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Modeling Ring-Barrier Traffic Controllers Using Colored Timed Stochastic Petri Nets

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Abstract — **As one of the many techniques used in modeling traffic processes and systems, Petri Nets are recognized as a tool for modeling in traffic signal control. In this paper, ring-barrier traffic signal control structure is modeled using Petri Nets. Colored Timed Stochastic Petri Nets is used in this paper to provide additional modeling capabilities. The proposed model incorporates all the main features of ring-barrier structure and includes the modeling of left-turning vehicles. We also describe and discuss possible control structures, previously developed Petri Net models and implementation issues.**

I. Introduction

TRAFFIC engineering is an area of transportation engineering dealing with safe and efficient planning, geometric design and traffic operations of roads, streets and highways, their networks, terminals, abutting lands relationships with other motorized and non-motorized modes of transportation. Urban traffic control, as one of the essential parts of traffic engineering is dealing directly with safe and efficient operations of road networks.

Since 1868, when the first traffic lights were installed, up to now, the role of traffic control in the overall national transportation network and traffic management is constantly increasing. Environmentally conscious traffic management, energy saving models and increased computer application in everyday real-time operation are just one of the many trends in urban traffic control throughout the whole world.

Traffic signal systems have always integrated the conflicting duality reflected in two main control goals: safety and efficiency[1]. These two goals have established all the fundamental principles related to traffic signals. Even in the future, most of these traffic engineering fundamentals are not going to change, but in the process of evolution in the operation of transportation facilities, they will be applied in new ways to meet incoming challenges. Today, traffic control technology is developed continuously in order to expand and increase its capabilities and help traffic engineers in more and more complex issues posed in front of them. On the other side, besides the development in the technology itself, a new modeling and optimization techniques, such as artificial intelligence techniques, knowledge based expert systems, and other various operations research and simulation techniques are under constant improvement and development.

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II. Petri Net Modeling

A. *Petri Net definition*

Petri Net is a particular kind of directed, weighted, bipartite graph with specific graphical representation, consisting of two kinds of network nodes, called places and transitions, and arcs which are either from place to transition or from transition to place [2]. Each place is marked with tokens whose movement trough the network is used for representation of modeling processes. From modeling perspective, concepts of conditions/states (using places) and events/actions (using transitions) are represented by the network nodes. In the graphical representation, places are usually represented as circles and transitions as rectangles. The advantage of this modeling technique is that it can be state and action oriented at the same time[3]. Petri Nets play a key role among the modeling techniques for discrete event systems because they are able to capture the precedence relations and interactions among the concurrent and asynchronous events. There are various types of Petri Net, from the most common ones up to a High-level Petri Nets, which are used to increase modeling capabilities and reduce the size of models of ordinary Petri Nets.

B. *Petri Nets in Traffic Engineering*

Since the 90's, Petri Nets had been used for addressing issues in traffic engineering such as traffic light planning, dynamic routing, special vehicle control and traffic flow modeling [4]. Petri Nets are also used in other transportation related fields of study, such as for example in automated guided vehicle system for logistical purposes [5].

One of the first papers on the implementation of Petri Net in the transportation modeling was in 1993 [6]. Some papers in the 90's have also recognized the potential of Petri Nets for safety-related and modular representation of traffic control systems, along with potentials for large-scale transportation systems implementation [7], [8]. All these papers used basic Petri Nets models in their modeling approach. In these very first papers, the universal issues related to traffic control were also discussed. On the one side are the issue of specified safety rules under which controller has to operate, and on the other hand, the issues of flexibility and serviceability of traffic control process. As it is

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discussed in these papers, both of these issues can be potentially resolved using Petri Nets.

This paper describes the potentials of Petri Nets application in typical traffic control strategies, with developed subnets for traffic control logic and traffic flow representation. Finally, as one of the important contributions of this paper, besides being one of the first to use Petri Nets in the area of traffic control, is that results of the performance evaluation are compared with analytical approaches from Highway Capacity Manual. Safety related issues such as predefined timed color sequence and impossibility of the occurrence of conflicting movements are successfully resolved using Petri Nets and verified with specified analysis methods that are developed for Petri Nets. Furthermore, Petri Nets as a modeling technique has been proven to have properties for providing enough flexibility for modeling the traffic control process.

After these initial papers, other authors started to develop and expand the possibilities of Petri Nets to model traffic control systems by introducing more data diversity and management capabilities into Petri Nets itself [9]. The research was directed toward specific type of Petri Nets - Stochastic Timed Petri Nets (STPN).

STPN, besides introducing the stochastic element in the traffic control modeling, lead to the significant reduction in the complexity of analysis. Stochastic nature of the time in the traffic process has been one of the main reasons for introducing this specialized type of Petri Net, and those issues are successfully resolved with properties that STPN have. On the other hand, this development did not bring in any improvements in the modularity or initial model complexity reduction.

After this, the following papers such as [4] and [10], brought in the idea of implementation of higher level Petri Nets – Hybrid Petri Nets, with an idea that a transportation network per se is considered to be a hybrid system, including both continuous-time and discrete event components.

The most recent developments have lead to the widening of the area of research into Colored Petri Net (CPN) as a more powerful upgrade of basic Petri Nets[3] [11], [12]. Besides implementation in fundamental traffic control models, other papers, have introduced the possibilities of Petri Nets implementation in the area of transit priority and emergency vehicle preemption [13], [14], or even the implementation in the area of micro and macroscopic modeling of traffic flow [15].

C. Stochastic Timed Colored Petri Net

In this research, Stochastic Timed Colored Petri Nets (STCPN) is selected to be a technique for the implementation. STCPN are chosen as a logical continuum of the previous research done in the area of Petri Net implementation in traffic control. STCPN provides primitives for the description of the concurrent processes synchronization and the supporting programming language provides the primitives for the definition of data types and manipulation of data values.

Each STCPN net used in this research consists of net structure, declarations and net inscriptions. Methodology of modeling timed processes in STCPN is based on global clock, which represents model time, and time stamp, which is associated with particular token. This feature allows modeling of deterministically or stochastically distributed time intervals.

All the previous research has lead to the conclusion that STCPN have several advantages:

- Provides means for clear graphical representation of control logic;
- Provides more relevant information using stochastically distributed time;
- Single token caries more complex information or data and thus reduce the size of the models;
- Can be constructed of hierarchically distributed individual sub-models and thus describe more complex systems;
- Has well defined and compact semantics, allowing formal description, analysis and performing of safety and deadlock control analysis; and
- Has available software tool for the analysis.

Petri Nets can therefore be used in the modeling of traffic control for the following reasons:

- Can express concurrency, competition and synchronization in the actions;
- Can implement mathematically defined analysis techniques for verification of control logic; and
- Can be used as a universal and direct graphical medium for communication.

III. NEMA Ring-Barrier Control Structure

In traffic control, phases, with all the related control parameters, are the essential mean for conducting the desired control behavior to the system user. The National Electrical Manufacturers Association (NEMA) provides detailed nomenclature for signal phases definition in order to eliminate misunderstanding between manufacturers and purchasers [16]. This is control type usually referred as ring-barrier-phase control or NEMA phasing and is used in North American traffic control implementations.

In ring-barrier control, controllers have five predefined time intervals – green, yellow, red clearance for vehicle movements and walk and flashing don't walk for pedestrian movements. Each of these intervals has a specified duration and each phase is assigned to compatible vehicle or pedestrian movements. Each of the phases is assigned to a specific ring and to a specific barrier (Figure 1).

The logic behind ring-barrier control, defined in phases having different ring or barrier compatibility is as following:

- Phases assigned to the same ring are timing sequentially,
- Rings times simultaneously, and
- Phases designated to different barriers are timing independently.

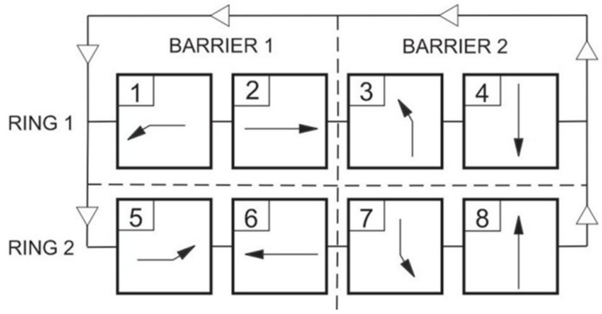

Fig. 1: Dual ring eight phase control defined by NEMA nomenclature

Ring-barrier-phase control logic (Figure 2) is the essence of any modern traffic signal controller operational structure. From Figures 1 and 2 it is observable that each movement has dedicated and standardized phase number. This standardized representation of control logic easiness programming, modeling and calculating of signal control parameters. In addition, this standardized representation is enhancing communication among traffic engineers.

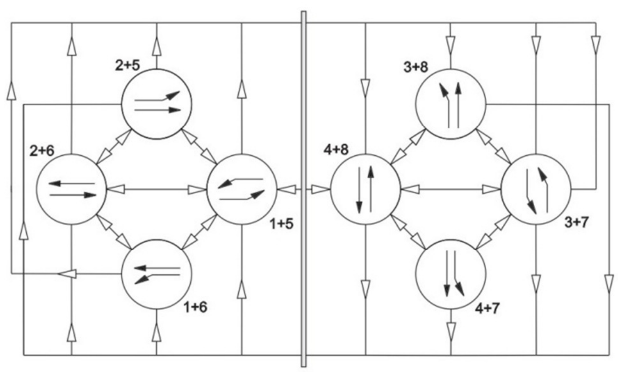

Fig. 2: Dual ring control logic implemented in traffic signal controllers

Because of the high importance of previously described control structure, there is a need to adequately represent and model its control behavior. For example, the recent development in the new techniques for representing traffic control systems is reflected in the usage of precedence graph models [17]. Proposed precedence graphs are illustrating the interactions among phases, intervals and overlaps, from a simple three leg intersection up to the example of advance flashing warning signals. The idea of this implementation is, using a structure-modeling approach, to create a representation that is leading up to a better understanding and improved development of signal control logic.

Using the similar idea as one of the basic premises, one of the techniques receiving more and more significance in the area of traffic control throughout the world is Petri Nets. Initially used in various expert areas, such as computer applications, protocol and operational process modeling implementations, this technique has found its place among the other techniques for modeling and simulation of traffic related processes and systems.

A. Model Formulation and Development

All the previous Petri Net models found in the literature are based on the control logic that is not directly used in North American NEMA standard. The model presented in this paper is representing structure that ring-barrier control has. The essential premises behind ring-barrier structure to disable certain conflicting vehicle movements while leaving enough flexibility for efficient control are imbedded in the logic of the Stochastic Timed Colored Petri Net model presented here.

In using Petri Nets to model certain system, modeler usually takes two different perspectives to model the system and its behavior. Those perspectives are based on the features of the modeled system and can be recognized as modeling flow of control or modeling flow of data.

In this particular case, and taking into consideration all the features that NEMA ring-barrier control system has, the researchers have decided to take the approach of modeling the flow of control. Here it also has to be stated that top-down design approach has been applied, in an attempt to break down the system into smaller sub-systems. These approaches consequently lead to specific modeling results.

Analysis of the modeled control system has produced a list of definite system features and components. Besides certain system features and components, that represent real life system, some of the system features are assumed or omitted. Assumption or omission of certain system features is not disrupting general system behavior or its safety related features, since all the features not represented in this model are related to greater system efficiency and flexibility. The premise behind this is that safety features of the traffic control system have primary role over any efficiency related feature.

As previously stated, the model's intention is to represent the logic imbedded in the traffic signal controller on the isolated signalized intersection. An intersection is considered to be fully actuated with detection mechanisms located on all major and minor approaches. Separate stop bar detectors are placed in each through and left turning lane. In addition, advance detectors are placed upstream in through lanes (Figure 3). This is the usual practice in detector location for fully actuated signalized intersections.

The initial assumption is that the ring-barrier control structure consists of eight signal phases. All the phases are assigned to specific vehicle movements. Vehicle movements considered in this model include both, vehicles going straight through the intersection and vehicles turning left in the intersection.

Vehicles turning right in the intersection receive the same phase timing as vehicles going straight through the intersection since no right turn on red is allowed. This model is the first model to consider representing left turning vehicles. The guiding idea behind this implementation is that omitting modeling vehicles in left turn significantly reduces the validity of the real world model representation and its safety/efficiency related features, thus reducing the model's fidelity.

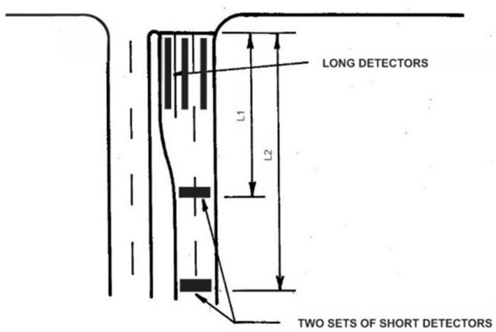

Fig. 3: Approach detector layout

On the other hand, inclusion of left turning vehicles is significantly complicating the modeling process and the model itself.

One of the assumptions made in this model is that no pedestrian signals exist on the signalized intersection under consideration. This of course does not mean that pedestrian flows do not exist or cannot be served on the intersection, but it means that pedestrian flows are referred to use the vehicle signal indications. Furthermore, because of the previously stated assumption, no pedestrian detectors are assumed to exist on the intersection. Nevertheless, signal timing logic is taking into consideration pedestrian movements in the duration of minimum phase timings.

Another assumption is that both barriers start timing with the phases dedicated for through movements – phase 2 and 6 for barrier 1 and phase 4 and 8 for barrier 2. Through phases in each barrier separately are also defined as dual entry phases. This means that call for any of two groups would also activate the other group signal in the absence of calls on the predefined detectors of non-conflicting groups.

STCPNs used for the model creation, as a discrete modeling technique, support stochastic nature of the traffic process on the signalized intersection. That stochastic nature of traffic process reflects in the distribution of vehicle inter-arrival times, which are assumed as exponentially distributed. Each particular vehicle arrival is assumed that places a call on the detector located in front of the stop bar. A detector call is assumed to be a signal, translated and conducted from particular detector unit to the controller's processing unit. As previously stated, because of the detector configuration, detector signal for trough and left turning lanes are separated. Vehicle that arrives on the approach and places a call for a specific direction, in the absence of all previous un-served calls (vehicle waiting in the queue) will assure the activation of particular phase and at least duration of minimum green.

Actual phase indication that will appear on the intersection signal head will depend on the simultaneous/asynchronous calls on other phases, previous phase activated, minimum and maximum duration of a particular phase and moment in system time. System time in the model is represented via global clock that is operating for the complete model. Global clock changes timing in discrete intervals depending on the particular timings in the model nodes. All of the model tokens have their own time represented via time stamp and they define the time steps at which model global clock is changing value.

Signal head indication, as previously stated, is directly depending on the tokens that represent different detector actuations in time and space. Change of the signal status is controlled by safety features of ring-barrier structure and is only possible if all the conditions for change are met. Constraints in the conditions are represented using different combinations of arcs and transitions in the model.

It has to be stated that the model represents only the control logic and not the movement of the vehicles through the intersections. The reason for this is that modeling of vehicle movement through the intersection is not going to directly provide benefit by improving model capabilities or potential outputs. Modeling of vehicle movements through the intersections is planned for future improvements of the model. At this point, the assumption is that modeling of vehicle movements would require modularity of the model that could be also implemented in Colored Petri Net having in mind this modeling technique has the ability to represent such a structure.

IV. PROPOSED STCPN MODEL

Developed model, being a Stochastically Timed non-hierarchical Colored Petri Net is a tuple STCPN = (CPN, R, r_0) that is consisting of:

CPN = (Σ, P, T, A, N, C, G, E, I) defined as:
Σ – finite set of color sets
P – finite set of places
T – finite set of transitions
A – finite set of arcs ($P \cap T = P \cap A = T \cap A = \emptyset$)
N – node function $P \times T \cup T \times P$
C – color function
G – guard function
E – arc expression function
I – initialization function

All these elements are specific for Colored Petri Net as a modeling technique and the software where model was developed – CPN Tools. In addition, model is consisting of global color set/variable declarations and functions based on Standard Modeling Language. One of the functions is a function for generating inter-arrival times by exponential distribution used on the transitions as a node function.

```
fun ExpTime (mean: int) =
   let
       val RealMean = Real.fromInt mean
       val rv = exponential((1.0/RealMean))
    in
       floor (rv+0.5)
 end;
```

A. Petri Net Construction and Refinement

As previously stated, the top down approach for model development has lead to structural and behavioral analysis of the control structure. Each of the analyzed parts of ring-barrier concept are modeled using specific Petri Net sub-network. Since safety concepts are given a prime role, initial model sub-networks were created to fulfill constraints that ring-barrier logic imposes on the conflicting vehicle movements.

The envisioned model representation of ring-barrier control is based on the control logic presented in the Figure 2. General model representation is presented in Figure 4. Places B1 and B2 represent state of the control mechanism with activated barrier 1 or barrier 2, depending on the vehicle actuations. Simulation process starts in the barrier 1 but the network configuration should allow transitioning from and returning to initial state. Transitioning between barriers is constrained with a specific set of actions taken and conditions fulfilled.

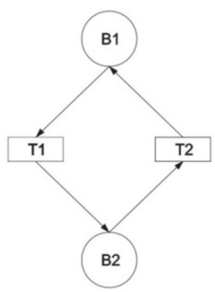

Fig. 4: Overall Petri Net model

Further structural development of the model resulted in the several sub-networks. Some of them are presented in the Figures 5, 6 and 7.

A sub-network in Figure 5 represents inner control structure of barrier 1. The idea for generating vehicle arrivals that are translated into detector calls, as previously mentioned, is developed and implemented in this sub-network of the model. Stochastic vehicle arrival process is located in the place named Arr. The generation of detector calls for activating phases from barrier 1 and 2 is separated thus resolving the possible issue of conflicting detector calls.

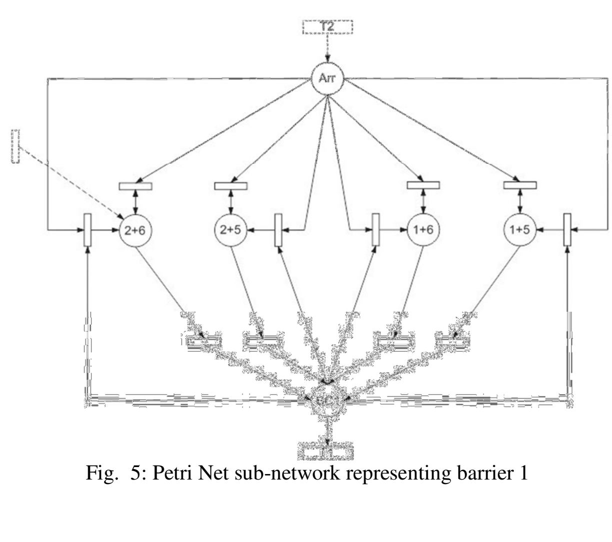

Fig. 5: Petri Net sub-network representing barrier 1

Sub-network is also defined in such way that signal timing is updated each time vehicle is served. Vehicles in the specific lane receive green time until the temporal gap between successive arrivals of detector calls is higher than predefined minimum (gap out) or until the green time reaches maximum allowable timing (max out). Presence of token in one of the places 2+6, 2+5, 1+6 or 1+5 is representing the activation of that specific phase combination. Each token carries information about the duration of phase timing. Dashed transition and arc on the left side of the figure represents the idea that phases 2 and 6 are the first one to be activated in the barrier 1. Dashed transitions T2 and T1 on top and bottom of the picture, respectively, represent the transitioning between barriers.

Furthermore, in the process of control structure analysis, additional sub-networks are created to resolve the issues of asynchronous detector calls (arrival of vehicles) in the same barrier. In the ideal case, simultaneous arrival of vehicles from different approaches would activate specific phase from a specific barrier. Since arrival of vehicles is random, in majority of cases the arrival of vehicles is not simultaneous. Figure 6 presents an example how is the issue of asynchronous detector calls for phases 2 and 6 from barrier 1 resolved using network structure. As previously assumed, phases 2 and 6 are dual entry phases.

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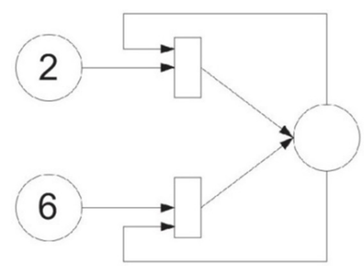

Fig. 6: Petri Net sub-network resolving asynchronous arrival of vehicles

Additional sub-network is presented in Figure 7. The intention of this sub-network is to resolve control priority between phases that serve through and left turning movement. As previously stated, phases controlling through movements on the intersection are timing together and before other phases in the particular barrier. The restrictions are primarily modeled by controlling transition firing.

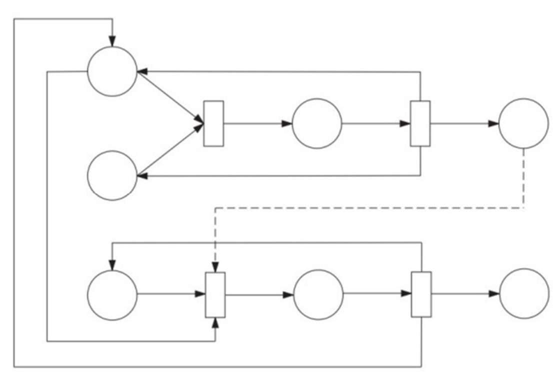

Fig. 7: Petri Net sub-network resolving control priority of phases that serve through movements

B. Model Analysis using Petri Nets techniques

During the control structure analysis and model creation, as previously stated, safety features of the NEMA ring-barrier structure are considered as the most important. Specifically speaking, control structure should not allow simultaneous movement of conflicting vehicle flows, should not deadlock in the specific state, should be able to return to initial state and should allow changes in the control output only when specific conditions are met.

Petri Net, as a modeling technique, has predefined properties that can be related to the expectation of model behavior and that can be investigated using several validation methods. All the validation methods have defined semantic and logic that can be implemented with software used in the model creation. In this particular case, discrete transition-based simulation, as a user-friendly and visually based tool for investigating model behavior, is chosen as an initial validation tool in the process of model development. Furthermore, specific developments of network structure, token colors assigned, and codes accompanying the network itself are introduced to restrict simultaneous movement of conflicting vehicle flows and allow the influence on the control output.

Final model validation using coverability tree method has confirmed that networks created are alive and able to return to initial state, thus preventing the occurrence of deadlock in the system. At the end, investigating the structural model properties it is confirmed that net is bounded, conservative, repetitive and consistent which provides additional real life implementation value to the model.

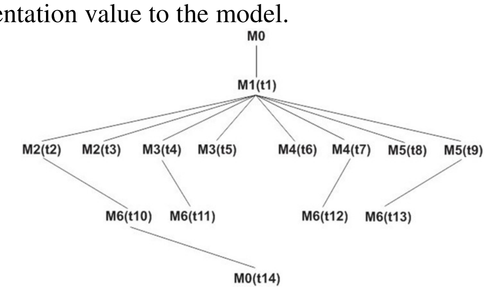

Fig. 7: Graphical representation of coverability tree for Petri Net sub-network representing barrier 1

V. Conclusion and Future Work

The developed Petri net model is based on the analysis of the ring-barrier control structure. The model captures the current practices in US signal traffic control and includes modeling of 8-phase full NEMA controllers, including left turning vehicles' phases. The model establishes the groundwork for developing new features in next generation controllers, and provides a mechanism for documenting and communicating these features to other researchers and developers.

There are many possibilities for applying the model and expanding its capabilities. Future work includes further model expansion with the goal of introducing optimization capabilities, testing of the model with the field data and comparison to commercially available simulation software.

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