CONSTRUCTION OF A HYBRID TRAFFIC MODEL BASED ON JUTS CELLULAR MODEL

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Abstract

This paper deals with a description of an extension of the JUTS traffic simulation system. The model is run on the basis of cellular automata model and is microscopic in its nature. However, there is a need for implementing some parts of the simulation map at a lower level of detail and perform the simulation over them together with the remaining microscopic parts. Moreover, there is a demand for a possible automatic set up of the simulation map macroscopic segments according to a previously validated microscopic model and also, as a future improvement, for switching different segments of the simulation map into a low detail macroscopic level during the simulation run. All these demands represent a hard task, but the main question is the connection between the microscopic cellular automata model of the JUTS system and the new macroscopic model designed for it. There are other models connecting macroscopic models and the microscopic ones. But these combinations involve macroscopic models and microscopic car-following model or models combining mesocopic queuing network models with the macroscopic ones or mesoscopic kinematic wave theories with macroscopic models. On the other side the hybrid model used in JUTS have to be very similar to JUTS structure to allow a possible automatic settings of model parameters or possibly switching the details level. The paper describes the construction of such a model and its incorporation into the JUTS system.

Keywords: simulation, traffic, traffic simulation, model, hybrid model, macroscopic models, microscopic models, JUTS, object oriented, Java

Presenting Author's Biography

David Hartman was born in Karlovy Vary, Czech Republic, and went to the University of West Bohemia, where he studied software engineering and obtained his degree in 2003. Then he entered PhD. studies at the Department of Computer Science at this university and has worked on traffic and general simulation problems, data acquisition problems and algorithm analysis. He is a member of DSS research group (Distributed Systems, Software engineering and Simulations) and creator and one of the leading members of the JUTS traffic simulation project.

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1 Introduction

The analysis of traffic problems is a very important task for all economies around the world. The traffic problems in cities and around or between them influence the whole region's economy since almost all goods are still transported by vehicles. The computer-aided analysis of such problems is almost 50 years old. The main research efforts (except some specialized implementations) are related to traffic flow model development. In this branch of science, a good model does not necessarily mean a better understanding of the traffic flow nature (as it is usual in physics), but it often means a sufficiently fast and accurate tool for analysis of traffic situation (as usual in computer aided systems).

Nowadays there are plenty of simulation models that are more or less fast or accurate. Besides that there are also many reasons for traffic simulation like prediction, traffic flow optimization, the road network structure optimization, control of the traffic lights, ITS (intelligent transport system) support, etc. The user determines the important requirements such as simulation speed, level of detail, communication with given devices, etc. The first two requirements (simulation speed and level of detail) are very important in general because as we enlarge the level of details, the speed of the simulation decreases. The problem is that these two components can be neither enlarged together nor enlarged for a long time.

One of the methods to increase speed with the constant level of detail is parallel processing. We usually need think of this in advance during model creation because a good structure of the model can ensure an excellent speed up. On the other side, there are usually plenty of methods that somehow lower the level of detail in an acceptable way and speed the simulation up. Construction of a hybrid model belongs to these methods. It is not the same as using the lower detail method because one can choose some parts of simulation with a high detail while the others will have low detail. This freedom of choice is widely accepted by users as they are experts and they can omit the parts of no interests to save their time.

In the traffic modelling field, same as in most of the modelling areas, the models can be classified according to the level of used detail into three basic classes (the deeper description of the following classes will be given later).

- macroscopic
- mesoscopic
- microscopic

There already exists the JUTS microscopic cellular automata model and therefore the goal of this paper is to construct a compatible macroscopic one to create the hybrid model. This will create a new hybrid model consisting of the microscopic cellular automata model and the new macroscopic one. Besides this combination, there is also a demand to allow the model to autoadjust which means to set up the macroscopic parameters from the microscopic run and, possibly as a future improvement, switching from the microscopic model into macroscopic one during the simulation run.

2 Required basis from traffic theory

This section describes the basic notions needed from traffic flow theory. For a detailed description of such a topic see [**?**, **?**, **?**, **?**, **?**]. It starts with the description of traffic flow characteristics because these are used by most users and experts in traffic description problem area and therefore are quite important.

2.1 Traffic flow characteristics

The description of traffic came from the description of liquid flow kinematic and therefore the characteristics are derived from there. The basic set consists of three characteristics:

- Flow (vehicle per unit time)
- Mean speed (distance per unit time)
- Density (vehicles per unit distance)

Usually these variables are called *fundamental characteristics*, according to their historical importance. There are also other used characteristics (occupancy, time headway, space headway, ...). The first one is *flow* q. It is defined by simple measurement of vehicles' number N in one point during the fixed period of time T. This means

$$q = \frac{N}{T} \tag{1}$$

The next characteristic is *mean speed*. There are two possible definitions of this characteristic [**?**]. Similar to all mean values, one can think about the mean values over time v_t or over space v_s which leads to

$$\overline{v}_t = \frac{1}{N}\sum_{i=1}^{N} v_i \qquad \text{and} \qquad \overline{v}_s = \frac{D}{\frac{1}{N}\sum_i t_i}. \tag{2}$$

where D is the measurement distance and t_i is the time of i-th vehicle for crossing that distance. This definition is also somehow adopted from measurement, where we measure the values of speeds v_i over a short section [**?**] (two points of measurements are needed).

The last characteristic is *density*. It is very hard to imagine the equation for that, because in real situation its accurate measurement can be obtain only from aerial photograph or other complicated method). Nevertheless the density can be usually estimated from the so-called *fundamental equation*

$$\rho = \frac{q}{\overline{v}_s} \tag{3}$$

It was developed by Wardrop, see [**?**] and since that time it has been widely used and investigated, see [**?**, **?**, **?**, **?**, **?**, **?**, **?**].

2.2 Relations

There has to be also a short part explaining the basic relations among these characteristics. There is a huge effort to derive a theoretical relation among the traffic variables, see [**?**, **?**, **?**] which leads to two traffic state theories or even to very complex three-state theory [**?**].

The first relation is the *flow-density relation* which seems to be able to be derived from the fundamental equation **??**, but this will lead to a linear function which is not a good representation. For that purpose the fundamental equation has to be rewritten into

$$q(\rho) = \overline{v}(\rho) \cdot \rho, \tag{4}$$

which can represent the evolution of q in a different way for a different ρ. Then usually two traffic states are defined, namely the *free-flow state* and the *congested state*. The congested state is very hard to describe and it is the place of difficulties in that modelling, for further description see [**?**, **?**]. The resulting basic shape of this diagram is at Fig **??**

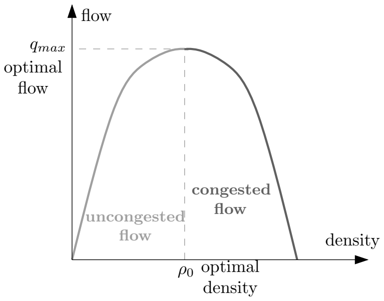

Fig. 1 The density-flow fundamental diagram

The influence of the existence of two states in traffic flow becomes important within the next density-speed diagram. There is a wide *hysteresis effect* with the metastable states [**?**]. The resulting diagram has the so-called λ-form shape.

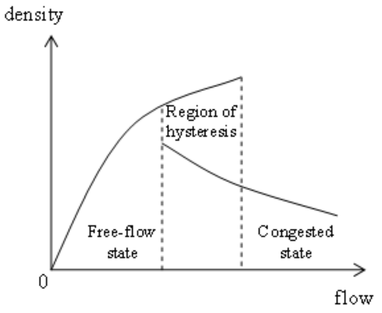

Fig. 2 The density-speed λ-shape diagram

The last diagram is the speed-flow diagram [**?**]. Its basic form is shown at Fig **??**

This is the basic set of diagrams often used for traffic situation description in graphical form.

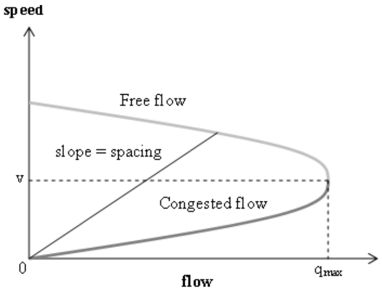

Fig. 3 The speed-flow diagram

2.3 Traffic Models

The most important thing for the hybrid model construction is the description of traffic models. Here is presented just the basic classification according to the level of detail. For more detailed description, see [**?**, **?**, **?**]. There are, of course, other classifications according to the representation of time or processes, etc. The levels of details classification is following

- macroscopic
- mesoscopic
- microscopic

The details are increasing from macroscopic to microscopic and of course hand in hand the computational difficulty is rising. The first macroscopic model (e.g. see [**?**, **?**]) is mainly based on enumeration of equations describing the relations among the traffic characteristics (i.e. determining the relations described above). For such purpose usually a set of differential equations has to be solved.

The second class, mesocopic, is a wide class with different models. There are some models coming from the macroscopic ones but they are mostly based on a gas-kinetic basis [**?**]. There are also models that are based on a queuing network theory [**?**].

The last class is the microscopic models class. These models represent individual vehicles, their interactions and behavior. Together with simulation it gives aggregate variables from the microscopic states. There are two main models used within these models. First older models are car-following models. They represent behavior of a vehicle as reactions on the preceding vehicle. It means that the preceding vehicle leads the actual one and shows him the way, speed, acceleration, etc (e.g. [**?**]). The second group is the cellular automata models that represent the road dynamic with cellular automation and the vehicle movement by applying the cellular automation rules. The most famous model from this class is the Nagel-Schreckenberg model [**?**].

The JUTS system uses cellular automata model based on Nagel-Schreckenberg and it will be combined with a modified macroscopic model.

3 JUTS model

This section describes the JUTS microscopic model. As it was mentioned above, the JUTS model is a microscopic model based on *Nagel-Schreckenberg model* (NaSch). But it has many modifications. These are

1. Introducing different vehicle length.
2. Changing the length represented by one cell.
3. Introducing a new crossroad model.
4. Introducing the Head leading algorithm.
5. Extended lane change decisions.

The meaning of these modifications arises after the basic model description. In the cellular automaton model, the lanes of road are divided into cells with a fixed length and vehicles are represented by particles moving inside these cells. The status of the road is continuously updated in defined intervals of time. In the JUTS model, the length of cell is 2.5m (NaSch has 7.5m), the vehicle can occupy more cells, the movement for such vehicle is performed by the Head-Leading algorithm which also handles the movement through the new crossroad model and the lane change decision works with more parameters. For all these, see [**?**, **?**, **?**].

From the cellular automata, a set of basic characteristics can be derived for each lane according to their definition. Description of model segments used in the JUTS system is important for further hybrid model description. There exist (in basic view) five basic segments

- Road,
- Crossroad,
- Roundabout,
- Generators.
- Terminators.

The structure of a simulation map for simple T-shape crossroad

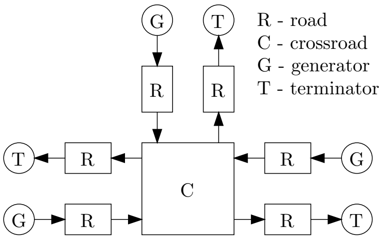

Fig. 4 Segment structure of simulation map

The road segment is used for moving the vehicle in cellular automata. The roundabout segment is represented by the road in circle with adjacent ramps and crossroad can be basically described as "matrix cellular automata", see [**?**]. This matrix represents a variable cellular automaton changing its orientation according to a direction of the actual vehicle's movement on this crossroad. It means that all segments dealing with movement have cells inside. On the other side the generators inject the vehicles into the simulation map and terminators terminate them after leaving the map.

The next important fact is that the segments together are connected with a special kind of objects called accessplaces that are used to move the vehicles from one segment to another.

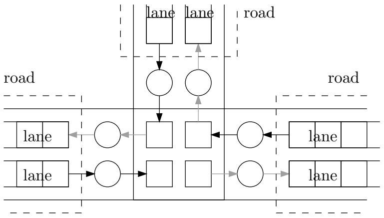

Fig. 5 Segment connections via accessplaces

All these features will be important for future hybrid model development.

4 Hybrid model

The hybrid modelling is quite popular nowadays because it allows the users to balance their needs and time. As mentioned above, there are several hybrid models using a car-following model together with queuing network model [**?**], car-following model with macroscopic model [**?**] or Kinematic wave theory with macroscopic model [**?**].

4.1 Macroscopic model for JUTS inclusion

The basis for our model is adopted from METANET model [**?**]. It starts with the conservation equation

$$\frac{\partial q}{\partial x} + \frac{\partial \rho}{\partial t} = g(x,t) \tag{5}$$

In order to determine the traffic lane situation this equation has to be solved for defined conditions. In oder to do so one usually needs (especially in urban traffic case) to solve it numerically which results in determination of flow, density and mean speed (q, ρ and v). The road is divided into small segments Δx for which all these variables are updated each step which is Δt long.

Fig. 6 Macroscopic discretization

Now it is possible to define the discrete form of the continuity equation used to cyclic numeric determination of traffic lane variables. In order to do so the time variable

τ has to be defined. τ is the multiple of the Δt intervals (i.e. real time can be calculated as $t = t_0 + \Delta t$):

$$\begin{aligned} \rho_i(\tau+1) = \quad & \frac{1}{2}[\rho_{i+1}(\tau) + \rho_{i-1}(\tau)] \\ + \quad & \frac{\Delta t}{2}[g_{i+1}(\tau) + g_{i-1}(\tau)] \end{aligned} \qquad (6)$$

The variable g_i here represents generation or dissipation of flow as a consequence of adjacent ramps or other structural inputs and/or outputs.

Once the density is determined, the speed should be also calculated. This equation is one of the most complicated variables and is in its form very dependent on parameters.

$$\begin{aligned} v_i(\tau+1) = \quad & v_i(\tau) + \frac{\Delta t}{\chi}[V(\rho_i(\tau)) - v_i(\tau)] \\ + \quad & \frac{\Delta t}{\Delta x} v_i(\tau)[v_{i-1}(\tau) - v_i(\tau)] \\ + \quad & \frac{\eta \Delta t}{\Delta x}\left[\frac{q_{i+1}(\tau) - q_i(\tau)}{q_i(\tau) - \kappa}\right] \end{aligned} \qquad (7)$$

This equation is constituted by these terms (the term $v_i(t)$ is clear and therefore omitted from the following list):

1. First term represents a relaxation of speed asymptotically towards the equilibrium speed which is determined by the generalized Greenshield model, see [**?**].

$$V(\rho_i(\tau)) = v_f \exp\left(-\frac{1}{a}\left(\frac{\rho_i(\tau)}{\rho_c}\right)^a\right) \qquad (8)$$

2. The next term is the convection factor representing influence of entering vehicles speeds.
3. The last density influence represents anticipation factor.

Now it is possible to simply state the last equation derived from the fundamental one which determines the flow value.

$$q_i(\tau+1) = \rho_i(\tau+1) v_i(\tau+1) \qquad (9)$$

These variables are continuously updated each macro step. In JUTS model, differently from METANET, this discretization is defined for traffic lanes (not the whole road) and Δx is defined as multiple of cell's length. Therefore the g_i variable means not only ramps inputs or outputs, but also the traffic lane change rate. Thus it is needed to include the new step for determining these values for specific lanes. After that the g_i is constituted by

$$g_i = g_i^{m,m-1} + g_i^{m,m+1} + g_i^{r}, \qquad (10)$$

where $g_i^{m,m-1}$ and $g_i^{m,m+1}$ are total values determining inflow (+) or outflow (-) to/from lane from the left and right neighbouring lane according to lane changing and g_i^r is computed normally. The lane change update rule that decides about the amount of vehicles performing lane change works for two lanes m and $m-1$ according to:

$$\begin{aligned} g_i^{m,m-1} = \quad & \omega Pr_{m,m-1}(\rho_m - \rho_{m+1}) \\ - \quad & \psi Pr_{m-1,m}(\rho_{m+1} - \rho_m) \end{aligned} \qquad (11)$$

where $P_{m,m-1}$ is probability of changing lane from m to $m-1$ and ω and ψ are correction factors. The probabilities are validated according to real state and the correction factors have only meaning for further generalization.

The next segment is macrocrossroad. There the situation is different.

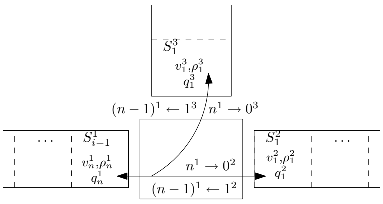

Fig. 7 Macroscopic crossroad

The crossroad will be presented normally as probabilistic division segment. There is no simulation of dynamic on the crossroad, just sending the values into corresponding targets. The further description concerns the hybrid model construction.

4.2 Hybrid model construction

The macroscopic model has to be included into the JUTS structure. At the beginning it must be said that all macro or hybrid objects are encapsulated in a special macro area holding some common values for the whole area represented as macro. Therefore the macrosubmap should be defined as a continuously closed subset of elements of the simulation map. The macroscopic road model is normally presented as a segment which is updated not each t times as the microscopic one but each $\tau \cdot t$ times and similarly the crossroad. The connections among the macrosegments are performed in the same way as among the microsegments. The only thing we need in the next segment from the previous one are the values of ρ, v, q from its last section. In other words the macroaccessplace only provides these values between successive macrosegments.

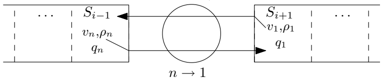

Fig. 8 Connection by macroaccessplace

The situation is more complicated within the accessplaces between different types of segments. The micro-macro accessplace is defined as a terminator. It absorbs vehicles from the preceding microsegment and store their length, speed (and possibly other) important variables into the macro area. These values are stored only for information about the rate of vehicles entering macroarea mainly with different lengths (later used by macro-micro accessplace). Moreover, this accessplace is looking for the corresponding lane (the entering one) in the previous microsegment and calculates the values ρ, v, q and then uses these values to update values ρ_0, v_0, q_0 of the successive macrosegments. Besides that, it stores some important vehicles like urban mass transportation vehicles into the macro area and invokes the method for handling them performing calculation of the delay time (should be changed later - for dynamic handling) and target accessplace derived from inner vehicle path information.

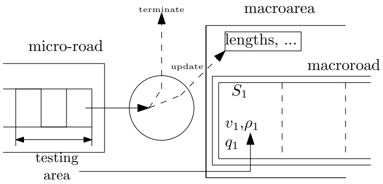

Fig. 9 Micro-macro accessplace

The next micro-macro accessplace on the other hand works like a generator. It generates the vehicles, not randomly but according to the previous macro segment density and speed values. For correction of these values (and to complete them), the information from macroarea previously stored by micro-macro accessplace is used. According to the rates in macroarea, the model is able to derive the new vehicles and update the rates (the rate represents the kind of vehicles inside the segment - in the simplest case the lengths of vehicles). These vehicles are normally injected into microsegment as it would be from the ordinary generator.

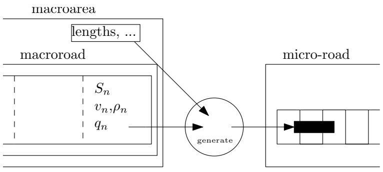

Fig. 10 Macro-micro accessplace

All these segments and accessplaces constitutes the macro area which is the part of ordinary JUTS microscopic model. This area is updated in steps τ which is multiple of t.

4.3 Autoadjusting and switching

Now the discussion about autoadjusting should be started. How can this model be autoadjusted? It is simple. The macrosegment is defined for macroareas. However, these areas are not only macroscopic but also have microscopic segments loaded. Than the simulation can be started. The microscopic run is performed normally as there is no macroarea. The macro model computation runs in parallel to it and uses the values of characteristics enumerated from the microscopic models and stores and aggregates the results from both runs. At the end (also possibly during the process, but it is not as accurate) the information can be compared and the parameters of the model can be determined.

Moreover, the switching can be also easy when the parameters of corresponding macroscopic models are defined. Then to switch and recalculate corresponding values of characteristics q, v, ρ for all sections from cells is an easy task. The global variables like lengths, etc. in the macroarea should be updated and values of g_i generated. All these operations should be easy to do and therefore the switching seems to be without problem.

5 Conclusion and future work

The construction of the new model seems to represent the required demands in a good manner. The autoadjusting is achieved through combination of microscopic and macroscopic models and the switching just follows automatically. The new multilane macroscopic model was easily included into JUTS cellular micromodel with the help of correspondence between sections and cells. Moreover the multilane character of the macromodel helps the JUTS system users work easily with different types of segments in the same way.

The next step is to test this hybrid model using real data to ensure accuracy of the results and to avoid problems related to increased number of errors. The main tasks then are implementation of the above mentioned autoadjusting method and verifying its correctness and utilization of the online segment of switching during simulation run.

A further possible improvement is testing the borders for simplification of macroscopic model in order to find the optimum for speed and good reality representation within the hybrid model.

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