Transportation
Infrastructure Engineering

INTERSECTII
INTERSECTIONS
http://www.ce.tuiasi.ro/intersections

Non-linear effects in traffic simulations

Tomas Apeltauer, Petr Holcner, Martin Kysely and Jiri Macur
Faculty of Civil Engineering, Brno University of Technology, Brno, CZ-602 00, Czech Republic

Summary

Growing requirements on transport of passengers and goods have a principle impact on life and economy. It is not need not intricately needed to search accurate formulation of economic consequences, on the contrary would be enough to quote, for example, United States Secretary of Transportation Norman Mineta, according to which local drivers lose in traffic jams almost 4 billions hours and 2 billions gallons of fuel each year. Upward trend is perceptible especially on highways, where some out of traffic jams affects two-thirds drivers every day, which is double compared to situation twenty years ago.

In Los Angeles at that time transportation problem lasted 4.5 hours every day, about two decade later in the same town transport breaks down for 7 hours every day. It is evident it is not always possible extend capacity carriage according to their users needs and is necessary to search alternative manners. One of these is transition to description of traffic flow via nonlinear dynamics, which explains the behavior of very complicated systems.

If we explain properties of the traffic flow, we can try to describe emergency of traffic jams and search manners, how those situation precede at least in part.

KEYWORDS: non-linear dynamics; traffic flow; congestions; traffic modeling; simulations

1. TRAFFIC CHAOS AS A TECHNICAL TERM

Nonlinear dynamics as a tool for understanding chaos emergency already gets through wide spectra branch. Presently it is perceptible that we cannot apply the clean deterministic look even on very simple system, whereas the meaning of nonlinear system features grows with their complexity. One of such dynamic systems is the traffic flow. A group of German physicists headed by Dirk Helbing, Boris Kerner and Michael Schreckenberg published in top class magazines like *Physical Review Letters, Journal of Physics* and *Nature* results of computer simulations of the vehicle movement. They noticed following interesting matter: while using equations for a gas molecule movement, supplemented by some specific characteristics of the human driver (among others the effort to avoid

ISSN 1582-3024

collision), they discovered special effects which truly copies real characteristics of traffic. For example in places of bottlenecks traffic started compression, whereas this perturbation expands as a density wave against the direction of traffic flow. It is the exact analogy of known retardation and accumulation out in fronts before bottlenecks – as soon as vehicles near bottleneck slow down, other vehicles will slow down too, which causes the wave of “stop-and-go” spreading upstream.

At all the biggest surprise was the following result: the traffic jam can emerge in certain circumstances spontaneously, without bottlenecks, traffic accident or other at first sight obvious causes. Traffic flow is able to flow freely, and nevertheless suddenly will change to the slowly ridden flow. Under certain condition the “negligible” fluctuation in the vehicle velocity or headway can lead to the system collapse, which last for long hours after primary impulse.

In spite of it is relatively cheerless inquest, it is absolutely in agreement with results of mathematical models of many physical and biological systems. All these studied systems have the common emergency of phenomenon known from popular literature as the “chaos”. Simply: in every complex system with many parts which influences each other a weak fluctuations can lead to big consequences. But we cannot predict the emergency of such turnover. Scientists these phenomena describe like non-linear – seemingly unimportant change in one characteristic might have unreasonably extensive incidence on entire system. Non-linear characteristics were detected in weather, biological systems or chemistry. And during recent decades it is also mentioned in transport.

2. REAL TRAFFIC DYNAMICS OBSERVING

Every correct physical theory requires agreement with experimental data. Good theory had to reproduce known system behavior as also predict its future. It will be shown further that selection of the right method for data collection on road is a very idyllic business with comparison to the construction of the right theory.

2.1. Measuring of the traffic variables

Probably the oldest and at the same time most complicated technology of traffic detection is *aerial photography*, by the help of whose we can obtain total view of the situation on tracked section. If we need to obtain concrete traffic variable such as traffic flow velocity, we have to use digital picture analysis. Problems of visual analysis generally belongs to the most complicated tasks, it is very time consuming and not balanced with corresponding result accuracy. Its usage in current traffic research is therefore rather border. But some advantage aerial photograph has further: emergency of traffic jam and its progress is apparent at the first sight.

Transportation
Infrastructure Engineering

INTERSECTII
INTERSECTIONS
http://www.ce.tuiasi.ro/intersections

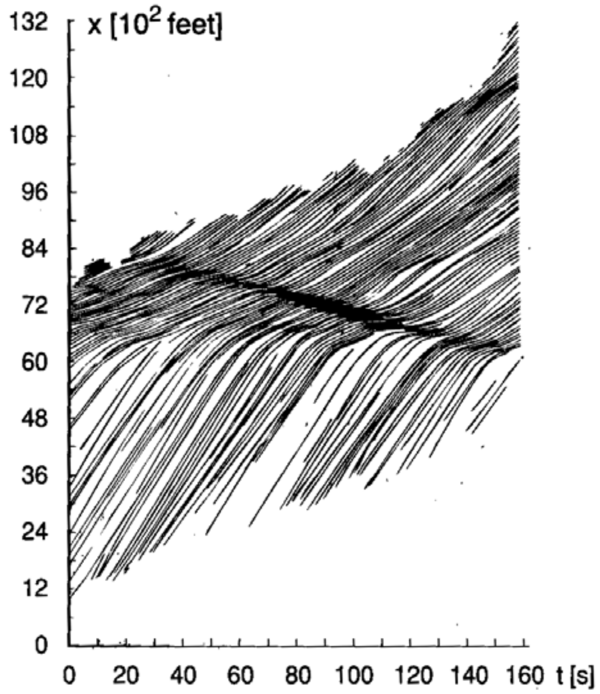

Figure 1. The traffic jam behavior, derived from aerial photography [17].

The second way can be taken with *floating vehicle*, which works as a movable detector. But the biggest data sets are now collected by detectors placed on concrete fixed place on the motorway. Most widespread is the *induction loop* placed closely below the road surface. Incoming vehicle turns its inductance and creates a weak signal.

From a simple induction loop we can obtain especially information about vehicles that passed tracked place during definite time, which matches the definition of *traffic intensity*. Today double induction loops ale placed in the most cases, which make possible to measure in addition vehicle lengths and its velocity. Combination of these values finally makes it possible to determine *traffic density* like second crucial traffic variable. Correlation between traffic intensity and its density is a very basic tool in the traffic research.

2.2. Measurement with induction loops

We can obtain a good notion about possibilities of detection via induction loops from A5-Nord highway nearby German Frankfurt.

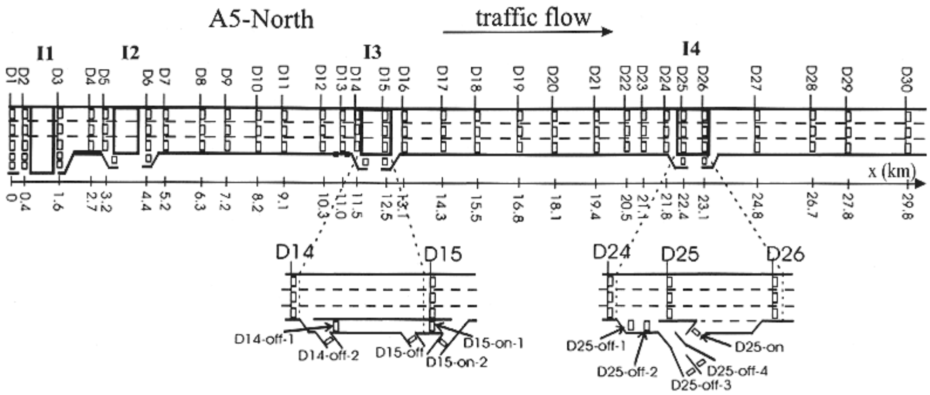

Figure 2. Location of induction loops on the part of A5-Nord highway [5].

Described section of highway has on the whole four intersections which join it on next communications. On that section there are deployed about thirty double induction loops with labels from D1 to D30. Each set of loops includes three detectors for every lane, special cases are slip and trunk roads.

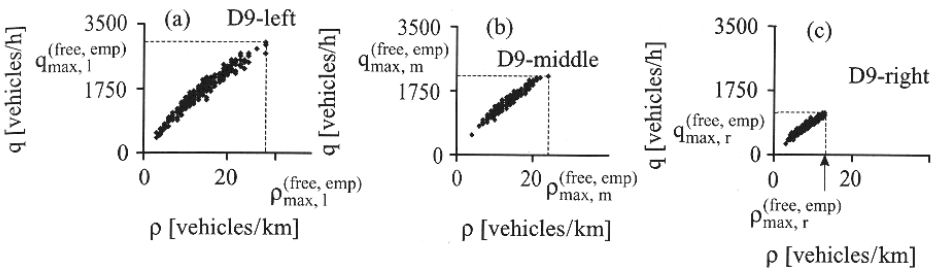

Figure 3. Data collected on A5-Nord highway. We can see one minute averages of traffic densities and intensities from lanes on the place od detector D6. Measurement was on 9th October 1992 between 7.00 – 12.00 [5].

We can see results on selected detectors on fig. 3. Three graphs a) to c) shows the dependence of traffic flow intensity on traffic density for every of the three lanes. How we will see further, in all cases this values correspond to *free traffic flow* and at first sight there are perceptible expressive differences in maximal measured values. Here we have to remark that the on German motorways there is a big asymmetry in vehicle types among lanes. Trucks here usually do not move in the left lane, only use the right one in some cases the middle one for overtaking.

Transportation
Infrastructure Engineering
INTERSECTII
INTERSECTIONS
http://www.ce.tuiasi.ro/intersections

2.3. Free flow and congestions

As mentioned above, there are three basic variables which characterize traffic flow in specific time and place: *traffic density* (number of vehicles in one kilometer), *velocity* (in most cases km.h^{-1}) and *traffic intensity* (number of vehicles which passed specific point in some period of time, one hour generally). It holds in steady traffic flow the traffic intensity is a product of its velocity and density. Unfortunately both these variables are not mutually independent and that is why it is necessary to determine its correlation.

We can start from obvious and empirically tested facts: maximal velocity in traffic flow corresponds to the density near zero, when each one vehicle in not influenced by another one. Then we denote that case as *free traffic flow*. From this we can define *congestion* as a state supplemental to the free flow, which contains some other traffic situations. One of these states is the critical value of density, when the speed of traffic flow drops to zero and the flow moves via small jumps or it stops definitely (headways are too small for safe and useful constant speed). We can see that between the free flow and this critical value the velocity must go down (usually supposed monotonously and continuously). Determination of this dependency is very basic and also very complicated task during investigation of traffic flow.

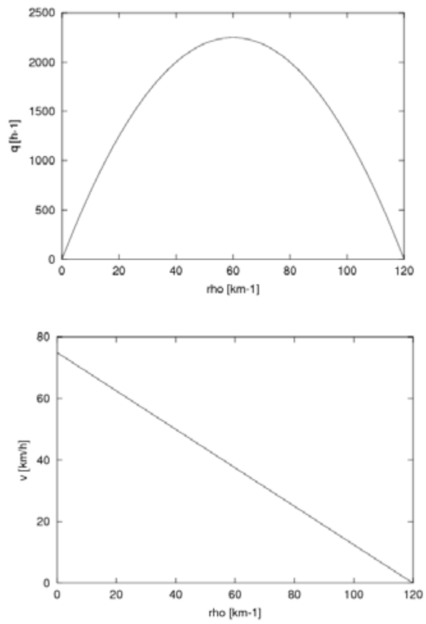

Figure 4. Basic and very simple traffic model according to Greenshields, which comes from strictly linear velocity-density dependency. Maximal traffic intensity is reached in middle velocity for this model.

2.3. Fundamental diagrams

The basic instrument for description of steady flow and its global properties is the fundamental diagram. Its most common type describes dependency of the traffic intensity on the traffic density. In is not obvious from diagram itself that the key correlation between density and velocity is uncertain and efforts to determine it precisely were not successful yet. Nevertheless we can some derive some basic characteristic also from empirically gained average values of traffic quantities. We can use for demonstration data from A5-Nord again (fig. 5).

Contrary from previous entry are now showed all measured values which clearly apportioned into two independent groups. Left part graph appertain to already discussed free flow, the right pat to congestions. The waveform corresponds to reality, when the traffic intensity is able to growth almost linear as far as to the certain critical value. Then be enough so ever minor perturbation to switch free stream into congestion. Traffic density nevertheless doesn't need to necessarily growth and may even temporarily tail off. We can see again the phenomenon of sudden emergency of traffic jams at the same time key feature of complicated systems.

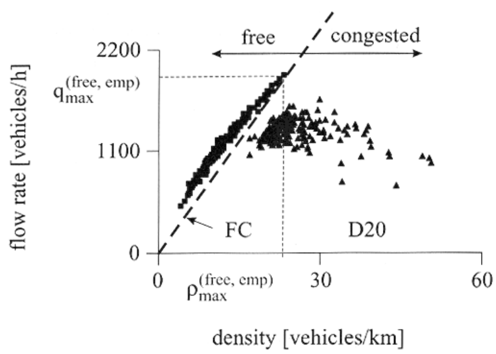

Figure 5. Fundamental diagram of traffic flow, gained from one minute averages traffic density and intensity. Data was collected on A5-Nord on 23. March 2001 between 9.00 - 15.00 via detector D20, it is an average from all three lanes [5].

3. TRAFFIC FLOW SIMULATIONS

It is possible to see dynamic properties of traffic also through the numerical simulation. We have to create a model, which truly describes vehicle behavior and at the same time won't contain unbearable quantity of parameters. As well it is necessary to choose a good simulation method which generates results in a good time. We will present methods at first.

ISSN 1582-3024

Transportation
Infrastructure Engineering
INTERSECTII
http://www.ce.tuiasi.ro/intersections
INTERSECTIONS

Till this time plentifully used access are *cellular automata*. Its principle is in dividing the motorway to the finite count of blocks and each block in each computation step contains or does not contain just one vehicle. That is why are cellular automata extreme discreet and then only crudest approximation of the real situation which is balanced by high simulation speed and low hardware exigencies.

Analog models as an opposite access have slow entrance only in last years. In contrast to cellular automata it works with vehicles, which are equipped with moving equations. Evolution of this model looks as moving of bubbles in narrow pipe for example. The model behavior is more realistic but also much more time-consuming for computational time.

Cellular automata were used for investigation of traffic flow at the beginning of wider focus to this problem. The main reason was relatively low level of computers and quite good results of this model. Especially the first reason is not actual in last years.

Together with choosing of good method we have to find a good model. This situation is much more transparent, because two main groups of models have difference in the basic principle.

We can consider the traffic flow as a complicated system with separated vehicles. Each vehicle is defined by its features and the main one is dependency between acceleration and the situation around the vehicle. Some used algorithms try to Describe observed properties of a real traffic flow (dynamics, physiological and psychological ability of a driver). These models are known as *microscopic*.

Macroscopic access assume with traffic flow as a continuum defined by the common presumptions. These can be derived by inference from border conditions, measured values in real flow may be based on analogies with physical phenomena, for example from fluxion liquids or gas.

It is often used the third combine approach, when the characteristics macroscopic features are derived from integration of microscopic transport models and presumptions about fluctuations.

The main advantage of the macroscopic access is the ability to describe evolution of traffic flow by one or more differential equations. Is however debatable, if is this presumption of possibilities this unification lawful – analytical complication and venture of this access appears to be also heavy cost behind aesthetics of classical theory.

Users of microscopic models on the other hand can get round of the danger of complicated equations. But it is not all, they early snarl up on crossroad of necessary numeral definition of this model pivotal parameters. About the uncertainty generally witnesses for example historical survey of 23 models defined by “safe distance from previous vehicles in dependency of its speed” and "responding time" [1]. Response time is between 0 – 2 s, its arithmetic mean is 0.78 s. The maximal value of traffic intensity is 1050 – 4800 vehicles per hour, with the realistic average 2050 vehicles per hour. The vehicle speed, at which is achieved full intensity, is between 10.6 – 55.2 kmh^{-1}, in some cases even growth to infinity (virtually it is necessary to consider about technical or legislative limit). The average (without infinite values) is 29.0 km.h^{-1}. Arithmetic mean itself do not give any help – rather only underscore frustrating motley of models, from which only little is unusable and unfortunately till this time any model is not implicitly good. Perhaps that is just it at projection and scheduling communication meanwhile dominates experiential access, which does not consider behavior inside traffic flow.

3.1. Car following models

Vehicle-following models, exactly Car Following Models (CFM) are investigated nearly for a half century. Determination of the dependency of vehicle acceleration on traffic conditions is in this case fundamental – in the simplest case just on the condition of the previous vehicle (the vehicle driving before). In spite of the fact that this task may appear at the first sight trivial, we did not manage to find a generally respected model which would reflect the reality and would be at the same time sufficiently compact, transparent and especially reasoned until today.

Thus certain general demands were accepted which would meet this proposal without the apparent internal connection of the model with reality. Among these "outer" demands belong especially:

- Non-collision character of simulations performed in the whole spectrum of possible parameters and initial conditions.
- Physically reasonable values of the vehicle velocities and accelerations in course of simulation.
- Asymmetrical character of the model – acceleration different from deceleration (usually a stronger deceleration is admissible, e.g. in case of a threatening collision).
- Emergency of global conditions corresponding to the real observation – non linear character of the model (waves "stop and go", spontaneous emergency of congestions in case of above critical densities, hysteresis of traffic flow intensity in case of above critical and under critical density etc.).

One of the most often studied models in last time, which partly satisfies the requirements mentioned above, is the so called Intelligent Driver Model (IDM) which was used for experiments of simulation. This model may be considered to be an interpolation of two members for acceleration and deceleration with different shapes in both parts.

ISSN 1582-3024

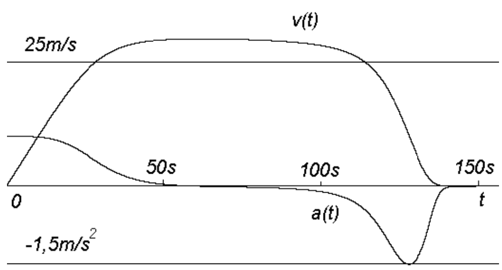

Figure 6. Vehicle velocity and acceleration according to IDM model. Start and stop before an obstacle at the distance 3000 m were used. This kind of test is a good indicator of the model relevance.

Before the simulation we can check for example the first outer demand via the simple experiment, when we test the ability of vehicle to stop ahead the block (fig. 6).

3.2. Model simulations

For the simulation itself we have created a program environment in Java programming language due its easy accessibility, simplicity and portability in internet. Each vehicle is represented by an object with its own parameters and the whole system of vehicles is represented by the so called binded list. In such way it is possible to dynamically change number of vehicles in the system.

For a traffic flow simulation it is advantageous to use the cyclic border conditions which are commonly used for a systems of interacting particles – in this case it means to put vehicles on a circular road with sufficiently large radius. In our case we have chosen the radius 1 km, the total road length is more than 6 km and so we can suppose the system behavior is not rather deformed by correlation between the first and the last vehicle.

3.2.1. System visualization

Direct system animation, when a movement of each vehicle is animated by an object on the circular road, is suitable just for program tuning – it does not bring a good idea about actions in the flow and more over it decelerates the calculation. The representation of time dependent development of density field is more interesting. We unwrap the road in abscissa, where we record each vehicle position by one point. After the selected time interval we similarly indicate a further line of the density field. After sufficiently long interval there arises a model giving a good idea about the development of a vehicle density on the whole road (fig. 7).

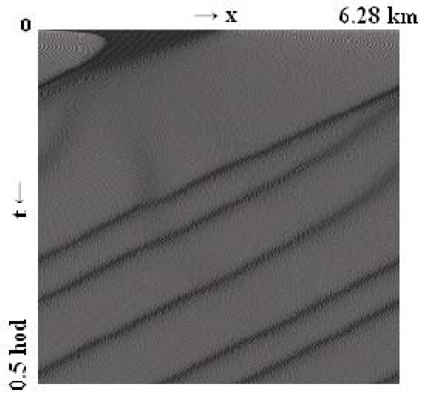

Figure 7. Development of vehicle density. In the beginning vehicles do not move and are homogeneously dislocated in the first half of the road length.

In the mentioned visualization of the density field development there is the distinct quick fixation to the stable state with three synchronized congestions moving upstream. The system moves to stable state with arbitrary initial vehicle distribution. Total number of vehicles in the system is 200.

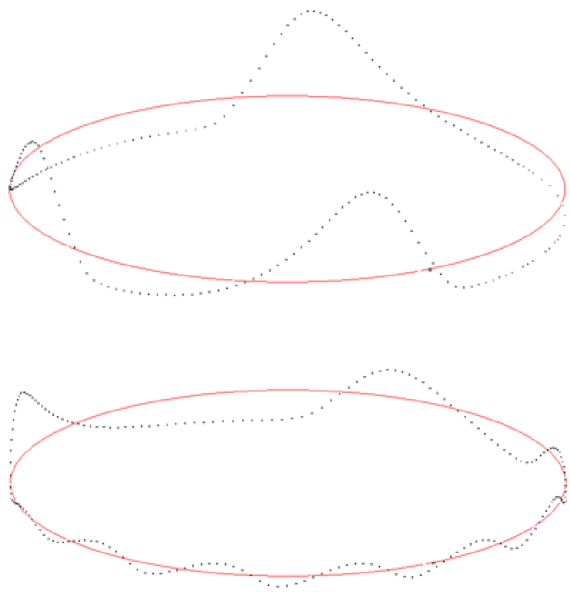

Figure 8. Screen shot from the animation of density distribution in stabilized condition. Full ellipse represents the average density level, which remains constant. The first picture shows the system state after one hour of simulated time, the second one shows the system after seven hours.

Transportation
Infrastructure Engineering

INTERSECTII
INTERSECTIONS
http://www.ce.tuiasi.ro/intersections

Another type of visualization of system development could be the local density animation (fig. 8). The calculation speed evidently suffers from the animation; however it gives a good idea about mutual interaction of density fluctuations during the stabilization of system and their motion in stabilized condition, which is always upstream.

We can make an interesting conclusion from the simulation: In spite of the fact that congestions in a flow can be unevenly distributed, they have the same form and size which is obviously an expression of vehicles with identical properties.

3.2.2. Obtained results

The main question could be the shape of fundamental diagram. In simulations we used mean values of traffic density and intensity gained from all vehicles on whole road. The final shape of fundamental diagram is too "smooth" and does not show real transient processes in the traffic flow (fig. 9).

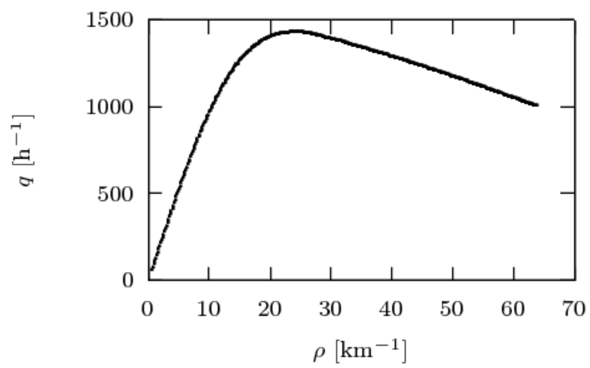

Figure 9. Dependency of simulated traffic intensity on average traffic density.

But we do not have so complex data during the real physical measuring. That is why the real fundamental diagram has so different shape. The main difference in not only in clear reasons: physical measuring do not work with stable traffic flow and vehicles do not have the identical properties. The basic reason is finite time interval, when we measure traffic intensity and density. With the sufficiently long time interval we can obtain similar results in modified simulation experiments, which reflect physical measuring.

It is possible to choose reference point on the simulated road. Each vehicle in each step tests, if it crossed over this point. In positive case the global counter increments with one. By this way we can simply "measure" the traffic intensity in the selected point for the selected time interval (corresponding number of computational steps).

The same trivial situation is during measuring of corresponding traffic density. This quantity is in real situation derived from measured vehicle speeds and time gaps. Each simulated vehicle has the value of distance from previous vehicle for computing of acceleration.

This value is then possible to use for calculation corresponding local mean density for a period of measuring interval. Then we have to collect to the other counter headways of vehicles, which goes through the reference point.

It is obvious that for traffic densities, when we have stable traffic flow without congestions, we will obtain same values for fundamental diagram as in averaging in the whole system. Totally different situation occurs when we have traffic flow with congestions. Then some few measurements will not give same values, but set of different values on discreet levels of traffic intensities. Dividing into groups is caused by counting only integer over of the vehicle on the bounds of time interval. By this way we will get fundamental diagram which looks more realistic despite of same vehicle properties and stable flow (fig. 10).

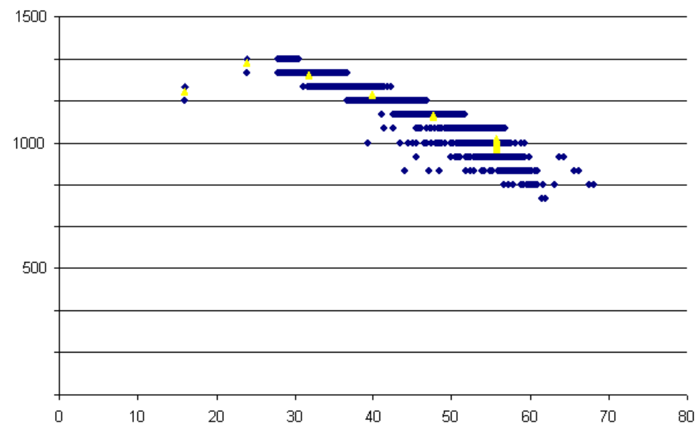

Figure 10. During profile measuring the fundamental diagram looks more realistic as the method of its construction.

From the figure it is apparent that in linear part of diagram is profile measuring concurrent with measuring on the whole system. With emergency of congestions data “blurred” and distances of these levels depends on the period of measuring. We can anticipate that for sufficiently long measuring interval the measured values will converge to values of the whole system.

Transportation
Infrastructure Engineering

INTERSECTII
INTERSECTIONS
http://www.ce.tuiasi.ro/intersections

3.2.3. Non-linear phenomena

The basic simulation experiment was performed on a system with a maximum number of 400 vehicles, i.e. with density of 63.7 vehicles/km. The flow stabilization was indicated by a stabilization of root-mean-square deviation of distances from an average value. The stabilization was considered as a difference between individual cycles (the passage of reference vehicle through the start) smaller than 10^{-5}. After each stabilization one vehicle was removed from the system while maintaining the existing states of other vehicles. The gap thus generated was quickly filled, though the existing imbalance was sufficient for the system to jump over into near state with various numbers of congestions. For comparison there an experiment was performed – after each change of the vehicle number, a new initial situation was set (vehicles homogenously distributed along the road without move).

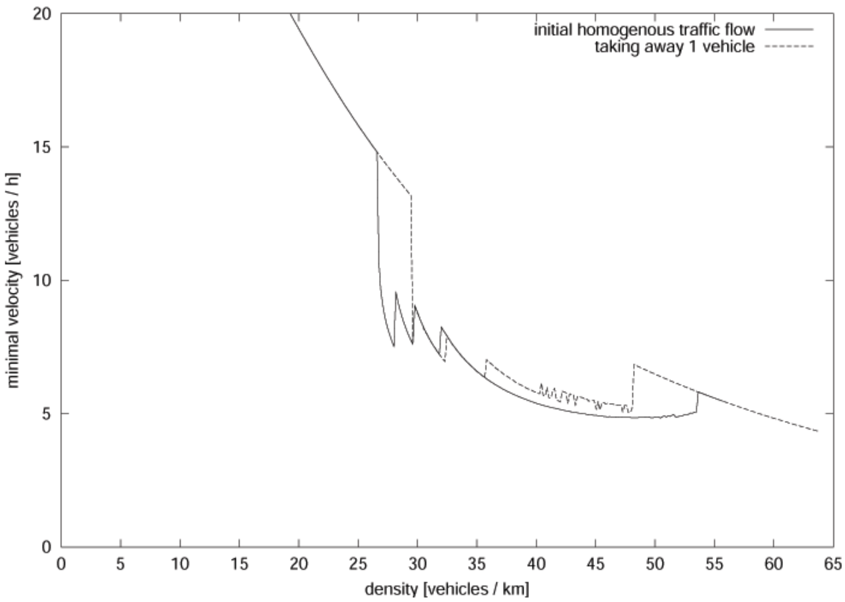

Figure 11. Comparison of dependency of velocities congestion on average density at various strategies of setting initial conditions. Bold line corresponds to the setting of the homogenous traffic flow, thin line to the taking away of the vehicle from the flow without any change of other vehicles states.

From fig. 11 we can see that the disturbance created by taking away the vehicle will be sufficient for the system to overlap into the congestion sooner than it is created by rounding up errors and discretization. In another words in the interval 48 – 53 vehicles/km at least two stable situations exist side by side – homogeneous distribution of vehicles and balanced congestions, while the final situation depends

ISSN 1582-3024

on the initial conditions. At densities about 45 vehicles per km there are stable situations with various numbers of congestions. During the stabilization from a homogeneous initial situation the system converges alternatively to five or six congestions distributed along the road; with a strategy of taking away vehicles the system stays in a stable state of four congestions. For a lower density the state with six congestions become unstable and extinguishes. A detailed investigation of stable areas of this model is difficult with regard to the fact that space of initial conditions is created among others by the density function.

Together with the state overlapping, occurrence of higher number of stable situations is a typical property of non-linearities.

4. CONCLUSIONS

The outlined microscopic models of traffic flow are only part of a wide spectrum of further models being used. Many of them are not sufficiently theoretically described because they are parts of commercial products, and therefore subject to commercial confidence.

At present a coexistence of models is admitted with some of them describing traffic flow better at higher densities and others at lower densities or other modes. Traffic engineers still wait for a model which would not contain large number of parameters with the necessity of calibration and which would at the same time characterize various traffic modes. Nevertheless it is possible to make a series of interesting conclusions even from the existing models which may be verified in practice – this is what we tried to do in this paper.

References

1. Bernard, M., Notes Notes on the Design Concepts for Transport Infrastructure: Past and Future, 4^{th} *Swiss Transport Research Conference*, Monte Verita, Ascona, 2004.
2. Transportation Research Board, **Highway Capacity Manual 2000**, *National Academy of Sciences*, USA, 2000.
3. Lighthill, M. J., Whitham G. B., *Proceedings of the Royal Society* A 229, 1955
4. Helbing, D., Hennecke, A., Shvetsov, V., Treiber, M., Micro- and Macrosimulation of Freeway Traffic, *Physical Review Letters* **82**, 2000
5. Kerner, B. S., *The Physics of Traffic*, Springer, New York, 2004
6. Schreckenberg, M., Schadschneider, A., Cellular automaton models and traffic flow, *Journal of Physics A: Mathematical and General* 26 **L679-L683**, 1993
7. Schreckenberg, M., Schadschneider, A., Car-oriented mean-field theory for traffic flow models, *Journal of Physics A: Mathematical and General* 30 **L69-L75**, 1997
8. Helbing, D., Traffic and Related self-driven many particle systems, *Reviews of Modern Physics* 73 **1067-1141**, 2001

ISSN 1582-3024