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MODELING AND STOCHASTIC SIMULATION OF ROAD TRAFFIC SYSTEMS

Ph.D. thesis

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Introduction

Actuality of the Research Area

Traffic flow is one of the essential elements of our age; therefore the handling of the passenger and goods delivery needs is a fundamental task. Transportation plays important role in both individual life and economy. The problems of traffic, including jams, congestion, accidents have high impact on our lives. All these reasons increase the demand for the development of transportation, and its design by up to date tools. (EU Transportation policy 2001–10 "White Book". Hungarian Transportation policy 2003–15, NFT2.) There has been major growth in traffic needs in the last decades. As a result, the infrastructure capacity problems have increased in spite of the fact that the development of infrastructure is also continuous. The presence of the problem is conspicuous in urban traffic, where capacity increasing is almost impossible. As a consequence, the role of traffic management is dominant.

Research Methodology and Objective

There are many uses of the answers of transportation problems. The main three application areas are the following: [Kach99]

1. **Transportation Planning**: Determination of needs, Trip time estimation, route planning, traffic assignment, determination of control modes; to determine the impact and effects of new infrastructural changes.
2. **Simulation**: Usable for the comparison of existing transportation control strategies (and many more). Able to analyze the effects of planning. Needs proper "origin-destination" data.
3. **Real-time control of traffic**: The control of real world traffic, using the real-time data and behavior of the traffic at a given area.

My PhD Thesis deals with the modeling and simulation of the transportation process, but does not discuss the empirical and analytical approaches. The approach possibilities of such problem are best summarized by Papageorgiou [Papa98] and after him, the transportation system models can be classified by the following criteria:

- The representation of the independent variables (continuous, discrete, semi-discrete);
- Model detail (submicroscopic, microscopic, mesoscopic, macroscopic);
- Representation of processes (deterministic, stochastic);
- Operation (analytic, simulation);
- Application detail (network, nodes, etc.).

During the investigation of the modeling problem, the simulation can take many forms, and has many applications. The reason for this is that the questions to be examined can be various. But there are some widely adopted fundamental steps [Vásá85, Lieb97]:

1. **Problem definition**: The determination of modeling objectives considering the expected results.
2. **The decomposition of the examined system**: The inquiry of the system elements, and their dependencies. The determination of the required system inputs.
3. **Model development**: Mathematical and computer model elaboration.
4. **Model calibration**: Data collection and building into the model, for higher model efficiency.
5. **Verification**: The examination of the model with the goal to determine, if the computer model corresponds to the mathematical model. This examination could be made for the entire model, or model parts.
6. **Validation**: The auditing, that the model (in the expected degree of tolerance) satisfactorily represents the real system.
7. **Documentation**: The automated registration and evaluation of the data acquired from the simulation, and their proper publication and interpretation.

During simulation execution the danger emerges, that either from inattention, or from the inappropriate exploration of the system, the developed model does not adapts to reality or (in special case) does not work as intended. To eliminate these dangers, some laws should be respected:

- Only those hypotheses should be accepted, whose effect and scope are made clear.
- Only those parameters/variables should be used, which are well defined and represented, and whose relationships to other variants are also cleared.
- It is not recommended to over-simplify the model, because it should defer from reality.
- In favor of practical feasibility, model complexity and numerical needs should be kept within bounds.

In the thesis, the main results and consequences of the research are implemented, in the following chapters:

- Modeling, where the guiding of microscopic traffic modeling, and the state of the art models are documented. Also the planning process of a new Fuzzy-Sugeno based microscopic model is implemented.

- Data acquisition, the presentation of microscopic data collection by video based traffic surveillance.
- Identification, where the data processing technique, and the determination of microscopic model parameters are documented.
- Simulation system build-up. The chapter explains a well-expandable simulation system for research studies, which implements the Fuzzy model and also some other microscopic models.
- Sample applications, case studies, where the modularity of the simulation system is proved through four applications, from which two were supporting external studies, one deals with the quality investigation of the identified models, and the last presents a soft-computing solution for traffic parameter estimation.

New Scientific Achievements

I've investigated the State-of-the-Art microscopic traffic models, with special regard to:

- the Nagel-Schreckenberg model-group;
- the Gazis-Herman-Rothery (GHR) model;
- the safe distance and collision avoidance models;
- the Linear (Helly) models;
- the psychophysical, "Action Point" (AP) models;
- Fuzzy structure based models.

Considering the recommendations of the literature dealing with modeling and driver psychology, I've described the practical criteria of the Fuzzy type microscopic following model design:

- The cardinality of Fuzzy sets, as a result:
- The partition tightening of the input parameters,
- The creation of the multi-dimensional partition,
- The "defuzzification" of all state variables, and
- Completeness.

On the basis of these criteria, I've developed a microscopic model:

<u>Thesis 1</u>: I've elaborated a two-level, Fuzzy-Sugeno type discrete time microscopic car-following model. After partitioning the following state space, a new decision making at the second level determines the system output, with special regard to individual driver differences.

Thesis 1 is based on the publications [2, 3].

Fuzzification of the speed is omitted in this model. Instead the determination of the follower distance expected can take place in a similar way like in the case of the first model using an additional predictional term dependent on the difference of speed and the reaction time:

$$D^*_{foll} = v(p_1 r_1 + p_2) + p_3 r_1 + p_4 + \Delta v \Delta T \,, \tag{1}$$

$$Close : DF_1 = \begin{Bmatrix} 1 & ,if & dx - D^*_{foll} < a_1 \\ \dfrac{(b_1 - dx)}{(b_1 - a_1)} & ,if & a_1 \le dx - D^*_{foll} \le b_1 \\ 0 & ,if & dx - D^*_{foll} > b_1 \end{Bmatrix}$$

$$Farther : DF_2 = \begin{Bmatrix} 1 & ,if & dx - D^*_{foll} < a_2 \\ \dfrac{(dx - a_2)}{(b_2 - a_2)} & ,if & a_2 \le dx - D^*_{foll} \le b_2 \\ 0 & ,if & dx - D^*_{foll} > b_2 \end{Bmatrix} \tag{2}$$

$$Approaching : DV_1 = \begin{Bmatrix} 1 & ,if & dv < c_1 \\ \dfrac{(d_1 - dv)}{(d_1 - c_1)} & ,if & c_1 \le dv \le d_1 \\ 0 & ,if & dv > d_1 \end{Bmatrix}$$

$$Leaving : DV_2 = \begin{Bmatrix} 1 & ,if & dv < c_2 \\ \dfrac{(dv - c_2)}{(d_2 - c_2)} & ,if & d_2 \le dv \le d_2 \\ 0 & ,if & dv > d_2 \end{Bmatrix} \tag{3}$$

Four conditions can be created by four sets that are the intersections of two sets of different dimensions:

$$\begin{aligned} &\mathrm{A} = \{A_i ; i \in [1,4]\} \\ &A_1(dx, dv) = t\big(DF_1(dx),\, DV_1(dv)\big) \\ &A_2(dx, dv) = t\big(DF_1(dx),\, DV_2(dv)\big) \\ &A_3(dx, dv) = t\big(DF_2(dx),\, DV_1(dv)\big) \\ &A_4(dx, dv) = t\big(DF_2(dx),\, DV_2(dv)\big) \end{aligned} \tag{4}$$

By using these sets, the output is given as the result of the following algorithm:

$$a^i_{dspe} = \frac{\sum_{j=1}^{n} PS^i_j(\Delta v) A^{i,v}_i}{\sum_{j=1}^{n} DS^i_j(\Delta v)}; \quad a_{dfoll} = \frac{\sum_{k=1}^{m} DF^i_k(\Delta x - D^*_{foll}) A^{i,f}_j}{\sum_{k=1}^{m} DF^i_k(\Delta x - D^*_{foll})}; \quad \begin{matrix} j \in (1..n) \\ k \in (1..m) \end{matrix}$$

$$a^{i,1}_{med} = a^i_{dspe} r_2 + a^i_{dfoll}(1 - r_2); \quad r_2 \in [0;1] \qquad ,(5)$$

$$a^{i,2}_{med} = (p_5 + p_6 r_2) a^{i,1}_{med}$$

$$f_i = \begin{Bmatrix} a_{\max} a^{i,2}_{med}; a^{i,2}_{med} > 0 \\ a_{\min} a^{i,2}_{med}; a^{i,2}_{med} \le 0 \end{Bmatrix}$$

A possible acceleration diagram of the composed model is presented in Figure 1.:

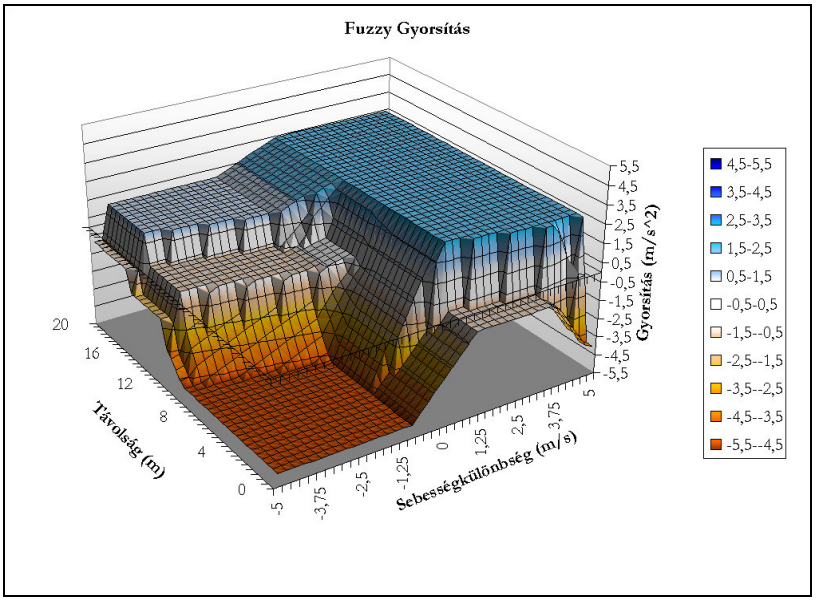

Figure 1.: Acceleration diagram belonging to 5 m/s of the state divided fuzzy model

Thesis 2 deals with the parameter estimation of microscopic following models, using real world traffic data. It is important to process the acquired data by:

- Vehicle registration,
- Position smoothing,
- Leading vehicle seeking.

To utilize the obtained data, the structure of the identified model is also needed. After this, the algorithm uses two main parallel optimum searching algorithms, from which the first is responsible for the determination of global model parameters. The search for the optimum in its final form was done by a unigenous genetic algorithm assisted by a simulated annealing that is:

- Elitist (in 5%);
- Has a real gene-representation;

- Modifies the fitness value with the function random(T)* of the simulated annealing;
- Thus realizing the selection with absolute sequencing;
- Applying the mutation in a radius of "random(T)" ;
- Applying a complete recombination;
- Has a constant size of population.

The second algorithm deals with the determination of individual parameters, represented by the individual parameters of the models. In this case, algorithm speed is critical, so the seeking process is a gradient search from multiple start points of the interval [0,1]. The optimum searching algorithm is presented in Figure 2.

<u>Thesis 2:</u> I've designed a methodology for the parameter-search of microscopic car-following models, which is able to determine model-parameters and individual differences simultaneously, by using real world microscopic data.

Thesis 2 is based on publications [6, 10, 11].

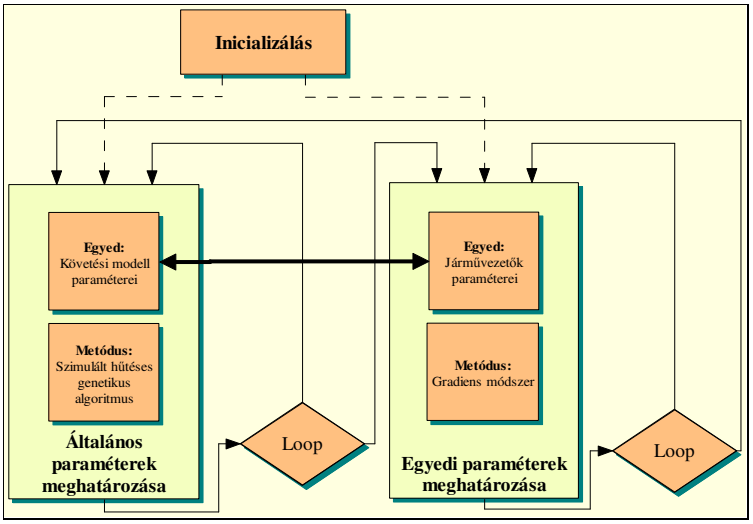

Figure 2.: Optimum searching

The developed algorithm can be used in the simultaneous determination of global and individual parameters.

The achievements of the chapter presenting the development of the software structure are summarized in thesis No. 3. The development aimed the creation of a simulation system that is able to implement multiple micro-models, and multiple situations. The environment emphasizes the dynamic class structure and modular nature. The environment holds:

- Network definition;
- Participant description;
- Base traffic management objects;
- Vehicle generation;
- Simulation kernel;
- Basic driver decisions.

Beside these functions, a dynamically extendable base-class is implemented establishing the possibility of implementing new objects or interfaces. The environment also contains a script language for network definition, and case studies.

Thesis 3: I've designed a structure of a modular, research-centric, road traffic simulation framework, which is able to simply simulate road traffic processes, and flexibly expandable.

Thesis 3 is based on publications [2, 3, 4].

The achievements of the chapter documenting the possible uses of the developed software bring thesis 4 and 5.

The model presented in thesis 1 is optimized in chapter 4 and thesis 2. However it is necessary to examine the model efficiency. Since model efficiency is hard to measure by itself, the parameter identification and evaluation of four other models are also performed. The examined models:

- Gazis-Herman-Rothery (GHR); [Gazi59, Chan58]
- Gipps (Aimsun); [Gipp81, Bern99, Barc04]
- Wiedemann (Vissim); [Wied92, Fell97, Fell01, Fell00]
- Simple fuzzy model;
- Fuzzy State model.

The model evaluation has been made from two points of view. Under microscopic study, the stability of the models (stable with stationer flow) were examined on a road section, with dynamically changing traffic flow. During this, the critical closing, and the number of collisions were recorded. Under macroscopic examination with the same simulation scenario, the comparison of the model macro-data and a reference model has been made. The efficiency of the model of thesis 1 is presented in Figure 3. and 4.:

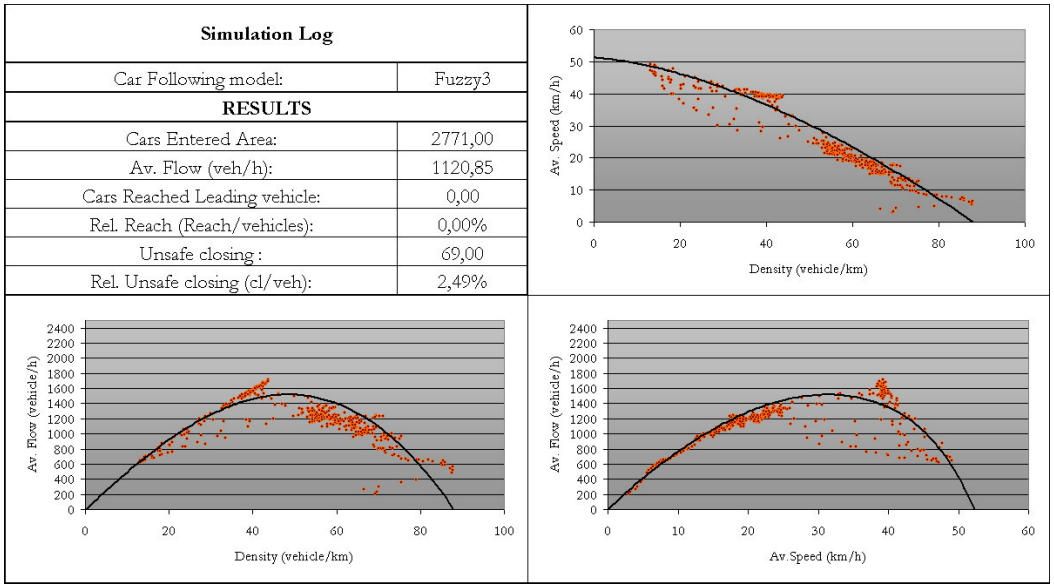

Figure 3: Evaluation of the microscopic and macroscopic attributes of the Fuzzy model

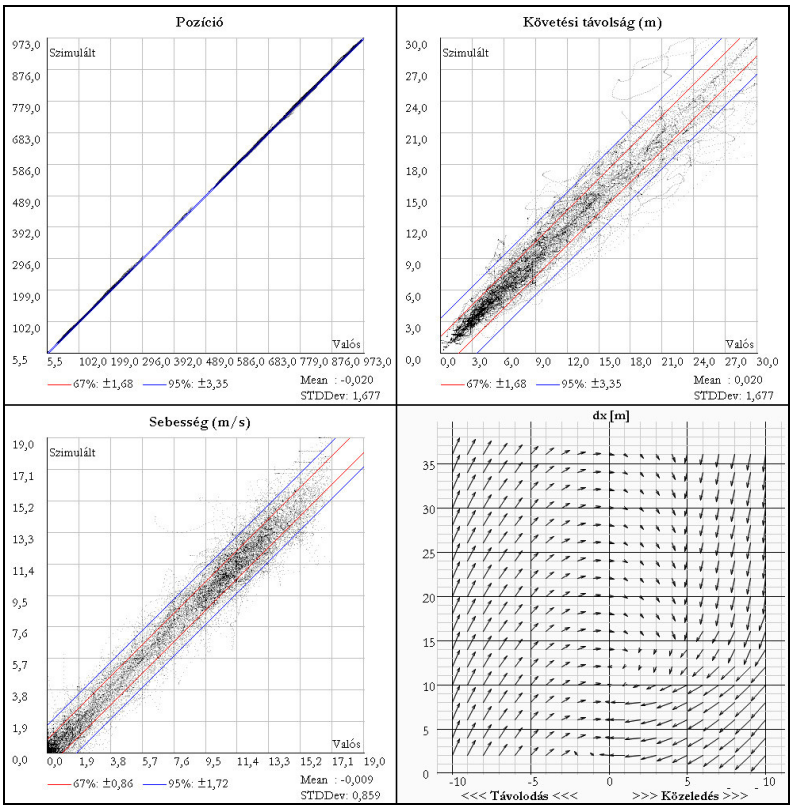

Figure 4.: The difference diagrams of the Fuzzy model and the acceleration field of direction at 5 m/s

<u>Thesis 4:</u> I've created a methodology for the evaluation of microscopic car-following models. By using this methodology, I've evaluated the model presented in thesis 1, and optimized by thesis 2, comparing with other classical models.

Thesis 4 is based on publications [11, 12].

One of the main advantages of a modular simulation, that by it, the testing of situations under planning process is easy, and the evaluation of situations not producible in real life (such as accidents, and congestion after accidents) is also feasible. For the recognition and management of such situations, the development of system able to handle these cases is necessary to improve the safety and capacity of road traffic flow. One of these possibilities is incident detection, having extended literature. A possible solution for this task is provided in thesis 5, through traffic flow estimation:

Thesis 5: By using adaptive Fuzzy-Sugeno-type macroscopic model, I've developed an algorithm for highway traffic parameter estimation.

Thesis 5 is based on publications [1, 2].

The algorithm is capable of the traffic flow estimation of one or more connected highway sections bounded by cross section measurement instruments, through density estimation. Therefore by comparing the incoming and outgoing car amounts as real data with the estimated data, it is able to determine if there is any anomaly on the section.

The main point of the algorithm that by using the incoming flow as input, it utilizes a macroscopic Sugeno type model for calculating the average time spent on the section, thus determining the load of the given section. For this task, any classical macroscopic model should be applicable, but the changes of real world parameters (meteorological, seasonal, road surface quality, visibility) indicate different traffic behavior from time to time. In compliance with it, it is necessary to use a model with adaptive nature to follow these changes. For that purpose, a micro-population genetic algorithm is implemented. The low number of entities in the population makes the algorithm able to work real-time. The optimum searching can be made individually for each section, or for all sections at the same process.

Practical Uses of the New Scientific Achievements

My PhD thesis deals with the modeling and simulation of road traffic, its structure and content summarizes my main researches in the area. The aim of the research was to develop applicable, implementable, feasible, real-time capable algorithms, procedures and structures without exception, therefore for all cases, the computational realization was also made. Within this framework, I've developed applications for:

- Video based traffic surveillance;
- Data processing, and model parameter determination;
- Simulation of road traffic able to:
    - Model efficiency evaluation;

- Communication with other applications;
- Highway state estimation.

The functionality of the softwares proves the proper working of the developed structures, with the additional advantage that their computational speed matches with the other algorithms.

The research of the area at this state cannot be considered to be finished. The research area is reckoned as highlighted subject, since the development of intelligent transportation systems is a contribution to the answer to the growing transportation needs. In this, the rapid development communication and information technology renders help, enabling the development of more and more complex real time systems.

Publications referenced

[Barc04] Barceló, J.: "AIMSUN Microscopic Traffic Simulator: A Tool for the Analysis and Assessment of Its Systems", Tech. Rep., TSS-Transport Simulation Systems, 2004

[Bern99] Bernauer, E. et al.: "Micro-Simulation Workshop", SMARTEST - Simulation Modelling Applied to Road Transport European Scheme Tests, [online]:http://www.its.leeds.ac.uk/smartest, 1999

[Chan58] Chandler, R.E., Herman, R., and Montroll, E.W. : "Traffic Dynamics: Studies in Car Following", Operations Research, vol. 6., 1958, pp.165-184.

[Fell97] Fellendorf, M.: "Parametrization of Microscopic Traffic Flow Models through Image Processing", in Proc. of. 8th IFAC Symposium on Transport, Chania, Crete, 1997

[Fell00] Fellendorf, M., and Vortisch, P.: "Integrated Modeling of Transport Demand, Route Choice, Traffic Flow and Traffic Emissions", 79th Annual Meeting of the Transport Research Board, Washington, 2000

[Fell01] Fellendorf, M., and Vortisch, P.: "Validation of the Microscopic Traffic Flow Model VISSIM in Different Real-World Situations", 2001

[Gazi59] Gazis, D.C., Herman, R., and Potts, R.B.,: "Car following theory of steady state traffic flow", Operation Research, Vol. 7, 1959, pp.499-505.

[Gipp81] Gipps, P.G.: "A Behavioural Car-following Model for Computer Simulation", Transportation Research Part B, Issue 2, Pergamon, 1981, pp.105-111.

[Kach99] Kachroo, P., and Özbay, K.: "Feedback Control Theory for Dynamic Traffic Assignment", Springer, 1999

[Lieb97] Liebermann, E., and Rathi, A.K.: "Traffic Simulation", in Revised Monograph on Traffic Flow Theory, Turner-Fairbank Highway Research Center, [online]:http://www.tfhrc.gov/its/tft/tft.htm, 1997

[Papa98] Papageorgiou, M.: "Some Remarks on Macroscopic Traffic Flow Modelling", Transportation Research A 32(5), 1998, pp.323-329.

[Vásá85] Vásárhelyi, B.: "A közúti forgalom lefolyásának szimulációja", Közlekedéstudományi Intézet, Budapest, 1985

[Wied92] Wiedemann, R., and Reiter, U.: "Microscopic Traffic Simulation: The Simulation System MISSION. Background and Actual State", CEC Project ICARUS (V1052) Final Report, Vol.2 Appendix A. CEC, Brussels, 1992

The publications of the author concerning the theses

[1] Bécsi, T., and Péter, T.: "An Adaptive Approach to Modeling Traffic Flow and Incident Detection on Highways", Proceedings of the 3rd International Conference on Global Research and Education in intelligent Systems, Interacademia 2004, Budapest, 2004

[2] Bécsi, T., and Péter, T.: "Szimulációs környezet a közúti forgalmi folyamatok hatékony modellezéséhez", Közlekedéstudományi Szemle LV. évf. 5.sz., Budapest, 2005, pp.170-178.

[3] Bécsi, T., and Péter, T.: "Sztochasztikus közúti közlekedési folyamatok vizsgálata a modellezést szolgáló hatékony szimulációs környezetben", Intelligens közlekedési rendszerek és jármű-controll. Előírások a közlekedés biztonságának növelésére. Magyar Mérnökakadémia Symposium Budapest, 2005, pp. 416-432.

[4] Kulcsár, B., Bécsi, T., and Varga, I.: "Estimation of Dynamic Origin Destionation Matrix of Traffic Systems", Periodica Polytechnica Ser. Transp.Eng. Vol.33, No.1-2, 2005, pp.14.márc.

[5] Bécsi, T., and Péter, T.: "Automatikus video alapú forgalommérő szoftver fejlesztése, a forgalom modellezéséhez", A jövő járműve, járműipari innováció, I. évf. 1-2, X-Meditor, Győr, 2006, pp.24-27.

[6] Bécsi, T., and Péter, T.: "A Mixture of Distributions Background Model for Traffic Video Surveillance", Periodica Polytechnica Ser. Transp.Eng. Vol.34, No.1, 2006, pp.9.jan.

[7] Bécsi, T., and Berta, T.: "Effects on Speed of Traffic Calming Tools Installed on Urban Roads", Proc.of Biztonságos utakon a XXI. században, Budapest, 2006

[8] Bécsi, T., and Péter, T.: "Forgalmi modellek identifikációja a videó-mérésből kinyert paraméterhalmaz alapján", Technical Report, BME EJJT, Budapest, 2006

[9] Bécsi, T., and Péter, T.: "Lakóterületi sebességszabályozás forgalomtechnikai tervezése", Innováció és fenntartható felszíni közlekedés, MMA, Budapest, 2007

[10] Bécsi, T., and Péter, T.: "Képfelismerésen alapuló technológiák gyakorlati felhasználása a közúti közlekedés vizsgálatában", Innováció és fenntartható felszíni közlekedés, MMA, Budapest, 2007

[11] Bécsi, T., and Péter, T.: "Mikroszkopikus követési modellek, a vezetői különbségeket figyelembevevő paraméterek meghatározására", A jövő járműve, járműipari innováció, III. évf. 1-2, X-Meditor, Győr, 2008. (under publication)

[12] Bécsi, T., and Péter, T.: "Development and Evaluation of a Fuzzy-based Microscopic Vehicle-following Model", Periodica Polytechnica Ser. Transp.Eng., Budapest, 2008. (under publication)