Reconstruction Quality of Congested Freeway Traffic Patterns from Probe Vehicles Based on Kerner's Three-Phase Traffic Theory

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***Abstract*—This paper discusses the reconstruction quality of spatio-temporal congested freeway traffic patterns depending on the information provided by different equipment rates of probe vehicles. Vehicles in spatio-temporal congested traffic patterns experience a sequence of accelerations and decelerations. To enable vehicles and vehicular assistance applications to react on the traffic conditions, high quality traffic information is required, i.e. a high quality reconstruction of spatio-temporal congested traffic patterns. The paper uses Kerner's three-phase traffic theory which distinguishes two different phases in congested traffic: synchronized flow and wide moving jam. This theory explains empirical traffic breakdown and resulting spatio-temporal congested traffic patterns. In the presented approach spatio-temporal congested traffic patterns are reconstructed from intelligent probe vehicle information generated by an onboard traffic state detection, identifying traffic states along a vehicle's trajectory at any time. With a data fusion algorithm combining the data of several probe vehicles a detailed picture of spatio-temporal congested traffic patterns is revealed. The quality of the reconstructed congested traffic patterns is assessed by introducing quality indices for (i) travel time, (ii) regions of synchronized flow and wide moving jams as well as (iii) fronts of synchronized flow and wide moving jams. The indices are evaluated by examining a congested traffic pattern with varying probe vehicle equipment rates. Comparing ground truth with the reconstructed traffic pattern shows that a reconstruction quality sufficient for some ITS applications is achievable with probe vehicle equipment rates of about 0.50 %.**

***Keywords*-Traffic monitoring; Traffic state detection; Traffic data fusion; Three-phase traffic theory; Traffic data quality**

I. INTRODUCTION

Nowadays congested traffic on highways is still a major problem with severe implications for personal life and the economy. In recent years congested traffic data was mostly gathered with stationary loop detectors. It is expensive to equip a road network with detectors of high quality and small detector distance. Recent progress in mobile communication technology, like WLAN and 3G/UMTS, allows traffic data to be gathered by probe vehicles. This paper tries to answer the question how many probe vehicles are needed to deliver a quality of traffic data comparable to a dense, high quality detector network.

At first Kerner's Three Phase Traffic Theory and its impact on vehicles is described. Then the proposed method for traffic pattern reconstruction and quality indices are introduced. The paper closes with results and conclusion.

II. KERNER'S THREE PHASE TRAFFIC THEORY

A. Elements of Three Phase Traffic Theory

Based on extensive traffic data analyses of available stationary detector measurements spanning several years Kerner discovered that in addition to free flow (F) two different traffic phases must be differentiated in congested freeway traffic: synchronized flow (S) and wide moving jam (J) ([1], [2]). Empirical macroscopic spatio-temporal objective criteria for traffic phases as elements of Kerner's three-phase traffic theory ([1], [2]) are as follows:

1) A wide moving jam is a moving jam that maintains the mean velocity of the downstream jam front, even when the jam propagates through any other traffic state or freeway bottleneck.
2) In contrast, the downstream front of the synchronized flow phase is often fixed at a freeway bottleneck and does not show the characteristic features of wide moving jams.

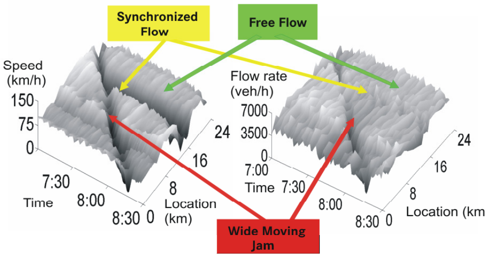

Figure 1. Explanation of traffic phase definitions from empirical data: Spatio-temporal overview of speed (left) and flow rate of traffic (right) on a selected freeway section

However, neither the observation of speed synchronization in congested traffic nor other relationships and features of congested traffic measured at specific freeway locations

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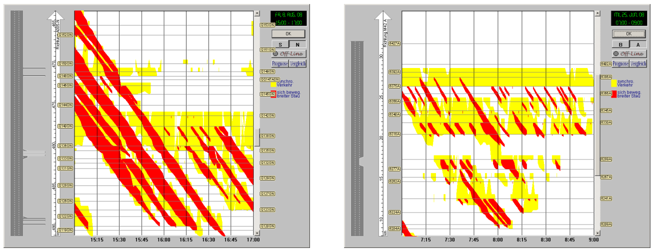
(e.g., in the flow-density plane) are a criterion for the phase differentiation. The clear differentiation between the synchronized flow and wide moving jam phases can be made on the above objective criteria 1) and 2) only.

Figure 1 illustrates a vehicle speed and flow profile over time and space based upon real measured traffic data. A wide moving jam propagates upstream as a *low speed valley* through the freeway stretch. In contrast, a second speed valley is fixed at the bottleneck location: this congested traffic phase belongs to the synchronized flow phase.

B. *Spatio-Temporal Congested Traffic Patterns*

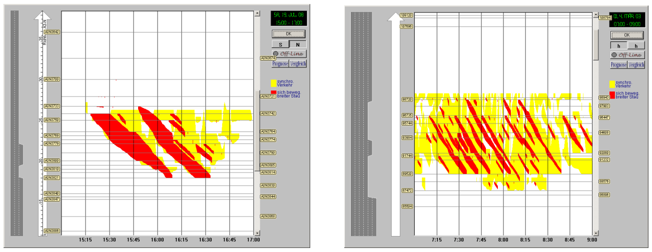
The distribution of traffic phases over time and space on a road represents a spatio-temporal congested traffic pattern. Kerner's three-phase traffic theory is able to explain all empirically measured traffic patterns on various roads in many different countries. For recognition, tracking and prediction of the spatio-temporal congested traffic patterns, based on stationary loop detectors, the models ASDA (Automatische Staudynamikanalyse; automatic congestion analysis) and FOTO (Forecasting of Traffic Objects) ([1], [2]) have been proposed by Kerner based on the key elements of the theory.

Nowadays the models ASDA and FOTO are deployed in the federal state of Hessen and in the free state of Bavaria where they perform online processing of data. In addition they have been successfully used in a laboratory environment on the M42 near Birmingham, UK and the I-405 in California, USA (Figure 2).



Stable structures on A5 in Hessen

Expanded pattern - M42 UK



A3 in Northern Bavaria

I405 in Orange County (LA) - USA

Figure 2. Resulting empirical spatio-temporal traffic patterns when applying the models ASDA and FOTO to traffic data measured in different countries [6]

III. IMPACTS FOR VEHICLES AND VEHICULAR ASSISTANCE APPLICATION

Vehicles driving through a spatio-temporal congested traffic pattern experience a number of traffic state changes. A traffic state change represents a unique and exact position in time and space where the traffic phase changes, e.g., from free flow to wide moving jam. It is experienced at any position, where a vehicle hits the upstream or downstream front of a region of a traffic phase. In contrast a traffic phase transition represents the start point or the end point, respectively, of a traffic phase and occurs only twice for each region of a traffic phase (see figure 3).

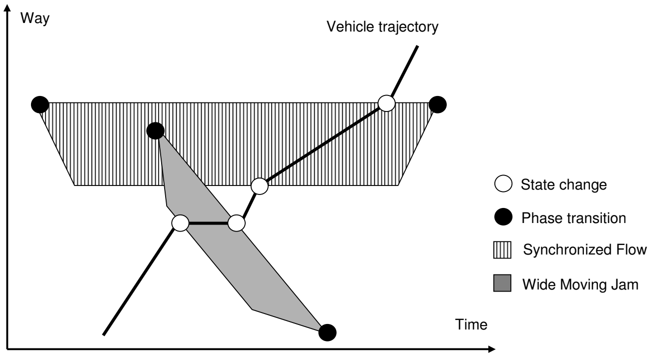


Figure 3. Qualitative explanation of traffic phase transitions and traffic state changes a vehicle experiences on its way through a spatio-temporal congested traffic pattern

Traffic state changes between the different traffic phases have impacts of different strength on the vehicle and vehicular assistance applications. Two of the most distinguishing parameters of different traffic phases from a vehicle's perspective are the vehicle speed v and the vehicle density ρ. Both parameters influence the ability of the vehicles to choose their driving speed as well as the possibility for them to overtake other vehicles and to freely choose their driving lane. Different traffic state changes have a different effect on the value of these parameters. Table I and table II show the expected changes for the possible speed v and the vehicle density ρ, respectively.

State	to F	to S	to J
F	-	Deceleration	Strong deceleration
S	Acceleration	-	Deceleration
J	Strong acceleration	Acceleration	-

Table I
VEHICLE SPEED: CHANGE DEPENDING ON SPECIFIC TRAFFIC STATE TRANSITIONS

State	to F	to S	to J
F	-	Increase	Strong increase
S	Decrease	-	Increase
J	Strong decrease	Decrease	-

Table II
VEHICLE DENSITY: CHANGE DEPENDING ON SPECIFIC TRAFFIC STATE TRANSITIONS

Vehicular assistance applications, like adaptive cruise control or hybrid engine control depend on and benefit from the knowledge of the current and in some cases future values of these parameters, as each traffic state change represents a control and parameter adaption point for these applications.

IV. TEST AND SIMULATION ENVIRONMENT

The Kerner-Klenov microscopic three-phase traffic model ([1], [2]) has been used for the generation of a large number of single vehicle trajectories. As input data for the model a description of the simulated track as well as initial starting conditions of speed and flow at the most upstream border are required. All other areas in space and time are governed by the Kerner-Klenov model. The microscopic model's output can be regarded as a realization of *ground truth* which is qualitatively comparable to spatio-temporal congested traffic patterns measured on highways ([1], [2]).

Ground truth means that the model output represents the reference information or the *reality* which should be reconstructed by the vehicle trajectories. Quality is therefore measured as the difference between ground truth and the cooperative reconstruction of spatio-temporal congested traffic patterns based on the generated trajectories.

First a traffic state detection is performed in each virtual vehicle, in order to detect all traffic state changes this virtual vehicle experiences. After that all traffic state changes are combined to a reconstructed congested traffic pattern by applying a clustering algorithm. It combines the autonomously detected traffic state changes of several probe vehicles to a collective and cooperatively reconstructed traffic pattern (see figure 4).

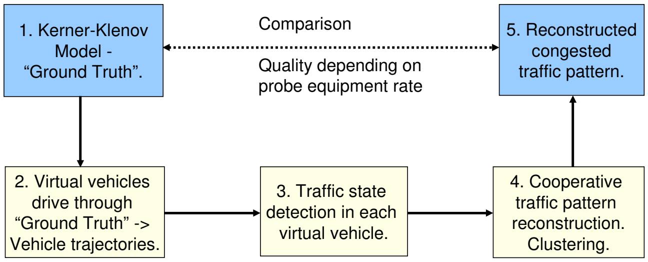


Figure 4. Steps necessary for probe equipment rate investigations

A. *Traffic State Detection in Autonomous Vehicle*

Instead of stationary loop detectors, probe vehicle data is used for the detection and reconstruction of spatio-temporal congested traffic patterns. Many systems using probes transmit only aggregated travel times for pre-defined road sections. Here we are not only interested in the travel time losses caused by spatio-temporal congested traffic patterns, but also in their detailed structure (figure 3, [1], [2]).

In Kerner's three-phase traffic theory there is one phase of free flow (F) and two phases of congested traffic, synchronized flow (S) and wide moving jam (J). Each traffic pattern consists of a unique formation and behavior of regions in time and space belonging to exactly one of these three phases. One of these three phases is assigned to each of the probe positions in time and space in an autonomous way ([2], [3]). A traffic state change is performed when the chosen measured values are above or below specific thresholds in speed and time, which are chosen according to microscopic traffic criteria [2].

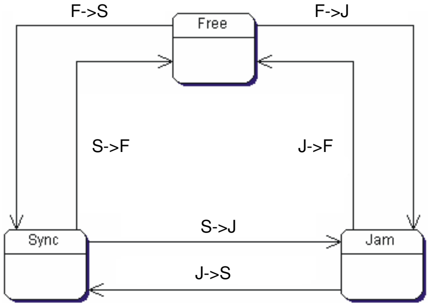


Figure 5. State diagram for three traffic phases [3]

B. *Cooperative Reconstruction of Spatio-Temporal Congested Traffic Patterns*

For the reconstruction of spatio-temporal congested traffic patterns a clustering algorithm is employed. First the traffic phase is identified, then depending on the identified traffic phase, an algorithm tailored for the specific characteristic features of the synchronized flow and wide moving jam traffic phases is applied as shown in figure 6.

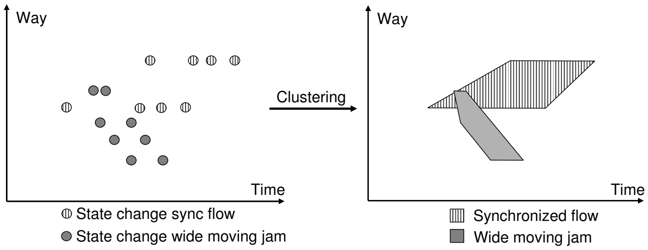


Figure 6. Using clustering to reconstruct traffic patterns from traffic state changes [6]

V. RECONSTRUCTION QUALITY INDICES

In order to assess the quality of reconstructed spatio-temporal congested traffic patterns, the reconstructed pattern is compared with a ground truth version of this pattern, which represents the best known information about this particular situation. Ground truth traffic patterns are either directly measured with high quality detection systems or generated by a suitable simulation environment as described above. Common to both approaches is that the ground truth information with the highest possible quality is a continuous information in both time and distance.

A continuous traffic reality assigns a traffic state TS to each spatio-temporal position $P(x, t)$, whereas x represents

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a continuous value in distance and t a continuous value in time. The traffic reality R represents the combination of all

$$TS(x,t) \in \{F,S,J\} \tag{1}$$

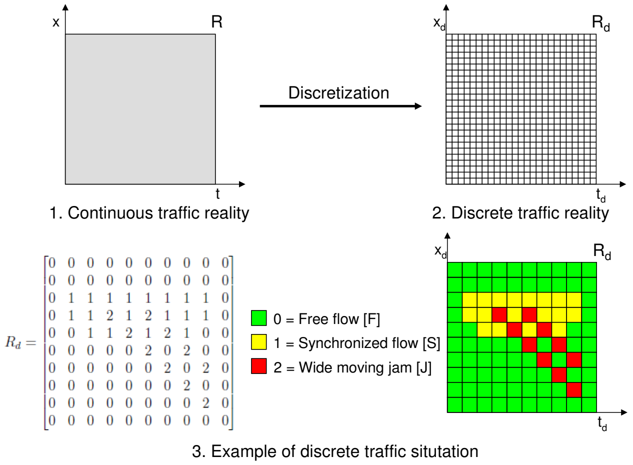
within the borders x and t, hence

$$R := \{TS(x,t) | x_s \leq x \leq x_e \wedge t_s \leq t \leq t_e\} \tag{2}$$

Compared to R a reconstruction of traffic patterns using a model M in most cases shows deviations in time and space. The quality Q of the reconstruction is given by the deviation D between M and R. Hence

$$M := \{TS(x,t) | x_s \leq x \leq x_e \wedge t_s \leq t \leq t_e\} \tag{3}$$

$$Q = D_{M \rightarrow R} \tag{4}$$



1. Continuous traffic reality

2. Discrete traffic reality

$$R_d = \begin{bmatrix} 0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0\\ 0&1&1&1&1&1&1&1&1&0\\ 0&1&1&2&1&2&1&1&1&0\\ 0&0&1&1&2&1&2&1&0&0\\ 0&0&0&0&0&2&0&2&0&0\\ 0&0&0&0&0&0&2&0&2&0\\ 0&0&0&0&0&0&0&2&0&0\\ 0&0&0&0&0&0&0&0&2&0\\ 0&0&0&0&0&0&0&0&0&0 \end{bmatrix}$$

3. Example of discrete traffic situtation

Figure 7. Discretization of spatio-temporal congested traffic patterns

Currently, it is difficult to measure, store and process continuous spatio-temporal information. Therefore, usually discrete values are used, which average time and distance in discrete intervals. Consequently x and t degrade to the discrete values x_d and t_d. Their resolution represents the quality of knowledge about the spatio-temporal information. Using x_d and t_d the continuous traffic reality R becomes the discrete traffic reality R_d as shown in figure 7.

$$\begin{aligned} R_d := \{TS_d(x,t) | x_s \leq x_0, x_1 ... x_n \leq x_e \\ \wedge t_s \leq t_0, t_1 ... t_n \leq t_e\} \end{aligned} \tag{5}$$

In order to determine the discrete quality Q_d a discrete model output M_d with the same spatial and temporal resolutions x_d and t_d is required. For Q_d this leads to

$$Q_d = D_{M_d \rightarrow R_d} \tag{6}$$

In the following a reconstruction is used synonymously with a model M_d while the known ground truth information used as a comparison reference is used synonymously with the reality R_d (see figure 8).

A. Quality Index for Regions of Synchronized Flow and Wide Moving Jam

The quality index for regions of a specific traffic phase assesses the general reconstruction quality between M_d and R_d. For each congested traffic phase the spatio-temporal areas they cover are compared against each other with regard to hits and false alarms. Figure 8 illustrates this concept, which is an adaption of the ROC (Receiver operating characteristic) analysis of traffic data presented in [7] and [8] to traffic data containing three distinct traffic phases.

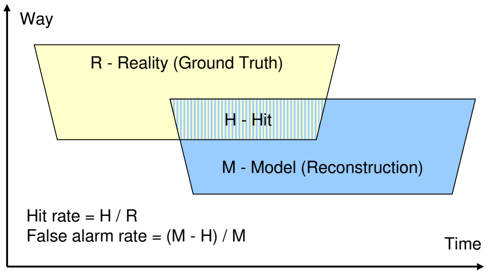


Figure 8. Definition of the Quality Index for Regions of Synchronized Flow and Wide Moving Jam

The definitions of M_d and R_d given in the previous section can directly be applied to yield a computationally efficient calculation of this quality index. For both M_d and R_d three binary matrices are calculated, one for each traffic phase, which contain a 1 at all spatio-temporal positions where a specific traffic phase occurs and a 0 at all other positions.

For R_d this leads to R_d^F, R_d^S and R_d^J and for M_d to M_d^F, M_d^S and M_d^J respectively. Using a row vector r_v and a column vector c_v with correct dimension for M_d and R_d with all $a_{ij} = 1$ allows to count the number c of elements a_{ij} within matrix A for which $a_{ij} = 1$.

$$c = r_v * A * c_v \tag{7}$$

Using this operation leads to the quality index for hits in regions of synchronized flow,

$$H_{Sync} = \frac{r_v * (M_d^S \wedge R_d^S) * c_v}{r_v * R_d^S * c_v} \tag{8}$$

the quality index for false alarms in regions of synchronized flow,

$$F_{Sync} = \frac{r_v * (M_d^S \wedge R_d^J + M_d^S \wedge R_d^F) * c_v}{r_v * M_d^S * c_v} \tag{9}$$

the quality index for hits in regions of wide moving jam,

$$H_{Jam} = \frac{r_v * (M_d^J \wedge R_d^J) * c_v}{r_v * R_d^J * c_v} \tag{10}$$

and the quality index for false alarms in regions of wide moving jam.

$$F_{Jam} = \frac{r_v * (M_d^J \wedge R_d^S + M_d^J \wedge R_d^F) * c_v}{r_v * M_d^J * c_v} \tag{11}$$

All of these quality indices yield a number between 0 and 1, whereas 0 represents the minimum value and 1 the maximum value.

B. Quality Index for Travel Time

For each point in time t the total travel time T_{total}, consisting of free flow travel time and congested travel time, can be calculated as shown in [4]

$$T_{total}(t) = \frac{L_F(t)}{v_F(t)} + \frac{L_J(t)}{v_J(t)} + \frac{L_S(t)}{v_S(t)} \tag{12}$$

where $L_F(t)$, $L_S(t)$ and $L_J(t)$ represent the lengths of the traffic phases and $v_F(t)$, $v_S(t)$ and $v_J(t)$ represent the average speeds within these phases at time t. The relative average deviation ΔT between the travel time reported by the reconstruction T_M and the travel time T_R reported by the reference ground truth information is now given by [5].

$$\Delta T = \frac{1}{N} \sum_{t=1}^{N} \frac{|T_M(t) - T_R(t)|}{T_R(t)} \tag{13}$$

As a result ΔT is a number ≥ 0, whereas a result of $\Delta T = 0$ represents the best possible quality.

C. Quality Index for Fronts of Synchronized Flow and Wide Moving Jam

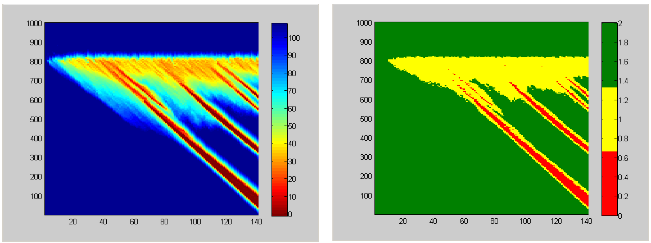
The quality index for fronts of synchronized flow and wide moving jam calculates the average deviation for each point in time t.

The deviation is calculated between the front position reported by the model M and the front position reported by the ground truth information R for both the upstream and downstream front. This results in Δup and $\Delta down$ respectively.

$$\Delta up = \frac{1}{N} \sum_{t=1}^{N} |pos_M^{up}(t) - pos_R^{up}(t)| \tag{14}$$

$$\Delta down = \frac{1}{N} \sum_{t=1}^{N} |pos_M^{down}(t) - pos_R^{down}(t)| \tag{15}$$

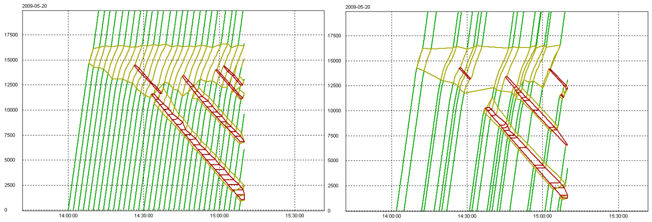
Again both Δup and $\Delta down$ give a result ≥ 0 m whereas a result of 0 m represents the best possible quality.



Speed

Traffic State

Figure 9. Kerner-Klenov simulation output of a general pattern - Ground Truth



0.75% probe density, uniformly distributed

0.50 % probe density, randomly distributed

Figure 10. Example results for uniform and random distributions of probe vehicles

VI. RESULTS

A. Examined Situation

For evaluation the Kerner-Klenov three-phase microscopic model was used to simulate a spatio-temporal congested traffic pattern. The simulation was configured to simulate a 20 km highway stretch with 2 lanes and one on-ramp. By increasing the incoming flow an on-ramp bottleneck was established, leading to an $F \rightarrow S$ traffic breakdown and the formation of a region of synchronized flow. Within the synchronized flow region several wide moving jams emerged (figure 9).

Example results of the traffic state detection and clustering processing based on probe vehicle data are shown in figure 10. In the following the quality index results of this process are compared with results of the ASDA/FOTO models. ASDA/FOTO was used with a high quality stationary loop detector network having detector distance of 1-2 km.

B. Quality Index for Regions of Synchronized Flow and Wide Moving Jam

Method	Det./Veh.	H_{Sync}	F_{Sync}	H_{Jam}	F_{Jam}
ASDA/FOTO	1 km Det. dist.	0.83	0.12	0.81	0.24
ASDA/FOTO	2 km Det. dist.	0.77	0.16	0.65	0.25
Probe Veh.	1.50 % uniform	0.89	0.17	0.83	0.24
Probe Veh.	0.38 % uniform	0.82	0.24	0.73	0.21
Probe Veh.	0.50 % random	0.78	0.21	0.72	0.22

Table III
QUALITY INDEX RESULTS FOR DIFFERENT METHODS AND DETECTOR DISTANCES / PROBE EQUIPMENT RATES

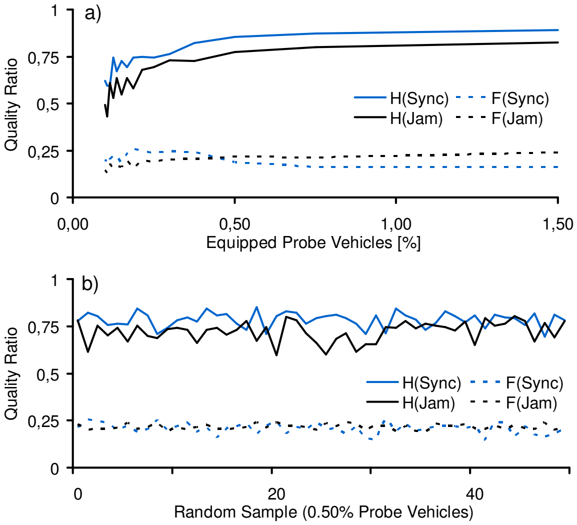


Figure 11. Quality index results for uniform (a) and random (b) probe vehicle distributions

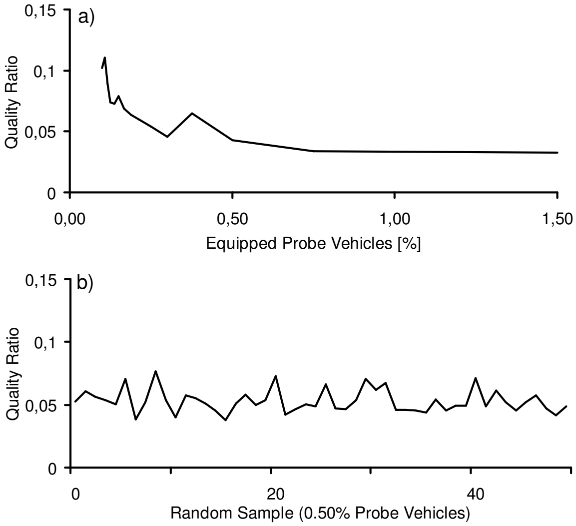


Figure 12. Travel time quality index results for uniform (a) and random (b) probe vehicle distributions

Table III and figure 11 show that the results of the region quality index for a equipment rate of 0.38 % uniformly distributed as well as a equipment rate of 0.50 % randomly distributed are comparable to the established ASDA/FOTO method using detector distances between 1-2 km.

C. *Quality Index for Travel Time*

Method	Det./Veh.	ΔT
ASDA/FOTO	1 km Det. dist.	0.038
ASDA/FOTO	2 km Det. dist.	0.061
Probe Veh.	1.50 % uniform	0.033
Probe Veh.	0.38 % uniform	0.065
Probe Veh.	0.50 % random	0.053

Table IV
TRAVEL TIME QUALITY INDEX RESULTS FOR DIFFERENT METHODS AND DETECTOR DISTANCES / PROBE EQUIPMENT RATES

The travel time quality index confirms the results of the region quality index (see table IV and figure 12).

VII. CONCLUSION

Probe vehicle equipment rates of 0.38 % uniformly distributed and 0.50 % randomly distributed processed with the proposed method are comparable to detectors with distances of 1-2 km processed with the existing system ASDA/FOTO. In addition the proposed method promises the provision of high quality traffic data on all highways while existing systems rely on stationary loop detectors. Higher probe vehicle equipment rates promise an even higher quality traffic data suitable for future ITS and vehicular assistance applications. Subjects of further ongoing research are the evaluation of the quality index for fronts of synchronized flow and wide moving in combination new vehicular assistance applications as well as system communication and architecture alternatives.

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REFERENCES

[1] B. S. Kerner, *The Physics of Traffic* Berlin, New York: Springer, 2004.

[2] B. S. Kerner, *Introduction to Modern Traffic Flow Theory and Control* Berlin, New York: Springer, 2009.

[3] B. S. Kerner, S. L. Klenov, J. Palmer, M. Prinn and H. Rehborn, *German Patent Publication DE 10 2008 003 039 A1, 2008.*

[4] H. Rehborn and J. Palmer, *ASDA/FOTO based on Kerner's Three-Phase Traffic Theory in North Rhine-Westphalia and its Integration into Vehicles* 2008 IEEE Intelligent Vehicles Symposium, Eindhoven, 2008.

[5] J. Palmer and H. Rehborn, *Reconstruction of Congested Traffic Patterns Using Traffic State Detection in Autonomous Vehicles Based on Kerner's Three Phase Traffic Theory* 16th World Congress on ITS, Stockholm, 2009.

[6] J. Palmer and H. Rehborn, *Vehicular Assistance Applications in the Scope of Kerner's Three-Phase Traffic Theory* Networks for Mobility - 5th International Symposium, Stuttgart, 2010.

[7] K. Bogenberger, *Qualitaet von Verkehrsinformationen* Strassenverkehrstechnik, Kirschbaum Verlag GmbH Bonn, 10:518 - 526, 2003.

[8] S. Lorkowski, *Fusion von Verkehrsdaten mit Mikromodellen am Beispiel von Autobahnen* PhD Thesis, Technical University of Berlin, 2009.