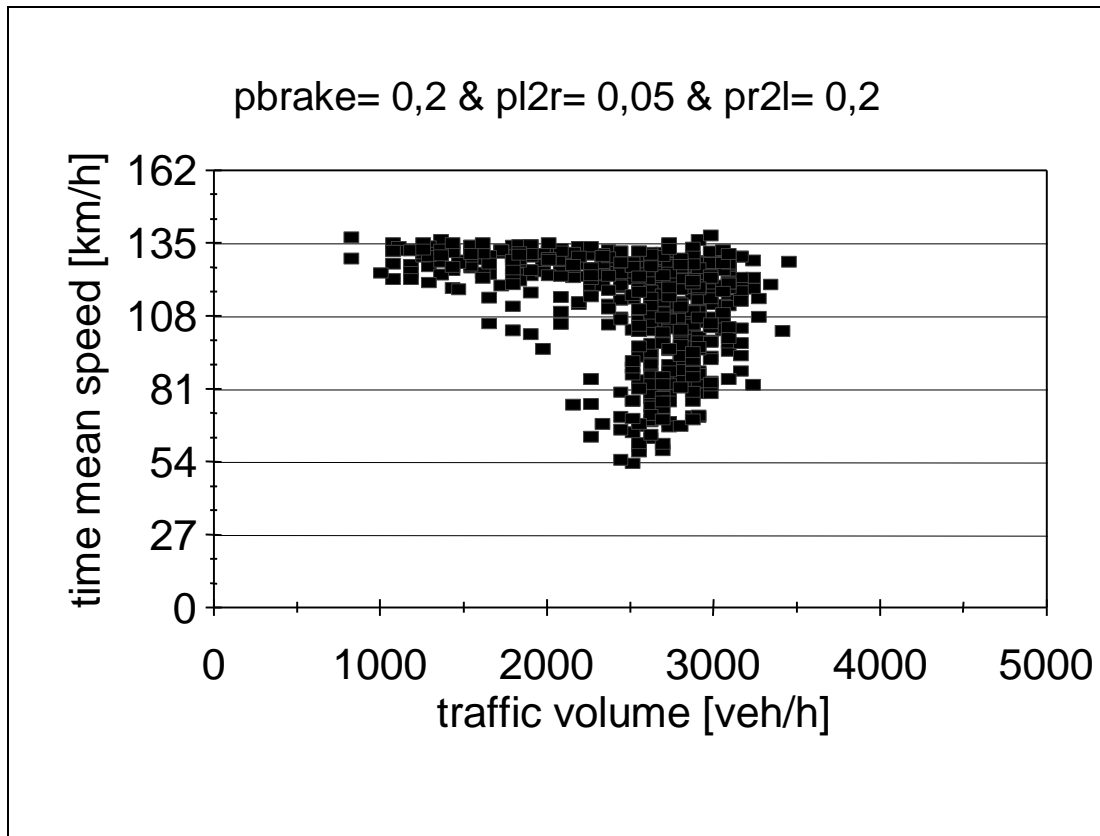


Fig. 8 - Speed-flow relationship from the STCA

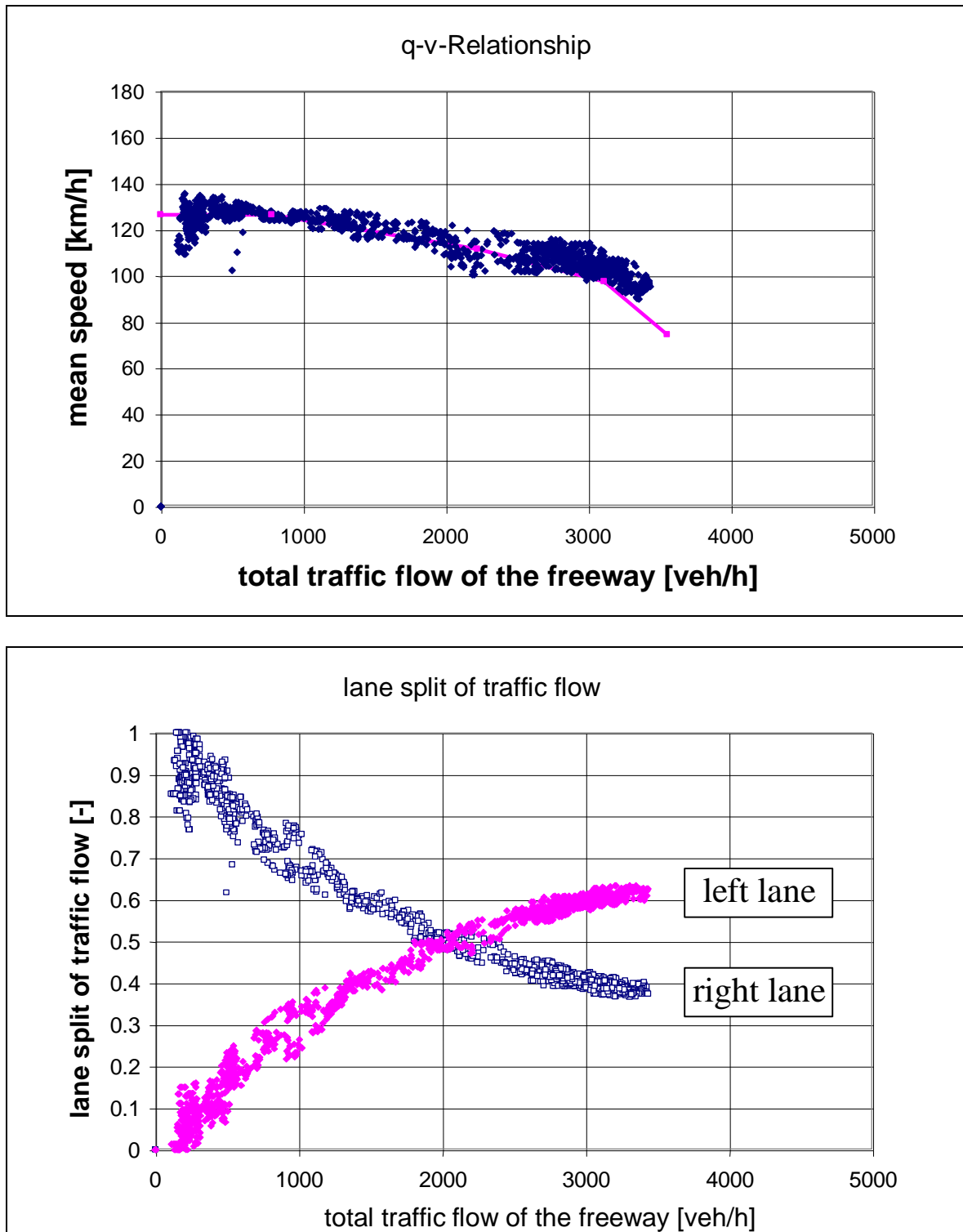


Fig. 9 – Example for a 2-lane freeway with $p_{\text{brake}}=0.05$, $v_{\text{offset}}=3$ and truck = 10%

Fig. 9 shows an example of the q-v-relationship simulated by STCA and the corresponding lane split of the traffic flow for a 2-lane freeway. In this example, the parameters $p_{\text{brake}} = 0.05$, $v_{\text{offset}} = 3$ and the truck portion = 10% are applied. Here, one can recognize again that the speed behavior and the capacity can not be calibrated simultaneously. Theoretically, the capacity can be further increased if a smaller value for p_{brake} is chosen. The resulted speed

behavior is then more unrealistic. Because of the properties of STCA mentioned earlier, the breakdowns of the traffic flow can not be modeled by the STCA.

Table 2 – Parameter catalog for ideal traffic conditions

| parameter | 2-lane long distance | 2-lane metropolitan | 3-lane long distance |
|------------------------|---------------------------------|------------------------|-------------------------|
| p_{brake} | 0.1 | 0.05 | 0.05 |
| $v_{car}: v_{max}=6$ | 25% of the personal car portion | | |
| $v_{car}: v_{max}=5$ | 50% of the personal car portion | | |
| $v_{car}: v_{max}=4$ | 25% of the personal car portion | | |
| $v_{truck}: v_{max}=3$ | 100% of the truck portion | | |
| p_{l2r} | 0.05 | | |
| $p_{r2l,car}$ | 0.2 | | |
| $p_{r2l,truck}$ | 0 | | |
| v_{offset} | 6 | 3 | 3 |

Table 3 – Capacities in veh/h simulated by STCA for ideal traffic conditions

| proportion of truck | 2-lane long distance | 2-lane metropolitan | 3-lane long distance |
|---------------------|-------------------------|------------------------|-------------------------|
| 5% | 3300 | 3500 | 4900 |
| 10% | 3250 | 3450 | 4800 |
| 15% | 3200 | 3400 | 4700 |

In summary, the results of STCA for modeling traffic flow on freeways are not very satisfactory. To describe the speed-flow relationship more accurately the STCA, especially the car-following rules in the STCA, has to be modified.

3 THE NEW TIME-ORIENTATED CELLULAR AUTOMATON (TOCA)

The major problem of the STCA is the unrealistic driver behavior caused by an unrealistic car-following model. Considering the rules of STCA, an extremely asymmetric car-following behavior can be observed. Here the threshold of changing speed is equal to the minimum time headway Δt . Thus, the time headway between two vehicles can never be smaller than the threshold of changing speed. In this car-following system, a vehicle can never over- and/or under-steer his speed. The oscillating motion which is the basic property of a car-following system in real-world cannot be realized (cf. Fig. 10). Therefore, the vehicles in a convoy form only an incompressible system which is always very rigid and stable.

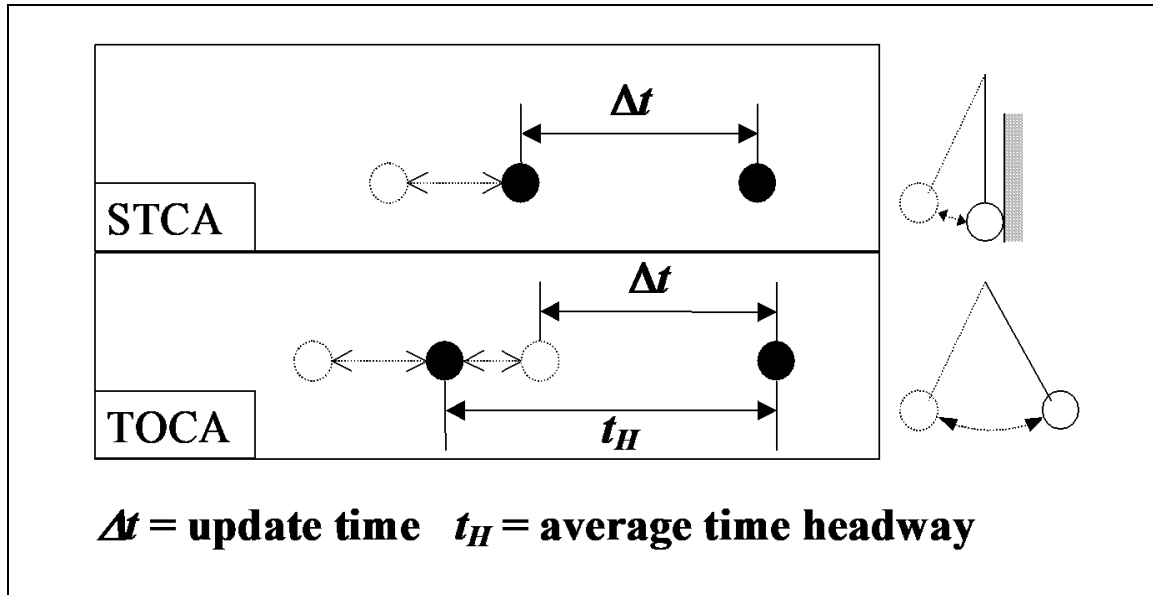


Fig. 10 – Car-following behaviors in STCA and TOCA

To solve this problem, a new model (time-oriented CA, TOCA) is introduced that uses a more elastic but still simple approach for representing the car-following behavior. The TOCA has similar rules as the STCA. Only the distance behavior (car-following) between vehicles is modified. A new parameter t_H (corresponding to the average time headway in a convoy) is introduced that represents the threshold for changing speed (causing acceleration or deceleration). The pseudo-code of the rules can be rewritten as

- (1) if ($\text{gap} > v \cdot t_H$) and ($v < v_{\max}$) then $v = v + 1$ with p_{ac} (The speed is increased by 1 with the probability p_{ac} if the time headway to the vehicle in front is larger than t_H . An average acceleration ratio with the value p_{ac} is resulted.)
- (2) if ($v > \text{gap}$) then $v = \text{gap}$
- (3) if ($\text{gap} < v \cdot t_H$) and ($v > 0$) then $v = v - 1$ with p_{dc} (The speed is reduced by 1 with the probability p_{dc} if the time headway to the vehicle in front is smaller than t_H . An average deceleration ratio with the value p_{dc} is resulted.)
- (4) $x = x + v$

Here the rules (1) and (3) are different from the rules of STCA. These two rules introduce a time threshold t_H that initializes changing of speed combined with random elements. If one chooses $t_H > \Delta t$ the car-following system becomes elastic and a realistic oscillation can be utilized (cf. Fig. 10). The parameters p_{ac} and p_{dc} represent the average acceleration and deceleration ratio of the vehicle population. The parameter p_{brake} in the STCA can be omitted.

As a result, two major shortcomings of the STCA in the microscopic level can be partly improved: the acceleration and deceleration ratio have independent values (p_{ac} and p_{dc}); the threshold for changing speed (= time interval initializing adjusting speed) can obtain arbitrary values ($t_H > \Delta t$). Consequently, the maximum flow ratio in the opening phase C_{open} can be set smaller than the maximum flow ratio in the closing phase C_{close} . This leads to the following macroscopic properties of the TOCA:

1. Capacity drops within the range of capacity become possible.

2. Non-stable convoy dynamics and therefore breakdowns in a open pipeline system becomes possible.
3. More realistic speed-flow relationship.

These macroscopic characteristics agree with the real-world traffic flow on motorways very well.

In the same manner, also the rules for changing lanes can be modified into time-orientated rules (cf. Fig. 11):

- (1) if $(gap < t_{H,r} \cdot v_{max})$ and $(gap_{left} \geq gap)$ then desire-from-right-to-left.
- (2) if $(gap > t_{H,l} \cdot v_{max})$ and $(gap_{right} > t_{H,r} \cdot v_{max})$ then desire-from-left-to-right.
- (3) if $(gap_{back} \geq t_{H,b} \cdot v_{back})$ then possibility-of-changing-lane.
- (4) if $(v_{right} > gap_{left})$ then $v_{right} = gap_{left}$ (prohibition of passing on the right).

The parameter $t_{H,l}$, $t_{H,r}$ and $t_{H,b}$ are the time thresholds that determine the lane-changing behavior. They can be set to the average time headways in a convoy. They can also take different values representing the behavior of change-to-left, change-to-right and look-behind. The parameters p_{l2r} and p_{r2l} in the STCA can remain.

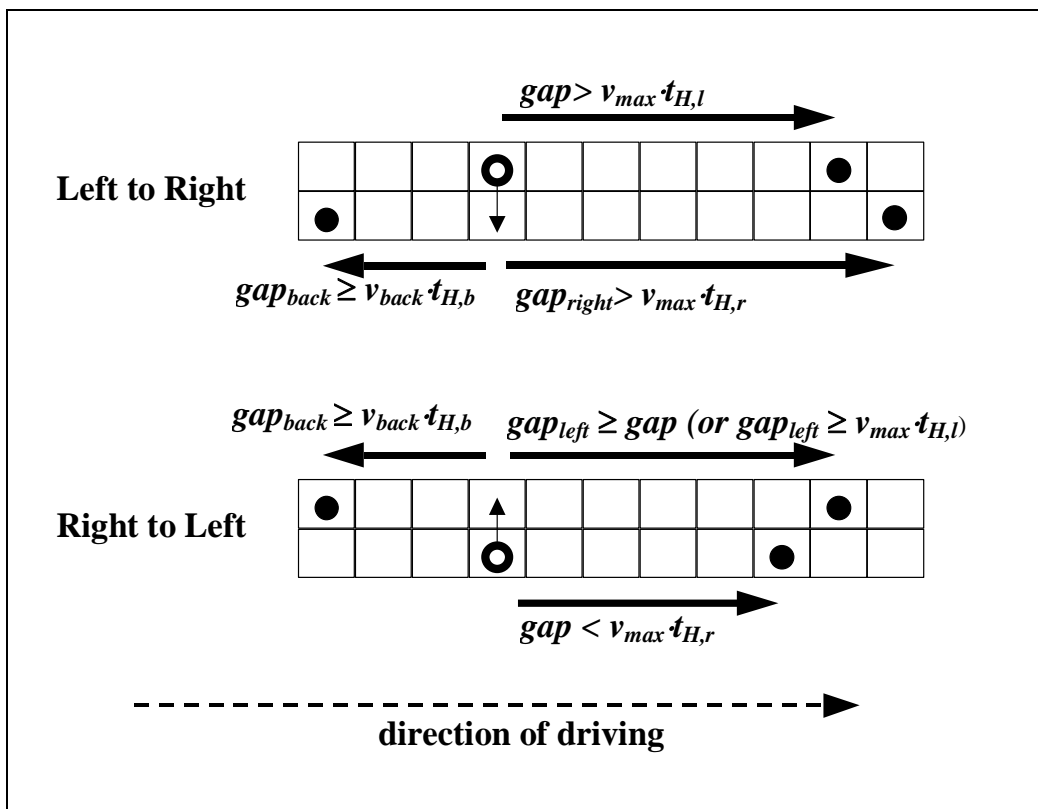


Fig. 11 – Principle of lane-changing in TOCA

The new rules of the CA result into a much better agreement with the measurements. Fig. 12 shows the results of the TOCA with the new rules for the same input flow pattern like the field data. Compared to the STCA an obvious enhancement can be observed (cf. Fig. 7 and Fig. 8). To obtain the speed-flow diagram in Fig. 12 the parameters in Table 4 were used.

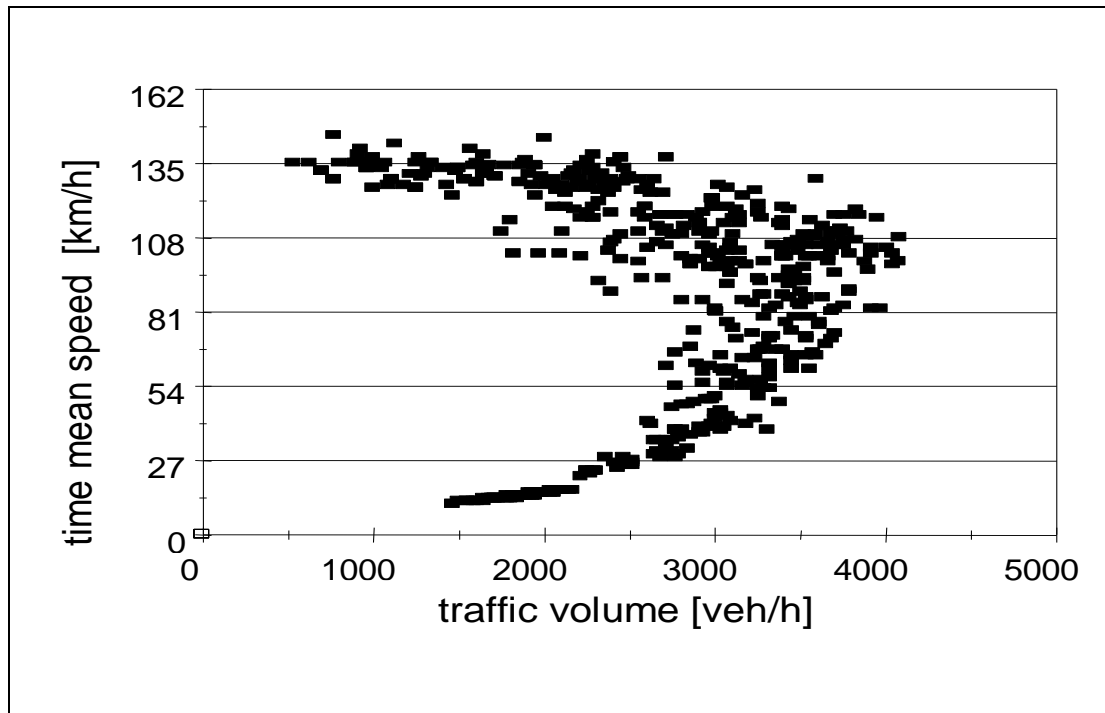


Fig. 12 - Speed-flow relationship from the new TOCA

Table 4 – Parameters of TOCA for the example

| car-following behavior | | | lane changing from left to right | | | lane changing from right to left | | |
|------------------------|----------|---------|----------------------------------|-----------|-----------|----------------------------------|-----------|-----------|
| p_{ac} | p_{dc} | t_H | $t_{H,r}$ | $t_{H,l}$ | $t_{H,b}$ | $t_{H,r}$ | $t_{H,l}$ | $t_{H,b}$ |
| 0.9-1.0 | 0.9-1.0 | 1.1-1.2 | 4.0 | 3.0 | 2.0 | 2.0 | 1.4 | 1.4 |
| - | - | sec | sec | sec | sec | sec | sec | sec |

As a summary, the properties and their assessments of STCA and TOCA are listed together in Table 5. The TOCA modified the shortcomings and retains most of the advantages of STCA.

4 CONCLUSION

Traffic on streets and highways can be simulated efficiently by the simplified microscopic CA-model. A CA can be described with the main properties: discrete division in time and space; isolate driving behavior and updating rules. The most important feature of a CA is the possibility of parallel computing.

Although the so-called STCA from Schreckenberg and Nagel produces good results for modeling queuing systems, it is not accurate enough for modeling the car-following behavior in the real-world and is therefore not suitable for modeling the traffic flow on motorways. The STCA was comprehensively calibrated and validated.

Table 5 – Properties and assessments of STCA and TOCA

| | STCA | Assessment | TOCA | Assessment |
|-------------------------------|--------------|------------|------------------------|------------|
| car-following | | | | |
| time | discrete | ± | discrete | ± |
| space | discrete | ± | discrete | ± |
| desired speed | discrete | – | discrete | – |
| acceleration and deceleration | ∞ | – | $< \infty$ * | + |
| min. possible spacing | $= \Delta t$ | – | $= \Delta t$ | – |
| number of parameter | 1 | ++ | 1 to 3 | ++ |
| threshold for changing speed | $= \Delta t$ | --- | $= t_H > \Delta t$ | +++ |
| flexibility | low | - | high | + |
| calibration | very easy | +++ | easy | ++ |
| lane-changing | | | | |
| number of parameter | 3 | ++ | 1 to 6 | ++ |
| threshold for changing lane | $= \Delta t$ | --- | $= t_{H,x} > \Delta t$ | +++ |
| flexibility | low | - | high | + |
| operation | | | | |
| bitwise implementation | easy | ++ | easy | ++ |
| parallel computing. | possible | ++ | possible | ++ |
| speed | very high | +++ | high | ++ |

The new TOCA presented here retains the structure of a CA and introduces some new time-orientated rules which represent the real-world car-following behavior more realistic. The rules can still be updated in parallel for any vehicles, so that the possibility for parallel computing on super computers is maintained. The new TOCA reproduces the macroscopic laws observed in real-world traffic much better than the STCA and should be recommended for simulating traffic flows in motion, especially for traffic flows on motorways.

Before the TOCA can be used in practice, the system parameters of the TOCA should be calibrated and validated with more field data for different types of motorways and two-lane rural highways regarding the macroscopic behavior of traffic flows, especially the speed-flow relationships and capacities for different driving conditions.

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