Long-Term Assessment of Traffic Quality in a Large Freeway Network by Macroscopic Simulation

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ABSTRACT

Traffic quality in a large road network is hardly to estimate because many components such as freeway sections, on- or off-ramps, and weaving areas have to be taken account simultaneously. In order to investigate the traffic quality in large networks over long time periods, a macroscopic simulation model is developed. This simulation model is developed similar to the so-called Cell-Transmission Model from Daganzo (1994, 1995) with some significant extensions. The simulation model is implemented for a freeway network with a length of ca. 2000 km over a time period of a whole year.

Using the proposed macroscopic simulation model, indicators of traffic quality such travel time and risk of disturbance of traffic flow in a large network can be estimated and analyzed over a long time period. The quality and reliability of a network and thus the economical and ecological impact of traffic congestions can be quantitatively assessed.

Key words: macroscopic simulation, network assessment, traffic quality and reliability

INTRODUCTION

Traffic quality assessment for a large road network is hardly to carry out because many inhomogeneous components such as freeway sections, on- or off-ramps, and weaving areas have to be taken account simultaneously. It is difficult to combine the traffic flow models for the different components. Furthermore, due to unbalanced distribution of traffic flows in the network and over the time, the traffic flow condition could be quite different from location to location and from time to time. To evaluate the traffic quality in a large network (i.e. several thousands of kilometers) and over a long time period (i.e. a year), mathematical models are not yet available.

In order to investigate the traffic quality in large networks over long time periods, a macroscopic simulation model is developed. The model consists of a net-generator with which a network can be easily constructed and a simulation tool which uses the generated network and the predefined traffic flow patterns for estimating the traffic quality in the whole network over a time of desire. The simulation tool is developed according to the principle of the so-called Cell-Transmission Model originally developed by Daganzo (1994, 1995) but some significant extensions are made in the new model. For example, the fundamental diagrams can be defined as input data for any road sections and the capacity of a road section can be randomized according to a probability distribution. The simulation model is implemented for a freeway network with a total length of ca. 2000 km over a time period of a whole year.

Using the methodology presented in this paper, indicators of traffic quality such as the travel time and the risk of disturbance of traffic flow as well the severeness of the disturbance in a large network can be estimated and analyzed over a long time period. The traffic quality and the reliability of a network and thus the economical and ecological impact of traffic congestions can be quantitatively estimated. The presented methodology provides also possibilities for assessments of work-zone, incidents, and measures of traffic management.

MODEL DESCRIPTION

Principle of the Cell Transmission Model

The Cell Transmission Model (CTM) was first developed by Daganzo (1994, 1995) as a discrete solution of a macroscopic approach for the LWR-Model (Lighthill, Whitham 1955; Richards 1956). It can be used for dynamic processes such as for analysis of traffic congestions including propagations of shock waves.

The original CTM uses a simplified fundamental diagram in shape of a trapezoid (Figure 1) with a constant free flow speed v_f and a constant wave speed $-w$.

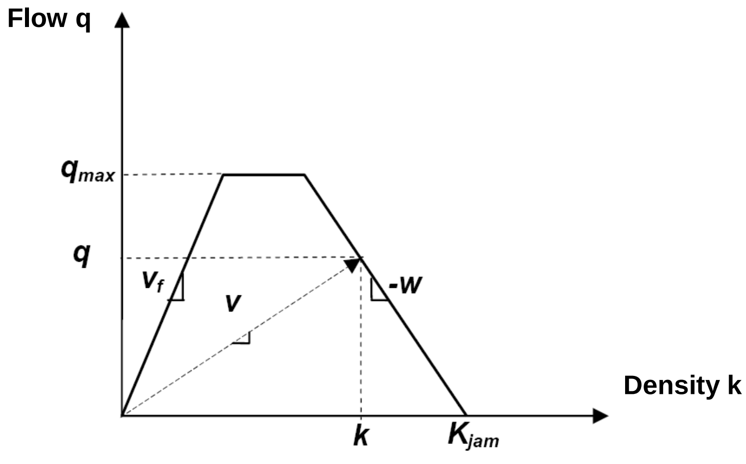


Figure 1 - Simplified fundamental diagram of the original CTM

In CTM, road sections of a network are constructed by consecutive cells. Any link *k* between two cells is defined by a beginning cell *Bk* and an ending cell *Ek*.

A node in the network can connect maximum three links. Thus, there are three possible connection orders of cells (Figure 2):

- The simple connection *k* with a beginning cell *Bk* and an ending cell *Ek*
- The entrance (merging) with a beginning cell *Bk* and an ending cell *Bk* connected by *k* and an additional complimentary cell *Ck* which is connected to the ending cell *Ek* by *ck*.

- The exit (diverging) with a beginning celll *Bk* and an ending cell *Ek* connected by *k* and an additional complimentary cell *Ck* which is connected to the beginning cell *Bk* by *ck*

Through combinations of those connection orders, arbitrary networks can be modelled.

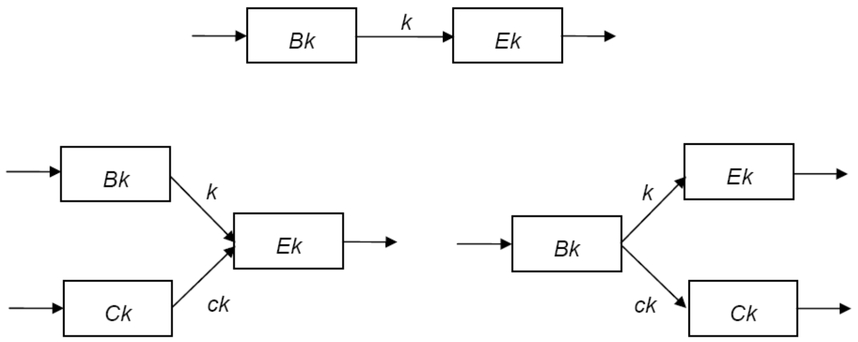


Figure 2 - Possible connection orders of cells in CTM

In CTM, time is considered in discrete intervals. In order to enable a location-independent updating of the simulation, the length Δx of a cell is selected to $\Delta t \cdot v_f$ where Δt is the duration of the time interval. Thus, using the simplified fundamental diagram (see Figure 1) and a time interval Δt=1, the LWR model can be implemented by the following equation:

$$q_k(t) = \min\{n_{Bk}(t), \min[Q_{Bk}(t), Q_{Ek}(t)], (w/v_f)(N_{Ek}(t) - n_{Ek}(t))\} \quad (1)$$

In this equation, $n_I(t)$ is the actual number of vehicles in cell *I*, $N_I(t)$ is the maximum number of vehicles in cell *I*, $q_k(t)$ is the flow rate of the link *k*, and $Q_I(t)$ the capacity of the cell *I* in the interval *t*. This equation takes into account three different cases of traffic flow:

- In the free flow state all vehicles at time *t* can get from cell *Bk* into *Ek* during Δt.
- For high traffic demand, the flow is limited by the lower values of the capacities $Q_{Bk}(t)$ and $Q_{Ek}(t)$.
- The flow is limited by the number of free places $N_{Ek}(t)$-$n_{Ek}(t)$ in the ending cell. w/v_f is a factor accounting for the wave speed *w*.

Defining $S_I(t)$ as the maximum number of vehicles which can leave (sent by) the cell *I* and $R_I(t)$ as the maximum number of vehicles which can enter (received by) cell *I*, the equation can be simplified as:

$$S_I(t) = \min\{Q_I(t), n_I(t)\} \text{ and } R_I(t) = \min\{Q_I(t), (w/v_f)(N_{Ek}(t) - n_{Ek}(t))\} \quad (2)$$

$$q_k(t) = \min\{S_{Bk}(t), S_{Ek}(t)\} \quad (3)$$

Modeling exits

Traffic flow at exists can be modelled using the principle mentioned above. Figure 3 (left) shows an exit from cell *Bk* into cell *Ek* and *Ck*. The maximum number of vehicles leaving cell *Bk* is determined by S_{Bk}, the maximum number of vehicles entering cell *Ek* and *Ck* by R_{Ek} and R_{Ck}.

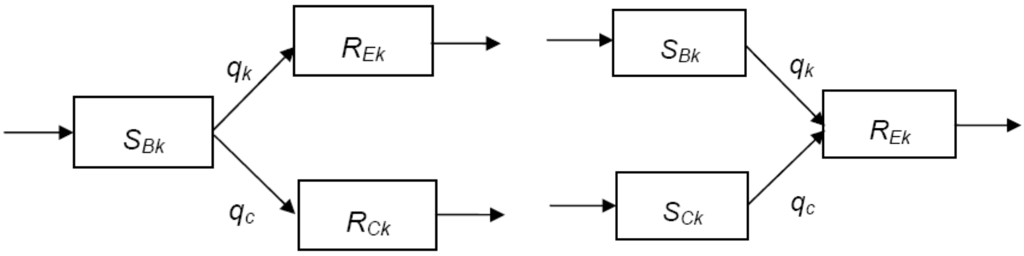


Figure 3 – Traffic flows at an exit and at an entrance in CTM

The traffic flow q_{Bk} leaving *Bk* is divided according to the proportions β_{Ek} and β_{Ck} for both of the leaving links ($\beta_{Ek} + \beta_{Ck} = 1$). If one of the traffic flows on the leaving links is limited by the downstream capacity, the total flow leaving the beginning cell *Bk* is also limited. However, the proportion the traffic flows on both links must remain constant. Thus,

$$q_{Bk}(t) = \min\{S_{Bk}(t), R_{Ek}(t)/\beta_{Ek}, R_{Ck}(t)/\beta_{Ck}\} \tag{4}$$

and

$$q_k(t) = \beta_{Ek} q_{Bk} \text{ and } q_c(t) = \beta_{Ck} q_{Bk} \tag{5}$$

Modeling entrances

The priority regulation between the merging streams is described by the proportion of the allocated capacities at the entrance (Figure 3, right). Those capacity proportions are defined by the factors p_k and p_{Ck} ($p_k + p_{Ck} = 1$). In case of limited downstream capacity $q_{Ck}/q_k = p_{Ck}/p_k$ must hold. For an entrance, three cases must be considered.

Case 1: The capacity R_{Ek} of the receiving cell is higher than the maximum number of vehicles $S_{Bk} + S_{Ck}$ of the sending cells. In this case is

$$q_k(t) = S_{Bk} \;\; and \;\; q_{Ck}(t) = S_{Ck} \;\; for \;\; R_{Ek} \geq S_{Bk} + S_{Ck} \tag{6}$$

Case 2: Both sending links are limited by the capacity of the receiving cell. In this case is

$$q_k(t) = p_k R_{Ek} \;\; and \;\; q_{Ck}(t) = p_{Ck} R_{Ek} \;\; for \;\; S_{Bk} > p_k R_{Ek} \cap S_{Ck} > p_{Ck} R_{Ek} \tag{7}$$

Case 3: One of the sending links is limited by the capacity of the receiving cell. In this case is

$$q_k(t) = S_{Bk} \ \ and\ q_{Ck}(t) = R_{Ek} - S_{Bk} \ \ for\ S_{Bk} < p_k R_{Ek} \cap S_{Ck} > p_{Ck} R_{Ek} \qquad (8)$$

$$q_{Ck}(t) = S_{Ck} \ \ and\ q_k(t) = R_{Ek} - S_{Ck} \ \ for\ S_{Bk} > p_k R_{Ek} \cap S_{Ck} < p_{Ck} R_{Ek} \qquad (9)$$

MODEL EXTENSION

Variation and randomization of fundamental diagrams

In order to take account traffic condition more realistically, a new model is developed in different ways. First of all, compared to the original CTM which uses a simplified standard fundamental diagram, the new model uses site related fundamental diagrams which can be calibrated by field measurements for any road sections. Furthermore, those fundamental diagrams account also for the phenomenon of the so-called capacity drops considering the capacities before and after a breakdown. The fundamental diagrams have two components for the free-flow and congested condition with different capacities (Figure 4). Thus, the phenomenon of Capacity-Drop can be modeled properly.

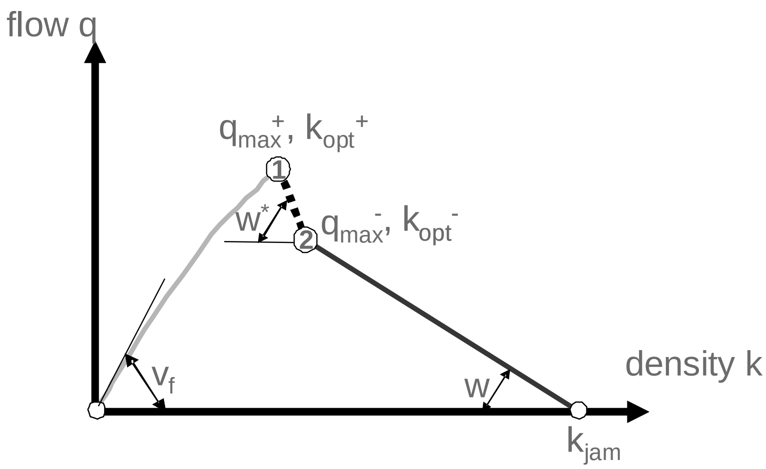


Figure 4 – Fundamental diagram with two components

In the free-flow region, the fundamental diagram is considered as a linear function in the density-speed relation and in the congested region, the fundamental diagram is considered as a linear function in the density-flow relation. Thus, the fundamental diagrams can be characterized by four data points in the *q-k* relation: 1) $k = 0$, $q = 0$ and $v = v_f$; 2) $q = vq_{max}^+$ and $k = k_{opt}^+$; 3) $q = q_{max}^-$ and $k = k_{opt}^-$; and 4) $q = 0$ and $k = k_{jam}$. The parameters q_{max}^+ and q_{max}^- are the capacities before and after a breakdown. The parameters k_{opt}^+ and k_{opt}^- are the corresponding densities. In addition, in order to avoid an uncontrolled wave speed w^* between the traffic state just before and after a breakdown and to maintain the ability of location-independent updating, the capacity after a breakdown is defined in such a way, that $|w^*| \leq v_f$ always holds. That is

$$w^* = \frac{\Delta q}{\Delta k} = \frac{q_{\max}{}^{+} - q_{\max}{}^{-}}{k_{opt}{}^{+} - k_{opt}{}^{-}} \geq v_f \tag{10}$$

Hence

$$q_{\max}{}^{-} \geq q_{\max}{}^{+} - v_f \cdot (k_{opt}{}^{+} - k_{opt}{}^{-}) \quad \text{or} \quad k_{opt}{}^{-} \geq k_{opt}{}^{+} - \frac{q_{\max}{}^{+} - q_{\max}{}^{-}}{v_f} \tag{11}$$

The maximum number of vehicles which can leave (sent by) the cell I, $S_I(t)$, and the maximum number of vehicles which can enter (received by) cell I, $R_I(t)$, are now functions of the density k. The generalized sending and receiving function for a given fundamental diagram are illustrated in Figure 5. Thus, for any cells with $\Delta x \geq \Delta t \cdot v_f$, the vehicle transmission between two consecutive cells is described by

$$S_I(t) = \text{Sending}\,(t,k) \quad \text{and} \quad R_I(t) = \text{Receiving}(t,k) \tag{12}$$

$$q_k(t) = \min\{S_{Bk}(t), S_{Ek}(t)\} \tag{13}$$

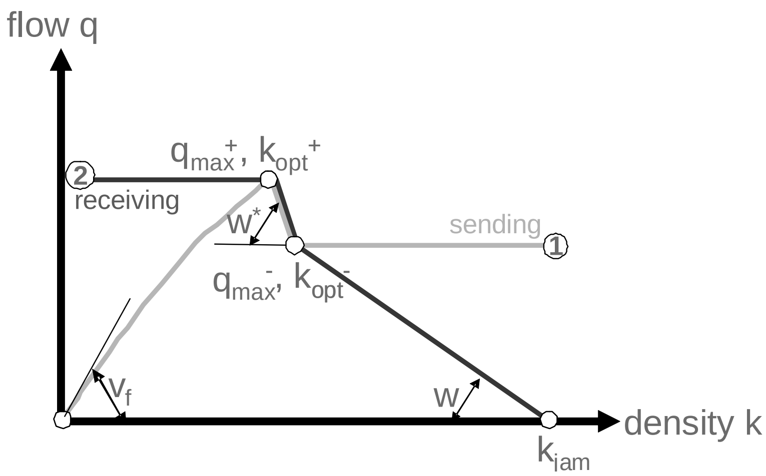


Figure 5 – Generalized sending and receiving function for vehicle transmission between cells

In addition, the capacities $q_{\max}{}^{+}$ and $q_{\max}{}^{-}$ can be randomized according to a given distribution. Thus, the stochastic nature of traffic flow can be sufficiently considered.

EXTENSION OF THE ABILITY OF NETWORK CONSTRUCTION

For allowing more complicated networks in the simulation, the network components are extended to nodes with up to three forerunners and three followers (Figure 6). That is, a cell can receive vehicles from up to three beginning (sending) cells or send vehicles into up to three ending (receiving) cells. The sent or received traffic flows are generalized to continuum flow in order to take account of mixed traffic flows with different speed levels.

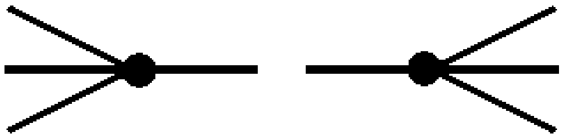


Figure 6 – New network components in the proposed model

The flow proportions β_i of the leaving links ($\Sigma\beta_i = 1$) from a sending cell are defined according to the traffic demands of the corresponding receiving cells. The capacity proportions p_i of the entering links ($\Sigma p_i = 1$) for receiving cell are defined according to the capacity of corresponding sending cells. The cell length Δx is selected to $\Delta x \geq \Delta t \cdot v_f$. This condition ensures a location-independent updating of simulation.

IMPLEMENTATION OF THE MODEL

The proposed simulation model is implemented for the freeway network in the federal state of Hesse in Germany with ca. 2000km carriageways (Figure 7) in order conduct a long-term investigation of traffic quality. The investigation is conducted for a time period of a whole year according to the measured flow patterns in the real world. Here the capacity can also be treated as Weibull distributed with a nearly constant shape parameter representing the variance. Using the distribution function of capacities, the probability of traffic breakdowns and thus the reliability of the freeway can also be investigated.

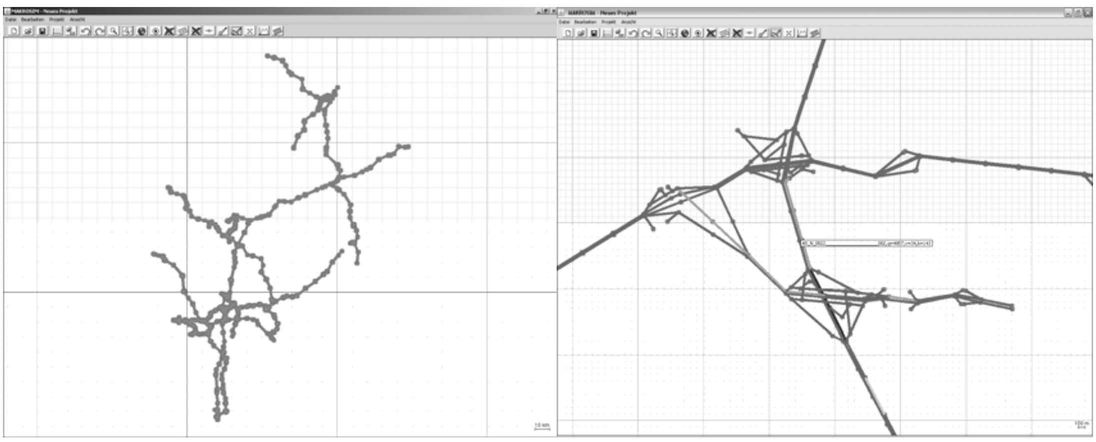
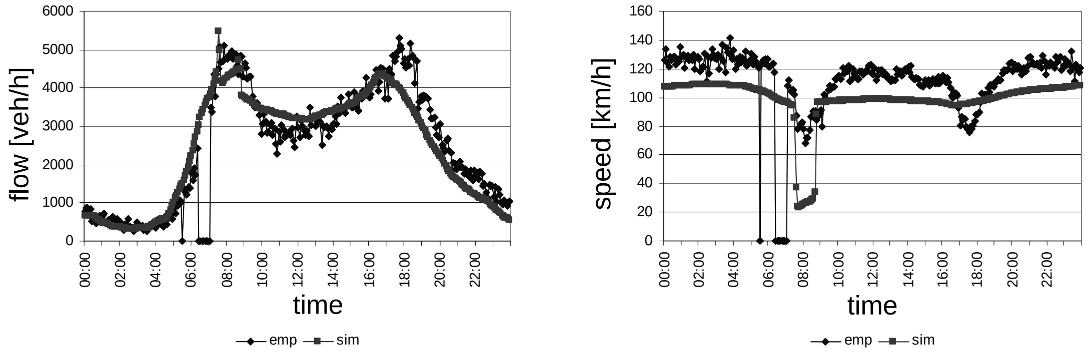


Figure 7 – Investigation area: entire network and detail

The capacity and travel speed on any freeway sections can be calibrated against measurements. Varying the parameters of the fundament diagrams the total network can be calibrated to the measured data (cf. Figure 8).



a) flow patterns b) Speed patterns

Figure 8 – Calibration of the model on a freeway section

The simulation model delivers very detailed information for every kilometer in the network and every minute over the time. This information includes detailed *q-v-k* relation for any road sections (Figure 9), travel speed, density, volume, and portion of heavy vehicles. Using that information, the travel time from and to any locations, at any times can be calculated (i.e. Figure 10 for speed in a selected time-way domain). Over the whole investigation network and time period, the travel time can be aggregated thus the efficiency of the network can be assessed (Figure 11). Furthermore, using the data of fleet emission, the total pollution of all vehicles in the network can be estimated as well.

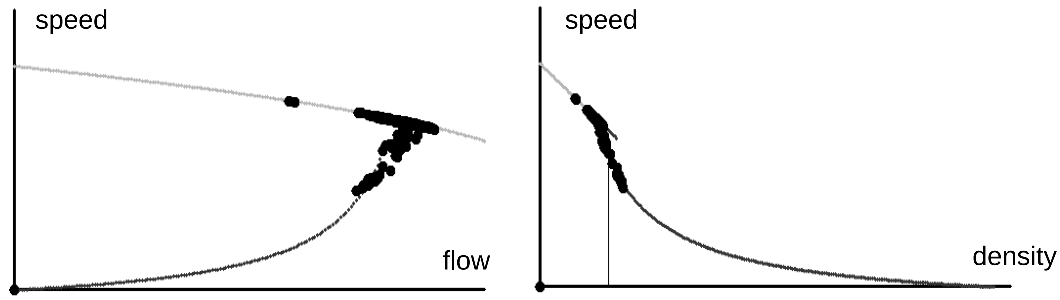


Figure 9 – Simulated q-v and q-k relationship (example)

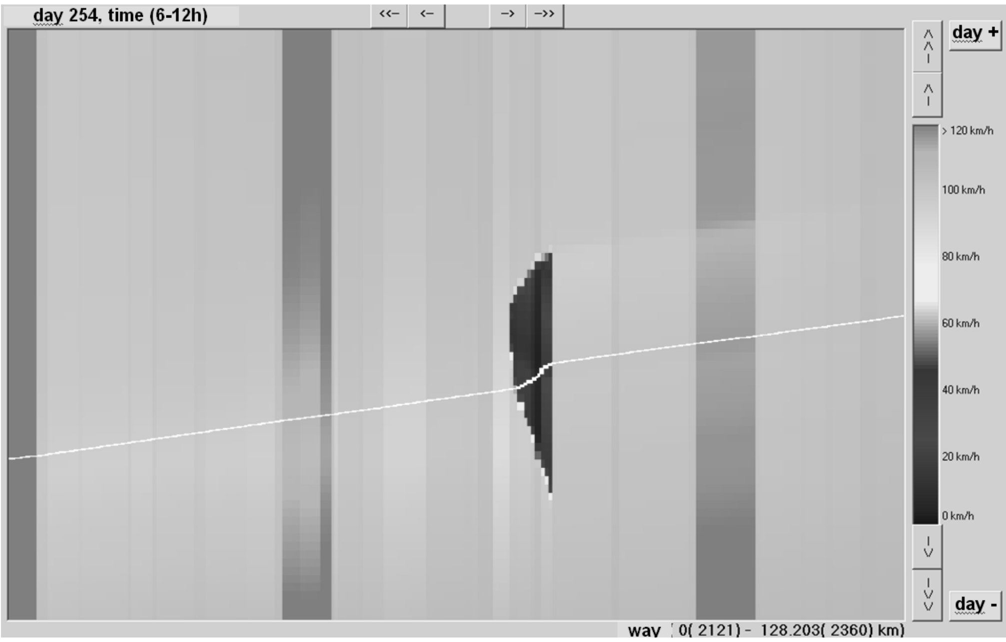


Figure 10 – Simulated speed in a selected time-way domain and the trajectory of a single vehicle traveling through a part of the network

	Namenfeld	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	day	Mean travel time		Total travel time		Traffic efficiency		Total time spent in cong.		Mean time spent in cong.		Total lost time		Mean lost time		Congestion
2		(s/km/veh)		(mill. veh*h)		(mill. veh*km)		(mill. veh*h)		(s/km/veh)		(mill. veh*h)		(s/km/veh)		(km*h)
3		Car	Lkw	Car	Truck	Car	Truck	Car	Truck	Car	Truck	Car	Truck	Car	Truck	
4	1	31,4	40	7,294	0,69	35,001	2,034	0	0	0	0	0,316	0	1,4	0	0
5	2	31,9	40	9,081	1,527	42,053	4,503	0,001	0	0	0	0,547	0	1,9	0	0,3
6	3	31,9	40	8,913	1,693	41,258	4,993	0,008	0	0	0	0,538	0	1,9	0	1,2
7	4	31,9	40	8,916	1,699	41,263	5,009	0,006	0	0	0	0,539	0	1,9	0	1
8	5	32	40	9,722	1,639	44,726	4,832	0,001	0	0	0	0,615	0	2	0	0,2
9	6	31,4	40	7,3	0,807	34,915	2,38	0	0	0	0	0,328	0	1,4	0	0
10	7	31,3	40	6,397	0,587	30,781	1,731	0	0	0	0	0,269	0	1,3	0	0
11	8	32,1	40	9,495	1,785	43,476	5,263	0,011	0,001	0	0	0,622	0	2,1	0	1,9
12	9	32,2	40	9,531	1,964	43,413	5,792	0,012	0,001	0	0	0,647	0	2,2	0	2,1
13	10	32,2	40	9,713	1,916	44,258	5,648	0,015	0,001	0	0	0,658	0	2,2	0	2,3
14	11	32,3	40	10,203	2,036	46,243	6,003	0,008	0,001	0	0	0,717	0	2,3	0	1,3
15	12	32,4	40	11,361	1,92	51,036	5,66	0,008	0	0	0	0,845	0	2,4	0	1,4
16	13	31,5	40	7,73	0,922	36,776	2,718	0	0	0	0	0,366	0	1,5	0	0
17	14	31,4	40	6,986	0,659	33,441	1,945	0	0	0	0	0,311	0	1,4	0	0
18	15	32,3	40	10,601	1,945	47,854	5,734	0,015	0,001	0	0	0,765	0	2,3	0	2,9
19	16	32,4	40	10,565	2,052	47,546	6,046	0,035	0,002	0,1	0	0,777	0,001	2,4	0	4,3
20	17	32,5	40,1	10,635	2,064	47,632	6,067	0,116	0,008	0,4	0,2	0,806	0,003	2,5	0,1	10
21	18	32,3	40	10,255	1,981	46,485	5,843	0	0	0	0	0,72	0	2,3	0	0,4
22	19	32,6	40	12,212	2,017	54,096	5,935	0,064	0,005	0,2	0,1	0,987	0,002	2,6	0	6,6
23	20	31,6	40	8,111	0,976	38,39	2,879	0	0	0	0	0,404	0	1,6	0	0
24	21	31,4	40	7,062	0,687	33,74	2,026	0	0	0	0	0,321	0	1,4	0	0
25	22	32,6	40,2	11,107	2,018	49,232	5,904	0,24	0,02	0,7	0,4	0,895	0,008	2,6	0,2	20,7
26	23	32,7	40,2	10,939	2,138	48,265	6,25	0,297	0,024	0,9	0,4	0,904	0,01	2,7	0,2	28,4
27	24	32,4	40	10,824	2,005	48,648	5,911	0,016	0,001	0	0	0,802	0	2,4	0	5,3
28	...	...														
29	357	31,5	40	7,529	0,689	35,834	2,031	0	0	0	0	0,355	0	1,5	0	0
30	358	31,4	40	6,884	0,739	33,025	2,179	0	0	0	0	0,299	0	1,4	0	0
31	359	31,4	40	7,311	0,794	34,91	2,342	0	0	0	0	0,334	0	1,4	0	0
32	360	31,6	40	7,781	0,731	36,871	2,155	0	0	0	0	0,384	0	1,6	0	0
33	361	31,8	40	8,767	1,429	40,838	4,213	0	0	0	0	0,503	0	1,8	0	0
34	362	31,9	40	9,409	1,402	43,558	4,134	0,002	0	0	0	0,568	0	1,9	0	0,5
35	363	31,5	40	7,608	0,782	36,179	2,307	0	0	0	0	0,363	0	1,5	0	0
36	364	31,3	40	6,198	0,547	29,883	1,614	0	0	0	0	0,255	0	1,3	0	0
37	365	31,4	40	6,927	0,764	33,169	2,253	0	0	0	0	0,307	0	1,4	0	0
38	sum	32,5	40	4145,089	683,979	18520,753	2014,202	15,197	1,233	0,1	0,1	318,587	0,512	2,5	0	2217,1

Figure 11 – Assessment of the total network over a year

LONG-TERM SIMULATION

The implemented network (ca. 2000km freeways) is simulated for a whole year. The result of the simulation is compared to the measured flow dada and to the recorded total duration of congestions in the whole year within the network. The capacities of the single freeway sections are first calculated according to the German Highway Capacity Manuel (HBS2001, FGSV 2001). Because the capacities given in the HBS2001 are hourly average values and the results of the simulation are average values for 5-min intervals, a factor $f_{HBS} > 1$ must be applied to the HBS capacities in order to convert the hourly capacities from the HBS to the simulated 5-min capacities. For calibrating the implemented network, three values for the factor f_{HBS} are investigated ($f_{HBS} = 1.275$, $f_{HBS} = 1.20$ und $f_{HBS} = 1.15$).

The interval of updating is selected to 4s. The lengths of the cells are between 150m and 500m. The simulation is conducted on a PC with 4 processors. A single run of the simulation (2000 km network, 1 year in the reality) takes ca. 22h. The simulated parameters for the traffic quality are illustrated in Table 1.

Table 1 – Simulated parameters of the whole network over a year

	Variation of the parameter f_{HBS}		
	f_{HBS}=1.275	f_{HBS}=1.20	f_{HBS}=1.15
Lost time [veh*h]			
car	332.4	499.6	620.1
truck	2.866	5.828	18.32
Cost [mill. €]			
car	1867.9	2807.8	3484.7
truck	82.66	168.1	528.4
Congestion [h*km]	11071.6	19906.1	54679.2
Time spent in congestion [mill. h]			
car	62.42	111.0	350.2
truck	5.452	9.765	29.67

It turned out, that the results with $f_{HBS} = 1.15$ are the most comparable to the reality. Thus, this value is recommended for simulation studies in the future.

CONCLUSIONS

In order to assess traffic quality of large networks over a long time, a macroscopic simulation model is developed and implemented. This macroscopic simulation model is developed according to the principle of the so-called Cell Transmission Model but it consists of significant extensions. The simulation results show, that it is able to simulate a large network over a long time on personal computers. Thus, a long-term traffic analysis of a large network is now possible. Therefore, the risk of disturbance of traffic flow and the severeness of the disturbance in a large freeway network can be estimated and analyzed over a long time period. The reliability of a freeway network and thus the economical and ecological impact of traffic congestions can be quantitatively estimated. The presented methodology provides also possibilities for assessments of work-zone, incidents, and measures of traffic management.

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