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On Urban Traffic Modelling and Control

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Abstract: The paper presents a dual approach for modeling urban traffic. The modeling goal is to eliminate congestion by controlling traffic lights cycle structure and duration. The control problem has to be solved using both analytical methods, and simulation, with continuous models implemented in Matlab/Simulink. Analytical methods are based on the Hybrid Petri Net approach. In the paper are presented both kinds of models and they are evaluated using the same input data. It results that the two modeling approaches are complementary and, by their similar behavior, they reciprocally validate.

Keywords: traffic models, hybrid Petri Nets, simulation models

1. INTRODUCTION

Traffic is an essential part of modern society. World economies require a fast and efficient transportation system. Congestion is one of the main societal problems in industrialized countries.

The main aspects related to traffic that drew the attention of the research community are traffic modelling and simulation, traffic management and control, as well as traffic forecasting.

Many of the research endeavours are directed towards optimizing the urban traffic flow in order to eliminate congestions and to reduce the average waiting time of vehicles.

Other research works have been directed towards developing driving assistance systems for route optimization, prioritizing intervention vehicles, enhancing public transportation, mitigating the effects of pollution and high level of noise in urban areas by means of evenly distributing traffic flow.

More recently, efforts has been done towards the integration of traffic control solutions within complex global solutions for urban sustainable development, such as Intelligent Transportation Systems (ITS). ITSs are those utilizing synergistic technologies and systems engineering concepts to develop and improve transportation systems of all kinds.

The main challenge is to efficiently fit within the constraints of the existing road infrastructure since this is usually difficult or costly to extend or modify.

This paper is structured as follows: section 2 gives a brief overview on traffic modelling approaches up to the moment; Section 3 presents the approach proposed in this paper for traffic modelling by a dual approach with RPH and Matlab/Simulink models. Section 4 presents a case study of the models proposed in the previous section. Section 5 reviews the latest trends in developing solutions to the problem of traffic control and describes some research perspectives using the models introduced in sections 3 and 4. Section 6 is dedicated to conclusions.

2. MODELLING OVERVIEW

A fundamental requirement in traffic research is a clear understanding of traffic flow operations and insight on related traffic phenomena.

From a systemic perspective, traffic can be seen as both

- a complex system – large scale, dynamic, nonlinear
- an open system – extendable, modularized.

Modelling such a system implies choosing a model for traffic flow representation together with a set of relevant parameters, identifying perturbing factors, their nature – congestive, or non-congestive, and their propagation pattern throughout the system, determining invariants – functioning states – for the traffic system, isolating spatial-temporal parameters of congestive states, a.s.o.

A wide range of traffic flow theories and models have been developed. These modelling approaches are widely discussed and compared in Hoogendoorn & Bovy, 2001. The most common classification criterion for traffic models is the level of detail, or the level of abstraction of the traffic entities distinguishable in the respective flow models. From this perspective, there are:

- *sub-microscopic* and *microscopic models* which describe in high detail the time-space behaviour of individual drivers and the interaction with their surroundings;
- *mesoscopic models* which are medium detail descriptions of the behaviour of drivers without explicitly distinguishing their time-space behaviour;
- *macroscopic models* that describe collective traffic flow in low detail.

Other classification criteria for traffic flow models may be:

- the mathematical modelling approach for the traffic flow, which can be *purely deductive* – applying known accurate physical laws, *purely inductive* – using the interpolation of measured input / output real data, or *intermediate*, where the basic mathematical model is fitted using real data
- the scale of independent variables: *continuous models* – the system's state changes continuously in response to continuous stimuli; *discrete models* – state changes occur discontinuously over time at discrete time instants; *hybrid models*.
- the chosen representation of the processes: *deterministic models* which assume that all entities in the model are defined by exact relationships; *stochastic models* which incorporate random variables.
- operationalization: *analytical solutions* of sets of equations, or *simulation models*.
- the scale of application: single road segment models; traffic junction models, or crossroads; entire traffic network models (up to an entire city).

3. PROPOSED MODELLING APPROACH

This paper proposes two modelling perspectives for the case of urban traffic since the problems concerning the traffic dynamics are most stringent in urban areas. The main metropolitan traffic problem is traffic flow congestion. Solving this problem is of great importance in terms of time saving and pollution reduction. There are two types of congestions:

- type I – consisting in long waiting queues formed at crossroads;
- type II – a result of type I congestion that affects connecting crossroads by saturation.

A good urban traffic model should take into account this saturation phenomenon. A saturated street prevents a normal passing through the crossroad as presented in Fig. 1.

The models proposed are deterministic mesoscopic models which concentrate on building modular models of crossroads. The modular crossroad models are then linked together to form urban networks and study their evolution with respect to the vehicle flow as a continuous process represented as a complex function of the temporization of traffic lights (the control input parameters).

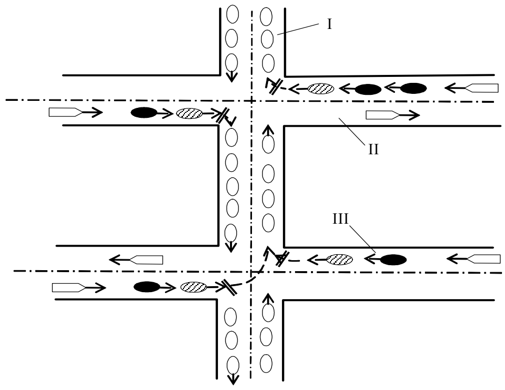

Fig. 1. The congestion of street I affects the flow on the II and III streets.

Traffic flow is modeled at the level of groups of interacting traffic entities, where each group is represented by the vehicle queue for a certain direction in a crossroad.

We have chosen a dual modelling approach – using both Hybrid Petri Nets and continuous equations implemented in Matlab/Simulink to build two equivalent models. The models were realized starting from the same assumptions, based on the ontology presented in Fig. 2.

For validation, the two models were simulated using the same input data to allow a consistency check and cross-validation.

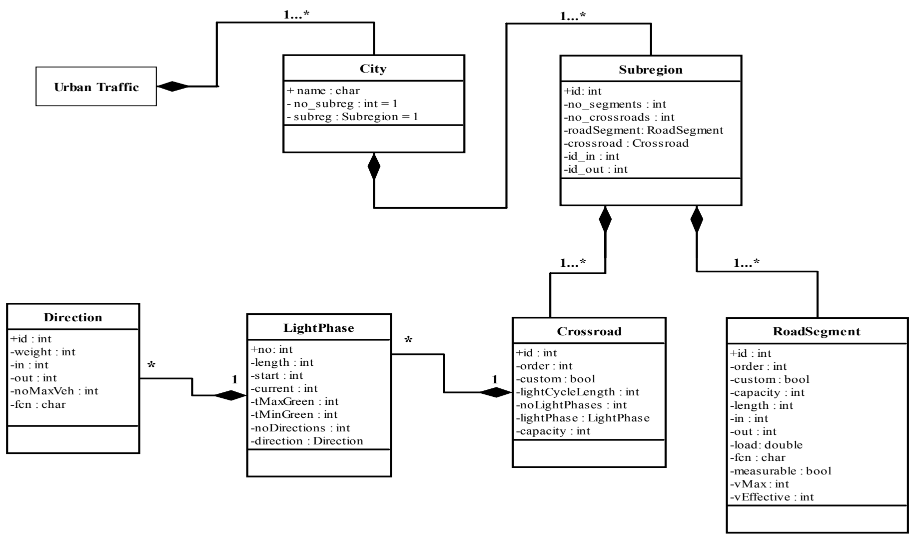

Fig. 2. Ontology definition for urban traffic modelling

3.1. HPN modelling approach

In the class of methods for modeling hybrid systems, Hybrid Petri Nets (HPN) [David & Alla, (1992), Demongodin & Giua, (2002), David & Alla, (2005)] represent a powerful formalism for modeling systems with hybrid dynamics (continuous and discrete), emphasizing their structural properties.

In addition, Hybrid Petri Nets preserve all the advantages offered by discrete Petri Nets, allowing the modeling of behaviors that involve synchronization, concurrency, and conflicts.

In the context of urban traffic modeling, this approach is very useful because it permits the representation of the dynamics of cars as they move along the network of streets and also the discrete events that occur in the form of phases of traffic lights assigned to each crossroad (junction).

The HPN model also has the advantage of clearly decoupling the continuous and the discrete part of the system allowing for a formal approach in calculating the control inputs for given sets of data.

3.2. Matlab/Simulink modelling approach

The second proposed class of models was created using Matlab/Simulink [Taylor et al. (2004)] which is an appropriate tool for modeling interconnected subsystems dynamics (evolution in time) taking into account the dependency between the composing objects. The dynamics and occurring events in an urban traffic network – containing several streets and crossroads that connect them can be easily observed using a simulation of this sort.

The Matlab/Simulink models offer a good simulation framework and rapid possibility of integration as a library in an existent software environment.

4. CASE STUDY

In order to test the conceptual models presented, an urban region of two traffic junctions was considered: a cross(X) junction and T-junction linked by a 500 meters road segment. The junctions are presented in Fig.s 3. and 4.

By convention, a junction consists of several access ways, a crossing area, and several exit ways. One access way may have multiple lanes, but has been characterized by a single waiting queue. A junction can also be viewed as a multiple input, multiple output system, and therefore in the following paragraphs we will refer to access ways as inputs of the junction and exit ways as outputs.

The X-crossroad in Fig. 3. is a junction of two road segments in a perfect cross, thus four inputs and four outputs.

Light phases particular to this junction are depicted in Fig. 3: during phase 1 the cars from I1 can go towards O2, O3, O4 and the cars exiting I3 can go towards O1 and O4; during phase 2 and 3 the vehicles leave from I4 respectively I2 and can take any direction. The total time of traffic light cycle is 147 seconds.

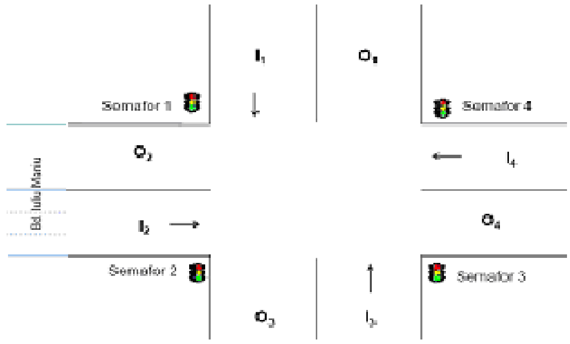

Fig. 3. Apaca X-junction

The T-crossroad is a junction with three inputs and three outputs. There are three phases: during the first phase the cars leave I1 and go towards the exits O2 and O3; during the second they leave I2 and head for O1 and O3 and similarly during the third phase they leave I3 and go to O2 and O1.The total time of the traffic light cycle for this junction is 125 seconds and the succession of light phases is the one displayed in Fig. 4.

Data taken directly from on site measurements (video files) was used to model and simulate traffic behavior of the considered region. Traffic light cycles and light phases were timed, and the number of cars that cross each junction has been measured over several light cycles at different times of day.

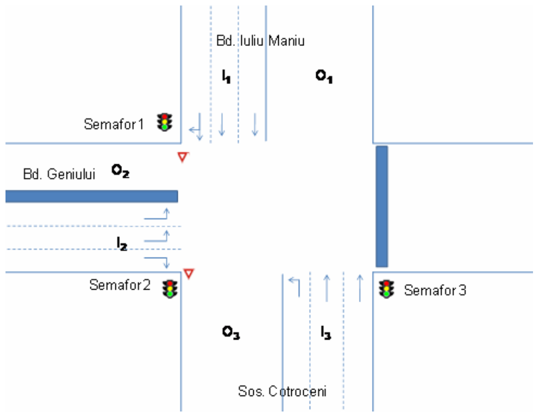

Fig.. 4. Cotroceni T- junction

The comparative study by simulation of the two models aimed to answer questions such as:

- Is it possible that in the given conditions (certain traffic light durations) and full entrances for both crossroads the dynamics leads to a congestion situation? And after how many phases?
- Are there any possibilities of choosing the traffic lights duration such that a congestion situation would never appear?
- Are there optimal values that not only avoid congestion but also lead to a traffic fluidization?

Such questions refer both to analytical aspects (the light cycle structure and the relation between this and the crossroad dynamics) as well as quantitative aspects (which can be obtained by simulation) of the traffic dynamics. In this context, the dual approach presented above was considered appropriate to represent the traffic flow within the chosen area (two interconnected junctions) from two complementary perspectives: the hybrid systems representation by HPN, and the Matlab/Simulink representation.

A first design objective of the dual approach was to cross-validate the two modelling methodologies, as well as to study the compatibility of the two perspectives. Subsequently, the HPN model will be used for the analytical synthesis of the traffic control solution, while the Matlab/Simulink model will be used to simulate the solution obtained analytically, thus proof-testing it.

4.1 Hybrid Petri Net (HPN) Model

To derive a HPN model for the traffic flow in an urban infrastructure, the following elements have been modeled:

- access ways or input paths into the junction, represented by continuous source place;
- exit ways or output paths from the junction, represented by continuous sink places;
- junction crossing of vehicles, represented by continuous transitions from the source places that model the inputs to the sink places that model the outputs of the junction;
- the light cycle of the junction, represented by the discrete part of the HPN;
- road segments or junction links, that enable the coupling of two junctions.

The marking of a continuous source place represents the number of vehicles waiting on that access way at the red light. The number of continuous transitions for a source place accounts for all the direction changes that are allowed for that input by the junction infrastructure. For each continuous transition the maximum speed of execution associated to it has been determined by the weights calculated in the experimental data.

The outputs of continuous transitions are the continuous sink places associated to the corresponding road segments of the outputs (exit ways) that collect the vehicles coming from all authorized directions, during a full traffic lights cycle. A sink place of a junction represents the source for recharging the source place of the next junction on the road segment considered. Flow of traffic on the road segment was modeled by a continuous transition, whose maximum speed reflects the constraints related to the capacity of the road segment and synchronization of the traffic lights.

Traffic light cycles are modeled by the discrete component of the HPN, through discrete places and discrete transitions. The delay for the continuous transitions represents the duration of green light on a specific light phase of the entire cycle.

The marking of discrete places is mutually exclusive and conditions the activation of the continuous transitions from the associated source place (access way), according to the succession of the traffic lights phases during the cycle. Exceptions make the discrete places with permanent marking 1, which model flashing green for turning right (where allowed by the junction infrastructure), allowing the permanent firing of the corresponding continuous transition during the entire traffic lights cycle.

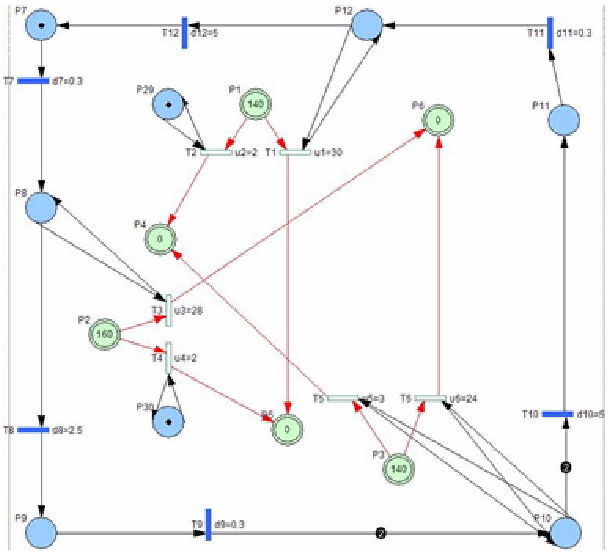

Fig. 5. HPN model of the T-junction

The model for the T-junction described at the beginning of this section is presented in Fig. 5 (in blue is the discrete light cycle) and the flow exiting can be observed in Fig. 6.

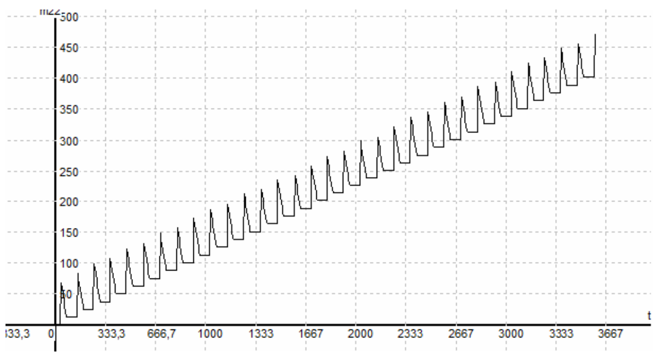

Fig. 6. Marking of the source place for the T-junction on the link segment, with initial green light timings

The HPN model for the coupled cross and T-junction is represented in Fig. 7. and was simulated on a time range of 3600 seconds (1 hour).

From the marking diagrams resulted for the continuous places the ones of interest are those corresponding to the source and sink places of the coupling link between the two junctions.

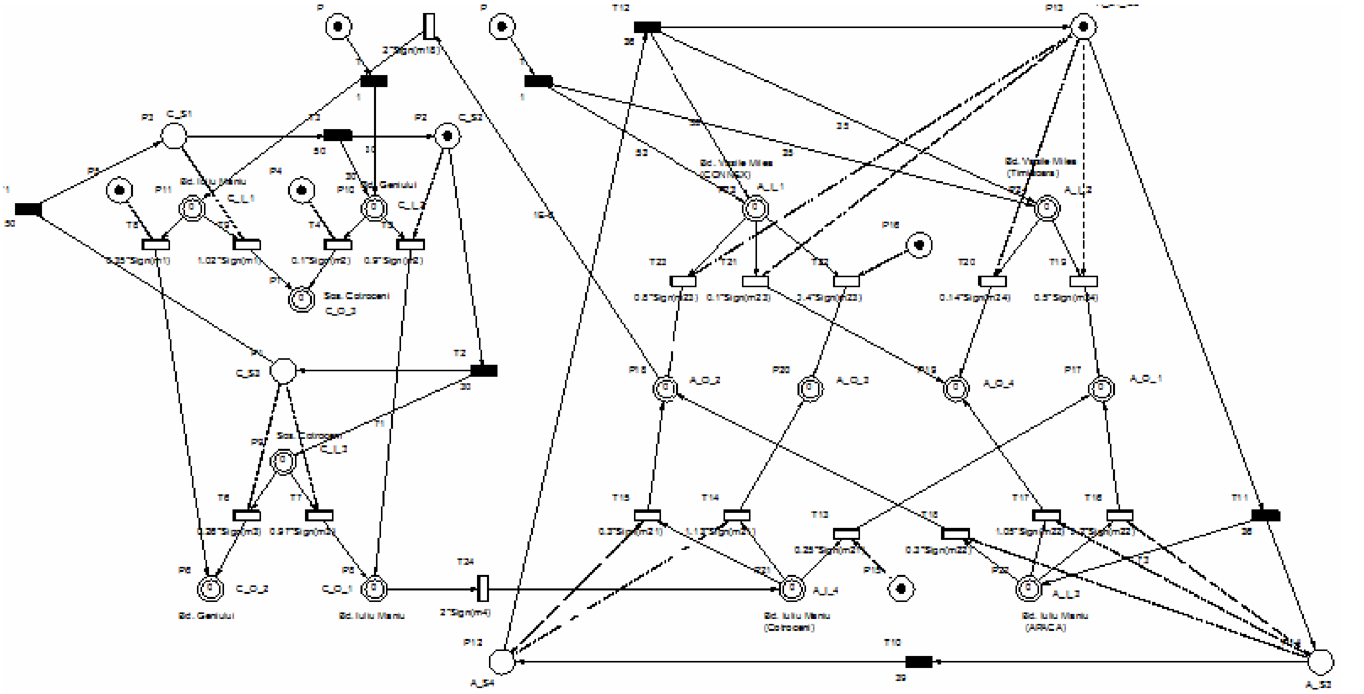

Fig. 7. HPN for the coupled T-junction and cross junction

Using the data for vehicle flows and green phases durations measured on field, we obtained a steady growth in the marking, which would eventually lead to an overload in the capacity on the link and thus a blockage (traffic jam) (see Fig. 6).

Since the vehicle flows on the inputs of the junction cannot be modified, the only control parameter that can be adjusted is the green light timing, by modifying the duration associated to the discrete transitions representing light phase changes of the traffic light. When the simulations was reiterated using the adjusted values for the green light timings, we obtained the evolutions presented in Figures 8 and 9.

The two figures present the evolution of the marking (in number of cars) of the places that model the link segment over time (in seconds). It can be observed from these figures a periodical evolution, with the limitation of vehicles number on the link segment, without accumulation.

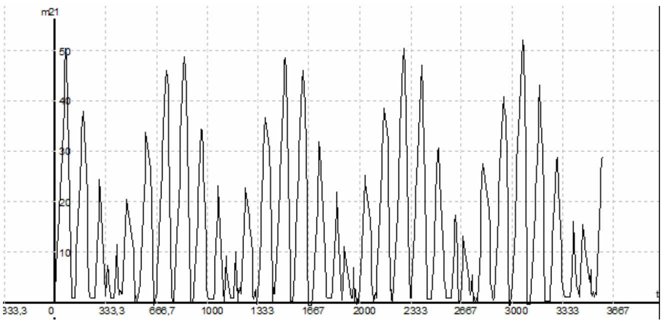

Fig. 8. Marking of the source position for the T-junction on the link segment, with the adjusted green light timings

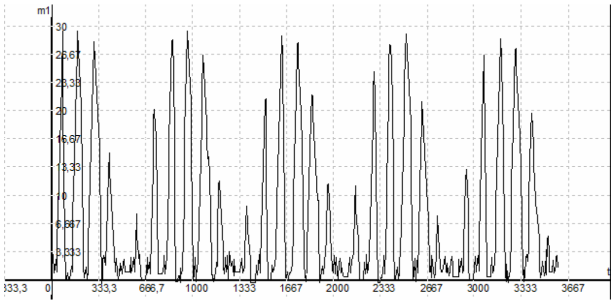

Fig. 9. Marking of the source position for the X-junction on the link segment, with the adjusted green light timings

4.2 Matlab/Simulink model

Considering the previously presented data, the Simulink block in Fig. 10 was created for the X-junction:

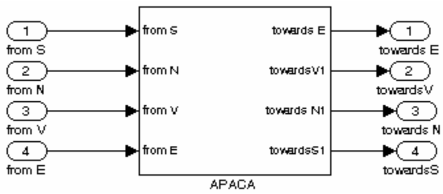

Fig. 10. Apaca X-junction – Simulink model

The inputs in the system are given by the 1-4 ports from S(south), N(north), V(west), E(est), and the exists by the ports 1-4 to(toward) S,N,V,E (as the direction were generically called). The inputs and outputs represent the variation of the cars number for a succession of crossroad cycles and can be observed graphically.

Firstly, we consider that the movement is instantaneous; in a following phase we will associate the dynamics function to the crossroad inputs and outputs.

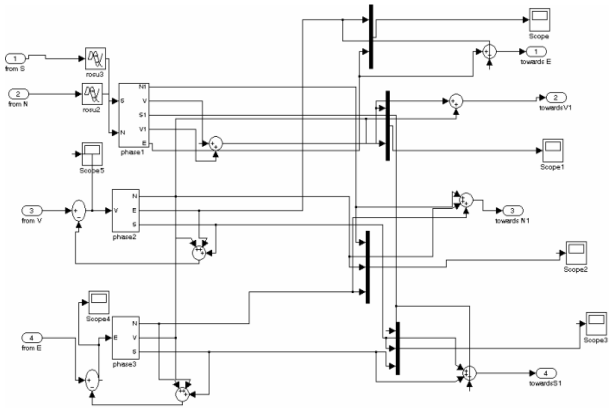

Fig. 11. Apaca phases – Simulink model

The internal structure consisting in three phases (1-3) that occur one after another in a crossroad cycle is represented in the Fig. 11. The number of cars leaving towards a certain crossroad output is sent to the targeted road and summed to that on that specific street sense. It is used as input flux for the following crossroad. The evolution of the cars passing through the crossroad can be also emphasized, if interesting.

The structure of a crossroad's phase is the presented in Fig. 12. The green light duration is restricted, that leads to a limited number of cars traversing the crossroad during a phase. In order to model this fact, a saturation block is included on each phase, marking the maximum number of cars leaving a street during the green light and heading for the following streets. The superior limit was set using the values obtained from the videos acquired from the crossroads.

Another limitation that should be considered is the free capacity of the targeted streets during green light.

If the number of cars targeting a certain street exceeds that allowed by the existing free space, then congestion will occur. Seizing this problem for a specific sub region is fundamental and the implementation procedure will be shown.

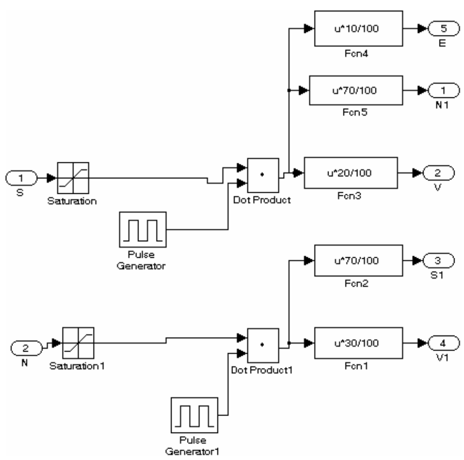

Fig. 12. Double phase of Apaca crossroad – Simulink model

The way that the phases succeed one another is implemented using the pulse generator block in order to set the period of time when the green light is activated (we have added the yellow light duration to this period).

Each phase includes the possible senses in which a car driver would decide to take and the probability functions for each sense (obtained from measured data).

Running the simulation on an interval of 500 second and considering that all the entrances contain the maximum number of cars all the time, we obtain the results listed in the Fig. 13.

These results show the way that phases periodically repeat themselves. The number of cars always reach the same value (superior admitted limit) because the entrances are considered at maximal capacity and the exists empty.

The number of cars reaches the maximum permitted value during a phase because all the inputs are considered at maximum potential at each moment, and that value is greater than the number of cars that can pass the crossroad during a phase. The evolution due to the alternation of phases can be observed.

The crossroad block previously presented can be generalized for no matter what type of crossroad an the entrances and output values can be acquired and set from reading a real time data file.

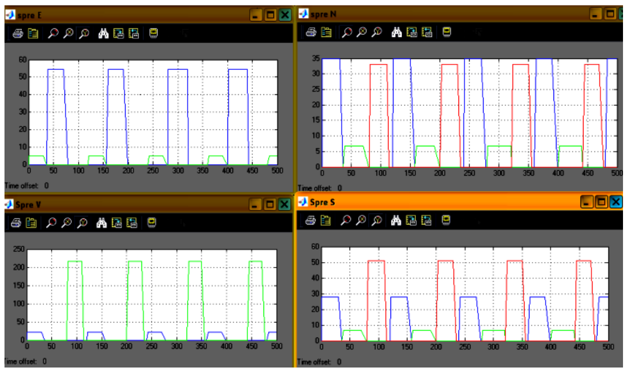

Fig. 13. Evolution of the number of vehicles for Apaca cycles when having saturated entrances

The T-junction was modeled in a similar way. The representation of this junction was given in the previous section and consists in three non simultaneous phases.

The model for the T-junction is even simpler - it consists in three phases also, but instead of the double phase represented in Fig. 11 we have a simple phase.

Coupling the two crossroads is made using two streets senses, physically being the two senses of Cotroceni Street.

The maximum capacity of the two street senses on the link segment between the X-junction and the T-junction was considered being equal to 300 standard vehicles. To catch the moment when this capacity is overran, a block that verifies the superior static characteristic (named street capacity) was included for each sense. This bloc will generate an error message for overrunning the capacity.

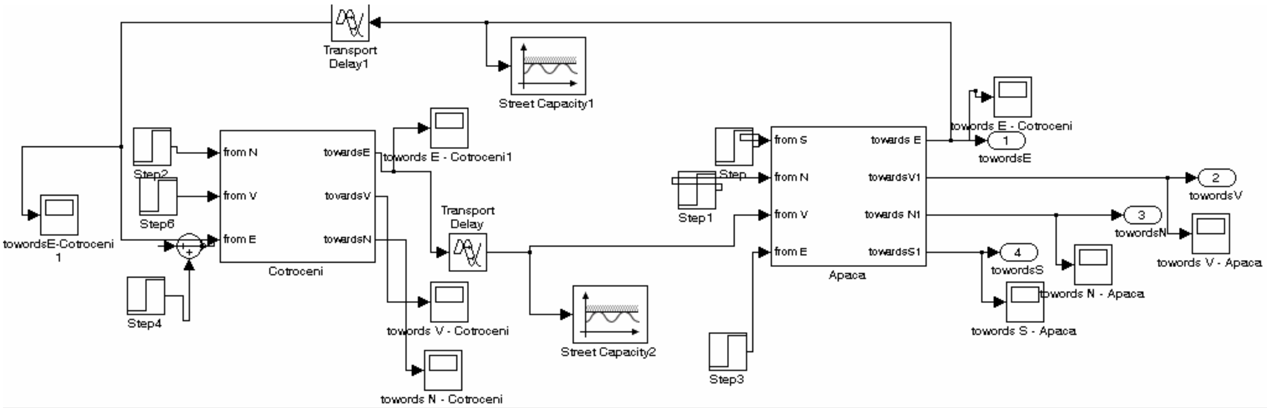

Fig. 14. Analyzed region in Simulink

In order to model the time lost by the vehicles to cross the distance between junction 1 and junction 2, a delay bloc of 40 seconds was introduced (see the model in Fig. 14).

By running a simulation of the real data we have obtained a congestion, similarly to the HPN model. In order to eliminate it a new set of duration for the phases has been chosen. The graphical results for the exits of the T-junction are listed below in Fig. 15. The graphical results for the exits of the cross junction are listed below in Fig. 16.

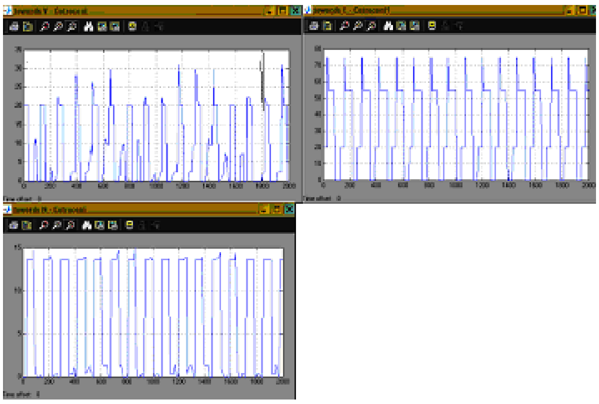

Fig. 15. Simulation results for the exits of the T-junction a. Number of vehicles heading towards V; b. Number of vehicles heading towards E; c. Number of vehicles heading towards N

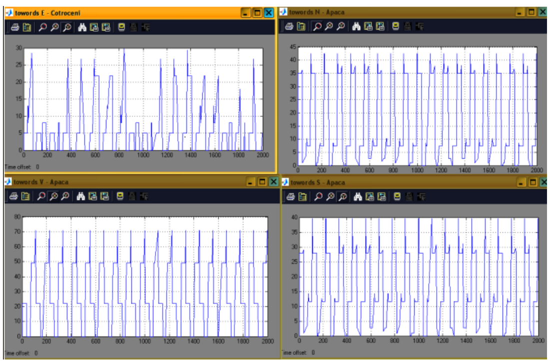

Fig. 16. Cotroceni a. Number of cars heading towards E; b. N; c. V; d. S

4.3 Observations

After connecting the junctions and represented the cars flows, a comparative analysis was done between the results presented in Fig. 8 and the ones in Fig. 15.a (common segment, enters Cotroceni), as well as the results presented in Fig. 9 and the ones in Fig. 16.a (common segment, enters Apaca). It can be noted that the same characteristics appear at the same moments of time.

Similar results were obtained for the two models for a series of other tests, which validates both models as well as the simulated results obtained by using them.

In the case in which the crossroads are linked, the number of vehicles varies accordingly.

When considering the street capacity parameter to be 300 standard vehicles and using a horizon of 300 seconds for the simulation in the chosen conditions, no congestions appear. This parameter was then modified in order to test the capacity overrun block and for a capacity of 80 vehicles or less, congestion was signaled.

These models gave satisfactory results for the aims initially set and performed as expected – for the green light duration of phases measured on site in the selected region congestion appeared when the entering queues were at maximal values.

As a first approach to correct this congestive situation a relative pass rate was computed as the number of cars that can pass through each junction per second of green light time and the duration of each phase was adjusted proportionally. The total duration of a traffic lights cycle remained constant.

A timing solution was reached that led to congestion elimination. Also, a periodicity in the traffic flow dynamics can be noticed for this solution, which proves the persistency of the non-congestive state for the external conditions considered (in-flow rates). The period for the region was observed to be the smallest common multiple of T1 and T2.

5. TRAFFIC CONTROL

In recent years, it became obvious that the traditional centralized approach to control large systems has reached its limits. Decentralization of control and decision making is seen as the future direction of research.

Due to its geographically distributed nature, the domain of traffic and transportation management is well suited to distributed architectures and/or multi-agent based approaches. The centralized traffic control paradigm is shifting towards more decentralised, hierarchical approaches with smaller control centers serving sub-regions of the intersection network in a city. A more scalable and flexible traffic control scheme is based on distributed control where intersections are represented by intelligent agents that mutually cooperate in order to reach an optimum traffic state. Prikryl (2006) reviews several directions of development in the use of distributed or multi-agent systems in the form of peer-to-peer networks of decision makers in urban traffic control.

The two modelling approaches presented in Sections 3 and 4 permit the definition of a set of generic objects like street segments and crossroads that can be embedded within complex software for traffic network simulation.

Modular models can be easily encapsulated into collaborating software agents that will reproduce the metropolitan network at the level of the communication paths established among them. A hierarchical control architecture can be designed that will simulate and evaluate the global model in order to synthesize the control input parameters to avoid congestive traffic states.

Because of the time-variability, non-linearity and uncertainties characterizing the traffic system it is difficult to design high performance control solutions using traditional methods. The latest research efforts in the area of traffic control are directed towards the use of artificial intelligence methods.

Fuzzy logic is a powerful tool for processing nondeterministic and non-linear problems, such as that of traffic control. Also, traffic control is generally controlled by rules, which makes fuzzy rule-based signal control a plausible choice. Membership functions can be defined for crossroad lane queue lengths using fuzzy terms such as “long-queue”, “short-queue”. More green time is allocated for a lane if there are many vehicles arriving in, and less green time otherwise.

Because their self-adapting, self-organizing, and self-learning properties artificial neural networks (ANNs) have non-linear mapping capabilities that are very suitable to solve traffic control problems, either as stand-alone solutions, or as hybrid solutions in conjunction with fuzzy logic. An ANN can be trained to output the best timing plan for traffic signal control based on real-time information received from field detectors, as well as other information (weather) and constraints (traffic load balancing, infrastructure-related constraints, etc).

The optimization of timing plans is essential for urban traffic control. However, this is a non-convex nonlinear optimization problem which is difficult to solve by traditional mathematical methods. Evolutionary algorithms are used to find solutions for such computationally demanding problems by simulation of reproduction and mutation of small genetic entities. All chromosomes search for an evolutionary stable strategy of the whole population which cannot be beaten by some other mutation.

Bayesian decision-making can successfully be applied to systems which intrinsically contain a lot of uncertainties, such is traffic in urban areas. Smidl & Prickryl (2006) presents and extension of the Bayesian decision-making theory to large distributed traffic systems in dense urban areas. A Bayesian Agent describes the whole intersection in the form of probability density functions (pdfs). Agents cooperate by exchanging their states as pdfs and have the task of reaching an optimum control strategy which can be obtained by a merging operation. An agent’s state can be represented by a triple: (traffic model – current state, control aims – desired state, control actions).

A summary and comparative analysis of the application of intelligent methods such as fuzzy logic, neural networks, evolutionary algorithms and agent reinforcement learning to urban traffic control can be found in Liu (2007). An up-to-date state of the art on advanced traveler information services, traffic management systems and traffic optimization systems is presented in Medina (2008).

A potential direction for the synthesis of a complete and versatile traffic control solution is by defining and implementing rules, or restrictions.

A first restriction can be defined in terms of the empty capacity of the road segments exiting a crossroad, together with the probability that the waiting vehicles will take a direction or another. During a phase, only that number of vehicle that can be supported by the next road segments will be allowed to pass.

Secondly, different priorities can be imposed, where required, to the road segments arriving in a crossroad, leading to longer green waves for the vehicles on the road segment with a higher priority.

Based on these rules, the phases’ duration within each crossroad light cycle can be computed on-line. By using the information related to improving flow-rate or arising problems up-stream, the length of the light cycles for the considered interlinked junctions can be adjusted, if necessary. In real time functioning, the cycles’ durations are not recalculated; this operation is always done offline.

The multitude of possible control methodologies gives proper reason for using two different modeling techniques, each model being more or less appropriate to be used for each certain control approach.

6. CONCLUSIONS

The paper presents a part of the research performed in the framework of the project “Intelligent techniques for modeling, analysis and optimization of urban traffic” (TIME-OUT – 7.1.108), financed by the National Center of Programme Management.

The main objective of the project is to eliminate congestions in urban traffic, using an adaptive, intelligent and re-configurable control system.

The main subsystem that is analyzed and modeled for control purposes is the crossroad, considered as a multi-input/ multi-output structure. Inputs and outputs are, respectively, car flows, and their number depend on the specific configuration of the crossroad. A library of cross-road models will result, used for configuration of large traffic networks, by a composition methodology that takes into account the capacity of streets.

The only control input available is the structure/ duration of traffic lights for every crossroad.

In order to appropriately evaluate the performance of a traffic network and consequently synthesize the control policy with respect to car flow evolution, a very important aspect is the accuracy of crossroad models.

For this reason a dual modeling approach was used, taking into account both analytical models, implemented as Hybrid Petri Nets, and simulation models, based on continuous equation set and implemented in Matlab/Simulink.

The reason is that the synthesis of control policies for hybrid Petri Net models should be based on some quantitative estimations of the system behavior, which can be easily obtained by simulation.

In this paper there are presented the two modeling methodologies as well as a cross-validation procedure of resulting models, based on the same input data.

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