SIMULATION MODEL OF A RAILWAY JUNCTION BASED ON PETRI NETS AND FUZZY LOGIC

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ABSTRACT

Railway track junctions have lower safety and limited capacity and require specific traffic management. When determining optimal infrastructural and technological solutions for a junction, it is essential to evaluate its parameters for various volumes of traffic, operating conditions, junction designs and safety conditions.

Complex traffic systems, like junctions, cannot be accurately described in detail with analytical or graphical methods. Thus, a simulation model is proposed in which junction systems are modelled by High-Level Petri Nets. Petri Nets formalism is an effective and advantageous way to develop a model for simulating railway junction processes, including safety requirements, train spacing, timetable and infrastructure data. *Tokens* represent trains, and *places* represent track sections. The model enables experimentation with input data (infrastructure design, train spacing, timetables, etc.). A subnet module represents each type of section, and the model is created by connecting modules according to the junction system section plan. The input data are imported to the model from an external database. Simulation results are stored in the database and then presented as data tables, like a track occupancy animation and train diagram (time – distance diagram).

Train delays in the model are calculated by a fuzzy logic system. A fuzzy system is defined by a set of rules and input variables: train category, train traffic intensity, train distance travelled and infrastructure parameters, such as a single or double track, number of stations, number of junctions and length of sections with limited speed.

The train time-distance diagram and animation window are used to validate and verify the simulation model by animating train movement and track section occupancy. The model is tested on part of the Belgrade railway node network.

Keywords: railway, junction, Petri nets, Fuzzy Logic, simulation model

1. INTRODUCTION

A Railroad Junction is a place on the railway line where another line diverges. It is a very complex system and is very difficult to describe with analytical models. A simulation model can compute junction parameters for various operating scenarios. The simulation of a junction system and experimentation with its input data is an inexpensive and effective analysis approach. A simulation model must incorporate all interlocking and operating rules and data. Petri Nets are tools for graphical and mathematical modelling of various systems. High-Level Petri Nets (HLPN; timed, coloured, stochastic and hierarchical) are tools that can model complex systems and provide good graphical presentation of the model. Simulation models for analysing railway systems can be found in the literature over the past 20 years.

Basten, Roland and Voorhoeve (1995) created a simulation model for the analysis of interlocking specification using coloured Petri Nets in the Expect software. Van der Aalst and Odijk (1995) proposed the interval timed coloured Petri Nets (ITCPN) for modelling and analysis of railway stations, where train delay is specified by an upper and lower bound, i.e., an interval. Fanta, Giua and Seatzu (2006) used a coloured Petri Nets (CPN) model of a dynamic rail system for determining deadlock situations. Daamen, Goverde, and Hansen (2009) developed a CPN tool for route conflict identification and estimation of knock-on delay.

Higgins and Kozan (1998) presented an analytically based model to quantify the expected delays for individual passenger trains (direct delay to trains, knock-on delays to other trains and delays at scheduled connections).

Landex, Kaas, and Hansen (2006) defined unexpected waiting time, primary delay and secondary delay and presented the analytical method for their calculations. Yuan and Hansen (2007) proposed an analytical stochastic model of propagation delays in the stations for the calculation of secondary delays caused by route conflicts and late transfer connections.

Three different approaches are possible (Mattsson, 2007): analytical methods, microsimulation methods and statistical analyses based on empirical data. An analytical model uses the Queuing theory and does not require a lot of input data. Analytical models usually apply some form of simplifying assumptions to the system. Simulation models are representations of railway systems and are the only reasonable way to model railway processes where different trains interact with each other and with the infrastructure. They require very detailed data about the infrastructure, the performance of the trains and, most importantly, about the timetable. If one of these data categories is unknown, it is necessary to make assumptions, and the results then depend on the quality of input data. Statistical analysis is mostly used for modelling the occurrence of primary delays. Observed delay data could be used to establish empirical relationships between capacity utilisation and secondary

delays, given the prevailing level of primary delays. This process can be applied in railway systems that are well regulated and operate in stable conditions. In systems where there are many possible sources for disruptions and a relatively high probability that external influences induce primary delays, it is difficult to find some relationship that would predict train delays.

Fuzzy logic has been shown to be a good mathematical tool for modelling traffic processes that are distinguished by subjectivity, uncertainty, ambiguity and imprecision (Teodorovic, 1999). Many researchers use the advantage of predictive modelling systems with fuzzy logic. Fay (2000) used a fuzzy system as a dispatching support system for use in railway operation control systems. The model is defined as a fuzzy Petri net model that combines expert knowledge of fuzzy systems and the graphical power of Petri Nets, making the model easy to design, test, improve and maintain. Cheng and Yang (2008) proposed a fuzzy Petri Net model that uses professional knowledge of dispatchers to create database rules to be applied for testing the system in the case of disorder.

Fuzzy logic models for the calculation of junction train delays could utilise the experience and knowledge of railway personnel who directly participate in regulating the traffic system. Data from personnel surveys, timetable information, and infrastructure parameters can be used to define a fuzzy system for forecasting train delays.

This paper is structured as follows. Section 2 starts with a definition of railway junctions and their influence on traffic. A High-level Petri Net model for the junction system is described in Section 3. Section 4 presents the fuzzy logical system for the computation of the train delays. Section 5 demonstrates a case study and the application of the HLPN and fuzzy logic model to Junction "G" located in the Belgrade railway node, and conclusions are given in the final section.

2. RAILWAY JUNCTIONS AND THEIR EFFECT ON TRAIN TRAFFIC MANAGEMENT

A junction is an arrangement of tracks and turnouts in which two lines are joined (Pachl, 2002). Railway tracks with junctions have lower safety and limited capacity and require specific traffic management. Safety is reduced at junctions because they are positioned on an open line where train routes conflict. Junctions reduce railway line capacity and can cause secondary delays.

The simplest junction allows the transition of trains from one line to another (branch line). In a double track junction, a double-track railway line is branched from a double-track main line. The speed of the trains at a junction is limited by switch properties.

Junctions that join double-track lines can be classified as follows (Figure 1):
- Junction with diamond crossing,
- Junction with double switch,
- Junction with two switches and connections between tracks,
- Single track reduced double junction,
- Junction with diamond crossing and wide centres,
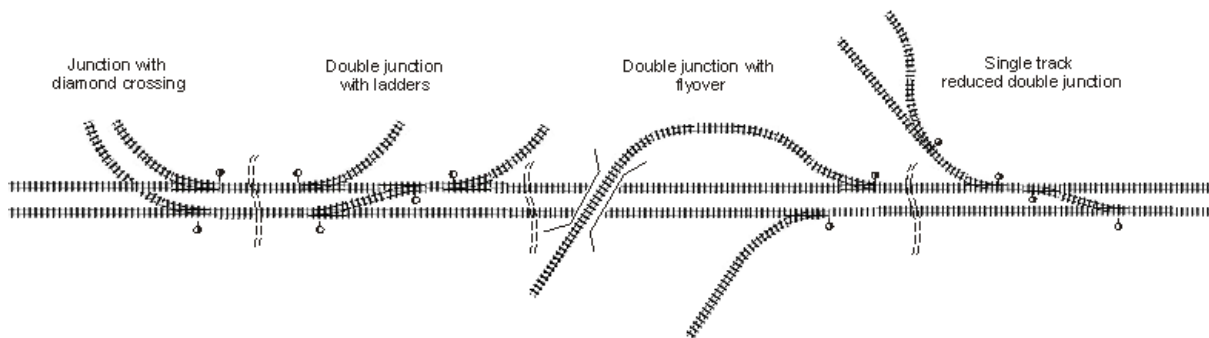- Partially graded separated junction.

Figure 1 - Types of junctions on a double-track railway line

Junction can be described by the follow characteristics:
- Position on a railway line (location),
- Types and characteristics of switches,
- Layout of junction block signals,
- Possible train routes that are dependent on junction design and signal and safety level,
- Train operating rules of a junction system (Automatic Block System-ABS or other system for spacing trains).

Relevant parameters for junction system evaluation and its influence on train traffic include the following:
- Utilisation or percentage of total and physical occupancy of a junction section and surrounding block sections,
- number of trains through a junction in a given period of time,
- number of trains and their total delay time at junction signals,
- number of trains and their total delay time in different parts of the junction system.

3. PETRI NETS AS A TOOL FOR MODELLING A JUNCTION SYSTEM

3.1 Petri Nets

Petri nets are mathematical tools for modelling used for analysis and simulation of concurrent systems. The theory of Petri nets is based on the mathematical theory of bipartite graphs. A bipartite graph (or bigraph) is a graph in which nodes can be divided into two disjoint sets V_1 and V_2 so that every edge connects a node in V_1 to one in V_2; that is, there are no two identical nodes in the same set. A Petri net is one of several mathematical descriptions of discrete distributed systems. The system is modelled as a bipartite-directed graph with two sets of nodes: the set of places that represent a state or system objects and a set of events or transitions that determine the dynamics of the system.

High-Level Petri Nets are defined as follows.

A HLP-net is a structure *HLPN = (S; T; C; C; Pre; Post; M$_0$)* where

a) *S* is a finite set of elements called Places
b) *T* is a finite set of elements called Transitions disjoint from *S* (*S* ∩ *T* = Ø)
c) *C* is a non-empty finite set of types

d) *C* : *S* U *T* → *C* is a function used to categorise places and determine transition modes

e) *Pre; Post* : TRANS →μPLACE are the pre and post mappings with
   $$TRANS = \{(t,m) \mid t \times T, \, m \times C(t)\}$$
   $$PLACE = \{(s, g) \mid s \times S; \, g \times C(s)\}$$

f) M_0 X μPLACE is a multiset known as the initial marking of the net.

Places are represented with circles, while transitions are represented with rectangles. The number of tokens in place p_i is equal to the value of marking μ_i. Input and output functions are represented with directed lines and arrows. System transition from one state to another occurs when an event occurs, where an event can also be the moment when the defined time period in some state expires.

Some of the characteristics that make Petri Nets a useful tool for developing, describing and analysing complex railway systems include the following:

a) effective analysis of concurrent systems enables verifying safety rules for train operations and timetable analysis,

b) good graphical presentation that is easy to understand, even for those that are not familiar with Petri Nets,

c) PN model is easy to modify because of its modularity,

d) initial marking of Petri net enables experimenting with different scenarios.

Petri Net formalism and software for modelling junction systems are selected based on the following requirements and criteria (Störrle, 1998):

1. it must capture both static and dynamic aspects of a system,

2. it must accommodate for state as well as for data and event-based modelling styles in a natural way,

3. it must be capable of representing systems on multiple levels of abstraction,

4. it must lend itself to simulation and animation,

5. there must be efficient analysis techniques available to check model properties.

3.2 Petri Net model of junction

The simulation model of a railway system with a junction must describe the complex relations and states of such a system.

In a Petri net model, *places* represent sections, *transitions* represent conditions for train movement, and *tokens* represent trains. Model hierarchy enables insulated sections to be defined as subsystems or modules. An insulated section can be a block section, switch section and station track section, but a more detailed description is needed (regarding the position of a section relative to signals, stations and the junction). A module is defined for each distinctive section. The model is created by positioning and connecting modules according to the railway line section plan. Although this approach requires more time for initial programming, it allows the use of defined modules for modelling systems with similar processes, such as modelling of traffic processes in the station or on an open railway line. The junction system model is created in ExSpect v6.41, where the High-Level Petri nets have the following dialects: hierarchical, timed, stochastic, and coloured.

Some of the distinctive modules defined include the following:

a) **module for generating trains** – timetable data are imported from an external database for generating tokens (trains). Additionally, each token is filled with

information about the train it represents, such as the train number, category, time of entering into the system and train route. Defined tokens leave the module when the simulation clock and the time of train departure match.

b) **block section module** (Figure 2) – represents a block section on an open line. The module contains *places*, *transitions,* and nodes to store parameters and objects for connecting with other modules. Transitions in the module enable or prevent entering and leaving the section based on the storage data. Storage nodes contain information about the state of the connected sections, the signals and the simulation clock. When the transition *trainin* enables firing, tokens are placed in *sectionbusy.* Simultaneously, information about the occupancy of the section is sent to the previous two sections and to the signal. The token remains in place until the conditions defined in the transition *trainout* are met:

- time required for train to cross section - section occupancy time (train travelling time for the section),
- the next section is occupied,
- the signal does not allow further movement.

When the conditions are met, transition is allowed; the signal is set to allow train movement to the next section; the token leaves the section module; an additional token is firing to the place *sectionfree;* and information about leaving the section is sent to connected modules. The purpose of module storage is to maintain data on the state of the section. Data are used in the transition processor to enforce logical conditions and to calculate the section journey time. There are several types of *storages*: *time, info* and *ceka.* The other storage type (*sectionstate*) gathers data sent by transitions. These storage nodes have information about the state of signals and sections. During the simulation, data from storage are sent to an external database.
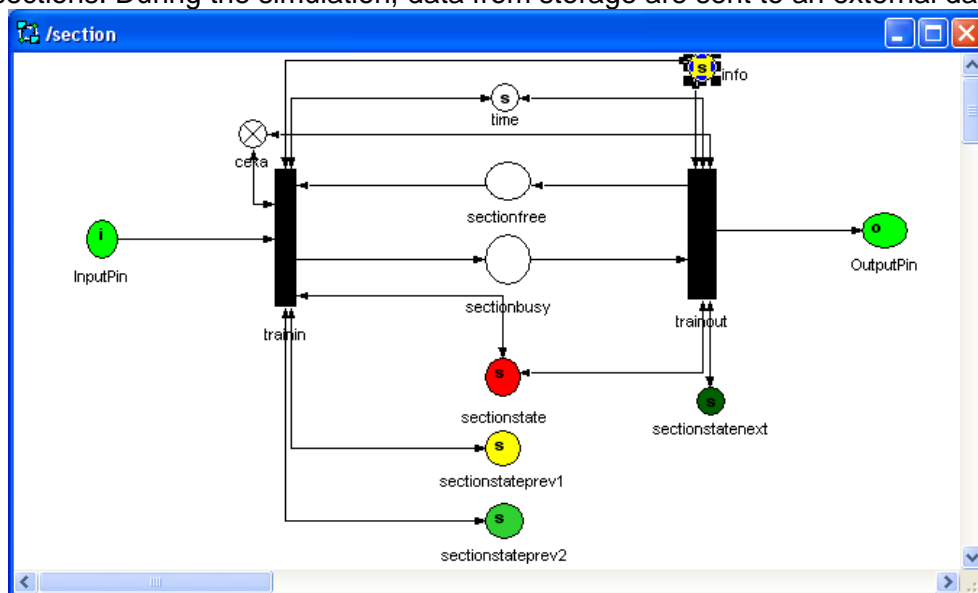

Figure 2 - Module of block section

c) **junction module – facing movement (Figure 3)** – switch section that represents the junction on an open railway line in the facing direction.
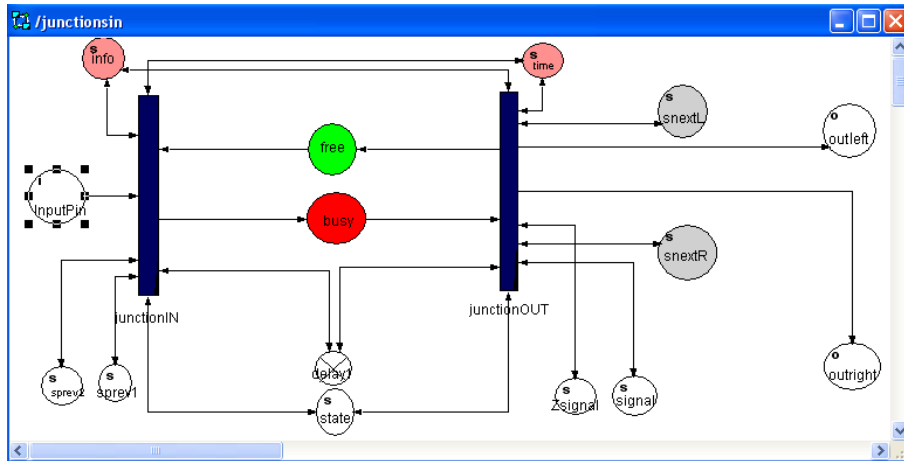
Figure 3 - Facing movement junction module

d) **junction module – trailing movement** – switch section that represents the junction on an open railway line in the trailing direction.

e) **station track section module** – represents the track section in a station.

f) **diamond crossing module** – section of diamond crossing on junction.

There are also modules similar to those already described that differ by implementation of the train traffic rules dependent on the location of the section in the system (for example, the block section prior to the junction section).

After defining the modules, creating the junction simulation model requires connecting modules according to the layout of sections in the railway line plan. The modules should then be connected to the storage node (Figure 4). Storage nodes defined in the model include the following:

- *time store;* storage node connected to the simulation clock,
- *random store;* storage node for generating random numbers (for stochastic data),
- storage type *info*; for storing section parameters (type, length,...),
- storage representing section occupancy; storage state can be *free*-0, *reserved*-1 i *occupied*-2. These data can be used in animating the simulation run.
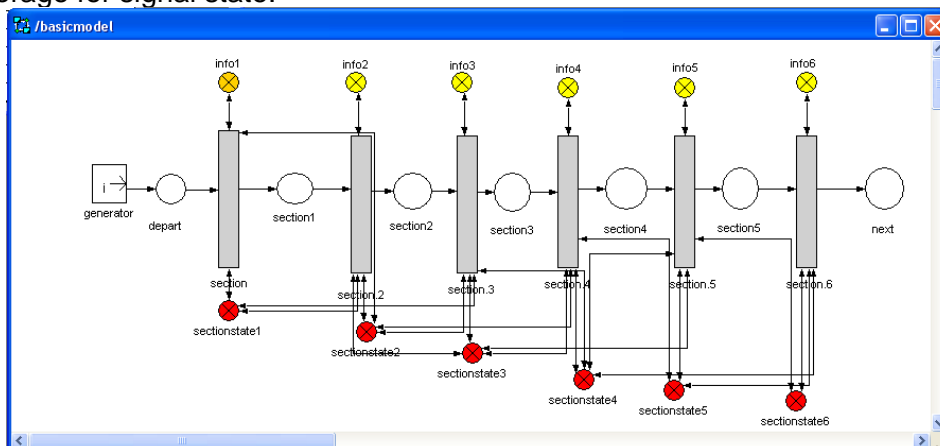- storage for signal state.

Figure 4 - Creation of the model by connecting section modules

The parameter values kept in storage vary dynamically with train movement.

Train input data are imported to the model before simulation. Places in the generator module are marked with coloured tokens that contain information from the train timetable. Trains in the model are defined by the train number, train type, train route and departure time. Train data are defined in the timetable database and can be easily changed to enable experimentation with different train timetables that are deterministic or stochastic. Each storage node of type *info* must be marked with initial values: section name, section length, maximum speed and its type.

The model is connected to external databases for storing input and output data. Output data are classified and filtered for statistical analysis and graphical representation of the simulation results. The simulation program provides data on the movement of each train through the model as well as data on the state of each section (total and physical occupancy of each section). The database is customised for creating quick reports based on queries and for filtering data by train, section, signals or train delay time in the model. Data can be presented in tables or graphs and can be easily validated.

With programmed macros, data from the database are used for creating train diagrams (time – distance diagram) with the vertical axis representing section lengths and the horizontal axis representing time.

Animation of the simulation run is done in the simulation program itself, by animating section states in the model. During the simulation, parameters (from storage nodes) of each section change when a train enters the section. These numerical data are used to animate sections. Storage numerical values provide the visual identity of the section occupancy symbol in the animation window.

4. MODEL FOR GENERATING TRAIN PRIMARY DELAYS USING FUZZY LOGIC

Train delays

A delay can be defined as the difference between the actual and minimum running times under ideal conditions (Mattsson, 2007). Train delays have great influence on the timetable and technological processes related to train traffic as well as on railway planning procedures. Train delay is often the first criterion for dispatchers' decisions. Primary delays influence railway capacity and timetable stability, accuracy and reliability.

There are primary and secondary delays (Landex, 2006). Primary delays are timetable disorders caused by disturbed train operation. Some causes of primary delays include the following:

- infrastructure failure,
- train breakdown,
- personnel actions in the train crew, routing crew or maintenance crew,
- preceding operations not directly related to traffic (loading and unloading, etc.),
- external and weather factors.

It is not always possible to avoid primary delays because of the many factors that generate them. Secondary delays are the result of "spreading" the primary delays through the timetable, e.g., transferring the delay factors from one train to the others. Secondary (or knock-on) delays and their propagation are subject to primary delays, railway network structure and the train timetable. Secondary delays are the result of surpassing (crossing) or waiting for trains with primary delays in operations where activities are dependent on actions such as exchanging passengers or direct wagons.

Serbian Railways data show that there are many causes of primary delays (Table 1). Due to poor track maintenance, sections with restricted speed are a common reason for primary delays. Another frequent cause is train failure due to inadequate wagon and locomotive maintenance.

Table 1 - Statistical data for train delays – Serbian Railways

	Description of a delay cause	Delay [%]
1.	Automatic block	5.6%
2.	Station shunting	1.6%
3.	Restricted speed sections	40.4%
4.	Temporary stops	0.8%
5.	Traffic situation	28.0%
6.	Travelled distance	0.2%
7.	Waiting for locomotive	7.1%
8.	Locomotive defect	9.3%
9.	Train cancelled	1.6%
10.	Collisions and similar events	4.2%
11.	Other causes	1.2%

Prediction of train delay is very difficult because of the many factors involved. As mentioned above, there are analytical models for calculating delays. When a system is not at steady state and operating conditions vary, the application of analytical models is time consuming. Primary delay model calculation is easy to use, easily adaptable to operating conditions and yields quality results.

Fuzzy set theory is a suitable mathematical approach for modelling processes characterised by subjectivity, uncertainty, ambiguity and imprecision, which makes it a very good tool for modelling timetable disorders (primary delays). Fuzzy logic enables decision making, even when based on imprecise information. Models based on fuzzy logic are defined by a set of IF-THEN rules. Input variables are linguistic variables that describe current operating conditions for each train. The defuzzified output result of a fuzzy inference system is train delay. Fuzzy model parameter values are defined in collaboration with traffic dispatchers, operators and experts familiar with the nuances of system operation. Their knowledge and experience, as well as train delay statistics, are used to define input variables, rules and output variables.

Input variable parameters

The fuzzy model is defined with four input variables: train category, timetable influence, train mileage and infrastructure influence (Figure 5).

a. **Train category**. Describes the train category. The train category and probability of train delay are highly dependent. This variable is defined using a value from 0 to 10, where numerical scores can be matched with words. The lowest score 0 is given to a freight train (μ_F), a score of 5 is a regional train (μ_R), and a score of 10 is high category passenger train (μ_P). The membership function of each train category is:

$$\mu_{1F}(x) = \begin{cases} 1 & x \leq 0 \\ 1 - \dfrac{x}{4} & 0 \leq x \leq 4 \\ 0 & x \geq 4 \end{cases} \qquad \mu_{1R}(x) = \begin{cases} 0 & x \leq 1 \\ \dfrac{x}{4} - \dfrac{1}{4} & 1 \leq x \leq 5 \\ -\dfrac{x}{4} + \dfrac{9}{4} & 5 \leq x \leq 9 \\ 0 & x \geq 9 \end{cases} \qquad \mu_{1P}(x) = \begin{cases} 0 & x \leq 6 \\ \dfrac{x}{4} - \dfrac{6}{4} & 6 \leq x \leq 10 \\ 1 & x \geq 10 \end{cases}$$

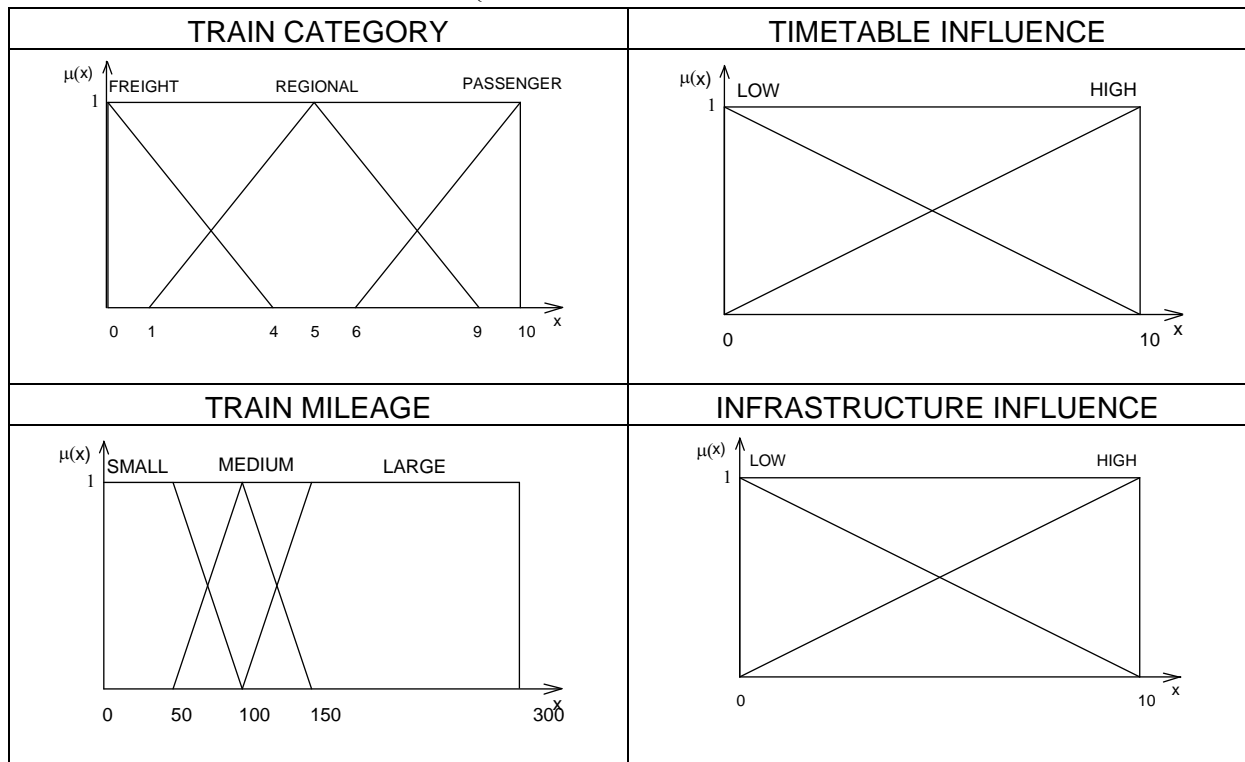Figure 5 - Membership functions of input parameters

b. **Timetable influence**. Timetable parameters in the observed period (time interval prior to the observed train) are quantified. The score for this parameter depends on timetable heterogeneity and number, frequency and train categories. Timetable influence is described by a score (0 to 10), where 0 is a minor influence (μ_L) and 10 (μ_H) is a major influence. The membership function for this fuzzy variable is defined as

$$\mu_{2-L}(x) = \begin{cases} 1 & x \leq 0 \\ 1 - \dfrac{x}{10} & 0 \leq x \leq 10 \\ 0 & x \geq 10 \end{cases} \qquad \mu_{2-H}(x) = \begin{cases} 0 & x \leq 0 \\ \dfrac{x}{10} & 0 \leq x \leq 10 \\ 1 & x \geq 10 \end{cases}$$

c. **Train distance**. Longer train distances travelled increase the probability of train delay. Fuzzy sets are defined based on routing personnel experience and analysis of statistical

data on train delays. The membership function for train mileage is defined with three fuzzy sets: small (μ_S), medium (μ_M) and large mileages (μ_L).

$$\mu_{3-S}(x) = \begin{cases} 1 & x \leq 50 \\ 2-\dfrac{x}{50} & 50 \leq x \leq 100 \\ 0 & x \geq 150 \end{cases}$$

$$\mu_{3-M}(x) = \begin{cases} 0 & x \leq 50 \\ \dfrac{x}{50}-1 & 50 \leq x \leq 100 \\ -\dfrac{x}{50}+3 & 100 \leq x \leq 150 \\ 0 & x \geq 150 \end{cases}$$

$$\mu_{3-L}(x) = \begin{cases} 0 & x \leq 100 \\ \dfrac{x}{50}-2 & 100 \leq x \leq 150 \\ 1 & x \geq 150 \end{cases}$$

d. **Infrastructure influence**. Similar to the timetable influence, this variable is defined based on railway parameters and expert knowledge. Scores are from 0 to 10 (low influence (μ_L) and high influence (μ_H)). Scores are quantified based on elements such as track condition, track parameters, number of tracks, length of sections with restricted speed, number of junctions, number of stations, safety and signalling equipment. The membership function for this variable is

$$\mu_{4-L}(x) = \begin{cases} 1 & x \leq 0 \\ 1-\dfrac{x}{10} & 0 \leq x \leq 10 \\ 0 & x \geq 10 \end{cases}$$

$$\mu_{4-H}(x) = \begin{cases} 0 & x \leq 0 \\ \dfrac{x}{10} & 0 \leq x \leq 10 \\ 1 & x \geq 10 \end{cases}$$

Output fuzzy variable – train delay

The membership function for output variable train delay (Figure 6) is defined with five fuzzy sets: very small (μ_{VS}), small (μ_S), medium (μ_M), high (μ_H) and very high delay (μ_{VH}). The membership function is

$$\mu_{OUT-VS}(x) = \begin{cases} 1 & x \leq 0 \\ 1-\dfrac{x}{5} & 0 \leq x \leq 5 \\ 0 & x \geq 5 \end{cases}$$

$$\mu_{OUT-S}(x) = \begin{cases} 0 & x \leq 0 \\ \dfrac{x}{10} & 0 \leq x \leq 10 \\ -\dfrac{x}{10}+2 & 10 \leq x \leq 20 \\ 0 & x \geq 20 \end{cases}$$

$$\mu_{OUT-M}(x) = \begin{cases} 0 & x \leq 10 \\ \dfrac{x}{20}-\dfrac{1}{2} & 10 \leq x \leq 30 \\ -\dfrac{x}{20}+\dfrac{3}{2} & 30 \leq x \leq 50 \\ 0 & x \geq 50 \end{cases}$$

$$\mu_{OUT-H}(x) = \begin{cases} 0 & x \leq 30 \\ \dfrac{x}{30}-1 & 30 \leq x \leq 60 \\ -\dfrac{x}{40}+\dfrac{5}{2} & 60 \leq x \leq 100 \\ 0 & x \geq 100 \end{cases}$$

$$\mu_{OUT-VH}(x) = \begin{cases} 0 & x \leq 60 \\ \dfrac{x}{40}-\dfrac{60}{40} & 60 \leq x \leq 100 \\ 1 & x \geq 100 \end{cases}$$
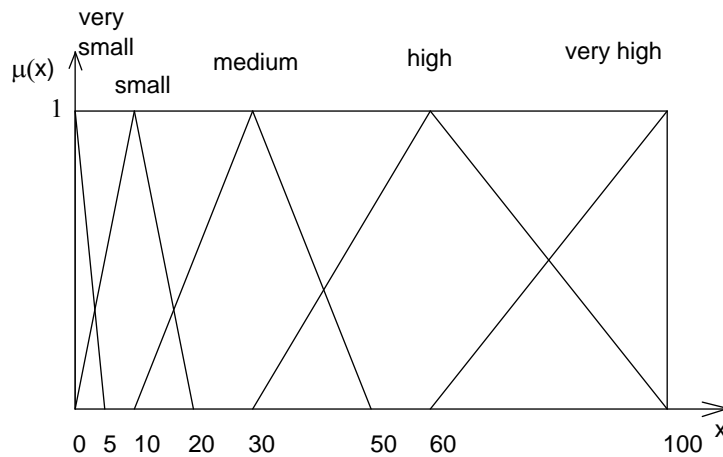
Figure 6 - The membership function of the output variable fuzzy set (train delay)

The fuzzy logic system is comprised of 36 rules. These fuzzy rules translate four input fuzzy variables into one output fuzzy variable. The logical AND operator is employed (the rule of minimum for AND relationships, the so-called Mamdani rule of minimum). In creating the consequent fuzzy set, MAX – MIN inference is used. Defuzzification of the output fuzzy variable is done via the centre of gravity method (COG). Figure 7 shows the relationship between train delay and selected input variables of the train category and train distance.
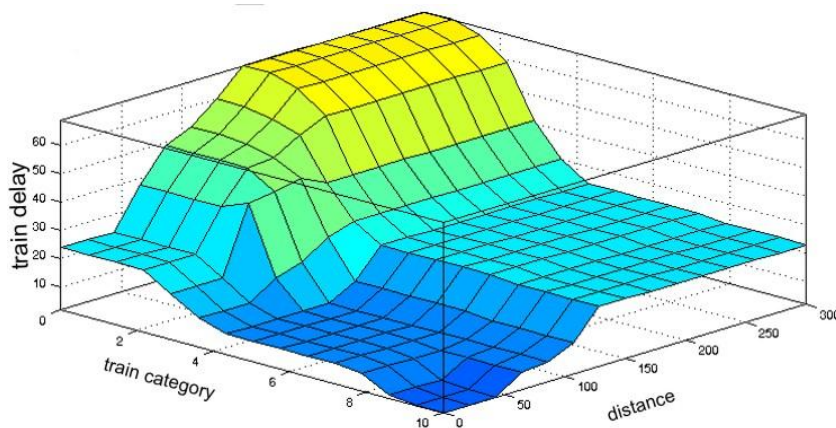

Figure 7 - Relationship between input and output fuzzy variables

Figure 8 presents a model example of fuzzy inference system. The test case is for the following input parameters:
- train category – 5 (regional train);
- timetable influence – score 4;
- train distance travelled – 40 km;
- infrastructure influence – score 2.

Four rules are related to this set of input data: rules 13, 14, 19 and 20. The defuzzified output variable gives a calculated train delay of 7.15 minutes.
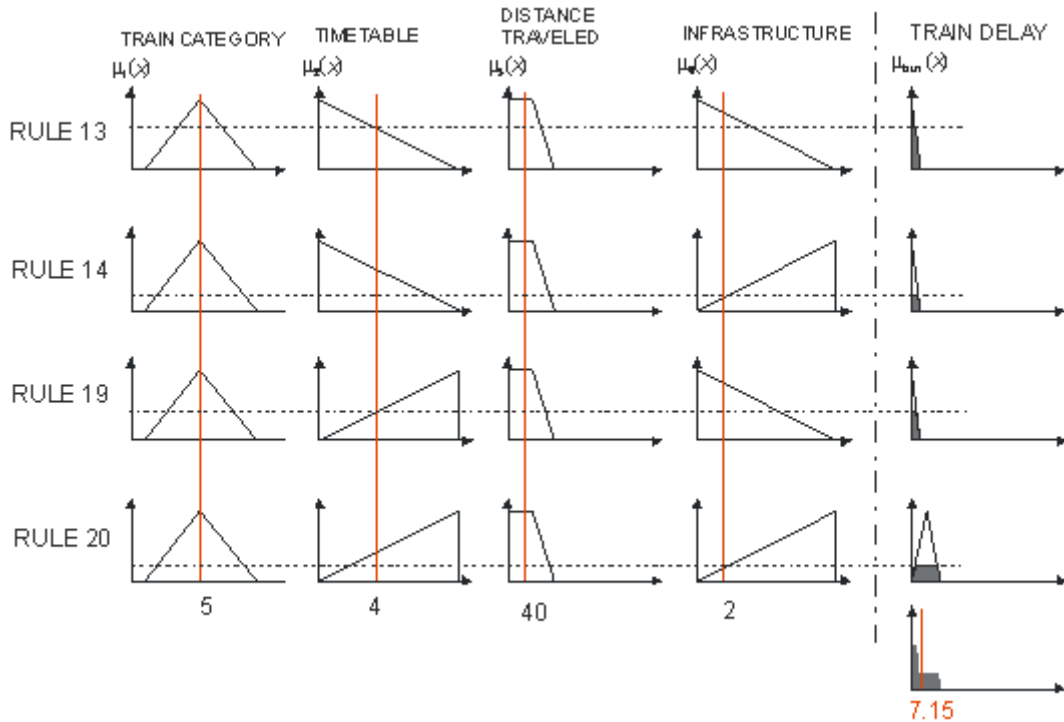
Figure 8 - Example of fuzzy inference system

5. PETRI NET MODEL EXAMPLE

5.1 Description

Junction G in the Belgrade railway node is chosen as an example for the Petri Net simulation model. It is a complex double-track diamond crossing junction. The boundaries of the model are the Belgrade Center, Topcider, Rakovica and Karadjordjev Park stations (Figure 9).
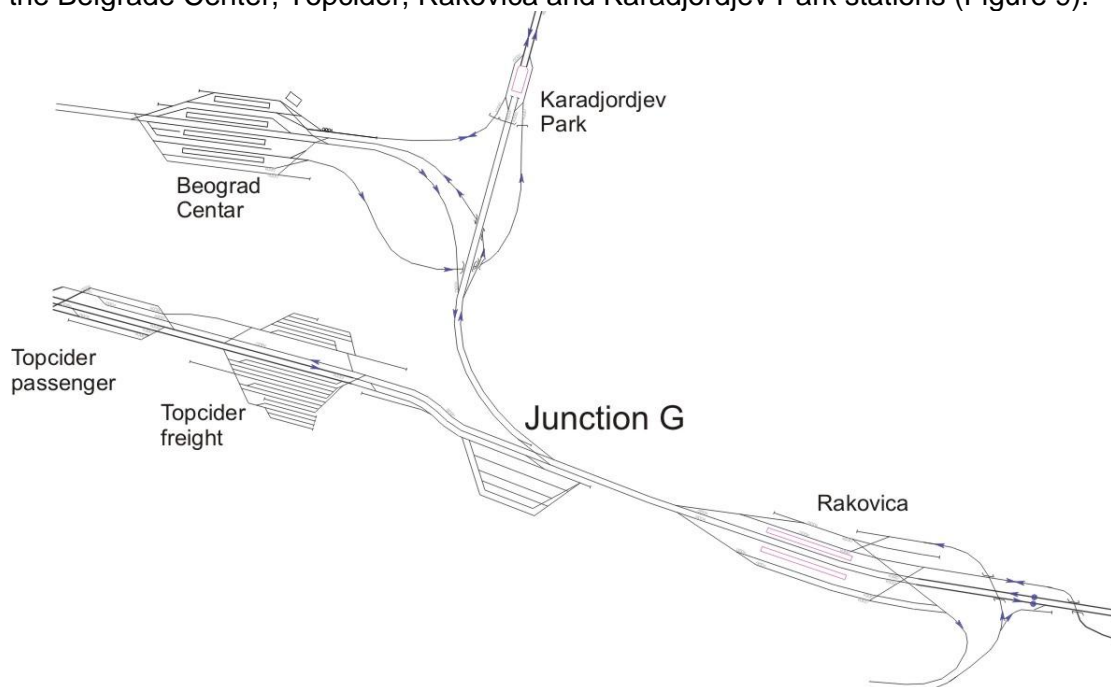

Figure 9 - Junction G of the Belgrade railway node

The model is defined with data from the section and railway signals layout plan and from the timetable for the year 2008. There are three train categories in the model: freight, regional and passenger. The three train categories were defined to model the train movement by sections according to their characteristics. Section occupancy time depends on train length, train acceleration and deceleration as well as on its maximum speed.

Train movement and spacing is determined by Automatic Block System rules and procedures. A section occupation time is calculated based on equations of train movement and maximum speed for the section (and speed limits). The section occupation time depends on section length and train speed $V=\min (\max V_{tr};\ \max V_{sec})$, where V_{tr} is the train maximum speed and V_{sec} is maximum section speed. The station sections have additional dwell time in the stations. The physical occupancy time of the section is the time from the moment when the first shaft enters the section to the moment when the last shaft leaves the same section. Additional train delays can occur when the previous train occupies the next block section. The total occupancy time is the period in which the section is occupied with trains in motion, and it accounts for the time in which the section is reserved for train routes in addition to the physical occupancy. Model parameters are defined for the section and for the token/train. Train parameters are defined in "coloured" tokens that carry information on the time of departure, train category, occupation time from the last section, and the time of entering and departing from the last section. Time data change dynamically in the token as the train moves between sections.

The principles of traffic organisation and train movement used in the model include the following:

- trains can be dispatched from the station if the following conditions are met: the output signal allows train movement, and the junction signals are set to forbid movement,
- the train can occupy the next section if two block sections are free,
- when entering the station, the condition needed to create the route is that all sections on the route must be free.

When creating a junction model, one must take into account all of the rules and operating conditions of a junction system. The following algorithm is used to create the model:

1. data sorting and analysing for junction G railway system data,
2. creating and defining modules that represent distinct types of sections in the model, such as the block and station,
3. creating a Petri net graph by connecting the modules,
4. defining storage nodes that represent signals, states of the section, etc.
5. connecting storage nodes with modules, entering the initial values of the storage nodes, such as the section lengths and maximum speed, and connecting the time storage (the simulation clock) and random storage numbers,
6. defining the database that contains data on train timetables and train parameters in the model (input data),
7. defining the database that stores data from the simulation program,
8. creating the animation window for the section state according to the section plan.

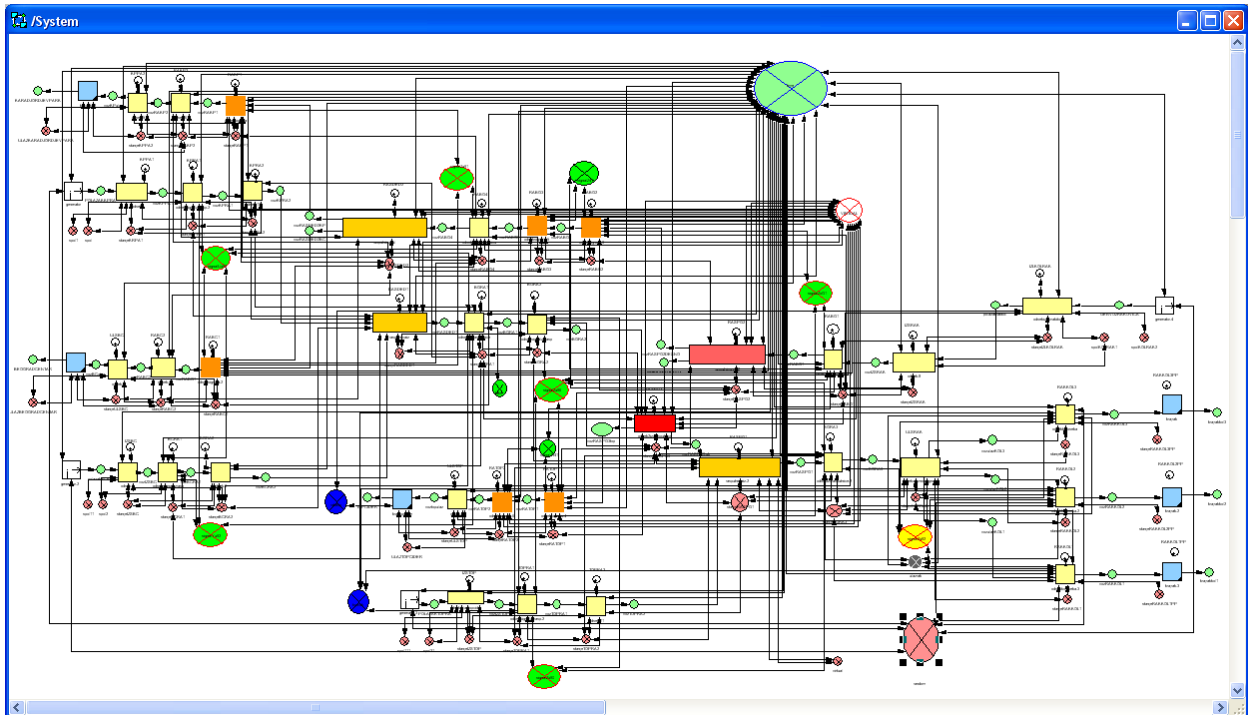The Petri net Model for junction G is shown in Figure 10.

Figure 10 - HLPN model for junction G

The simulation can be observed by viewing the token movement through the Petri Net Graph, the storage state indicators and the animation window that shows the state of each section in the model.

The model allows for experimentation by inserting new tokens in *places* during simulation (marking of a Petri Net model). After the simulation, the results can be viewed in the external database and subsequently edited in the form of reports, graphs, sketches, and tables.

Two methods of generating trains were tested in the model:

- a pulse timetable, in which the trains are generated in a constant time interval (5, 10, 15, and 20 minutes). This simulation method tests the model. In such a dense periodic timetable, any deviation from standard system behaviour can easily be spotted. Additionally, this is one of the ways to analyse system behaviour when overloaded and to identify its bottlenecks, i.e., capacity limitations. In addition to fixed timetable intervals, the model can also generate trains according to some statistical distribution. Stochastic train generation in the model is done with statistical functions incorporated into the program library or with external databases where the stochastic times of train departures are defined.

- a deterministic timetable created using the official timetable for the current year. The timetable is implemented into the model by loading data from the database. For creating a realistic timetable, the departure time for every train is supplemented with primary delay calculated by the fuzzy logic system.

5.2 Verification and validation of the Petri Net junction model

The Petri Net simulation model can be validated and verified by the following:

- monitoring if token movement is in accordance to operating rules;
- inspecting storage indicators;

- animation window that shows the state of each section in the model (Figure 11);
- data analysis. Simulation results are stored in a database from with reports can be generated. Additionally, the database generates a time – distance diagram. Any irregularities in the model can be easily identified on the train diagram.
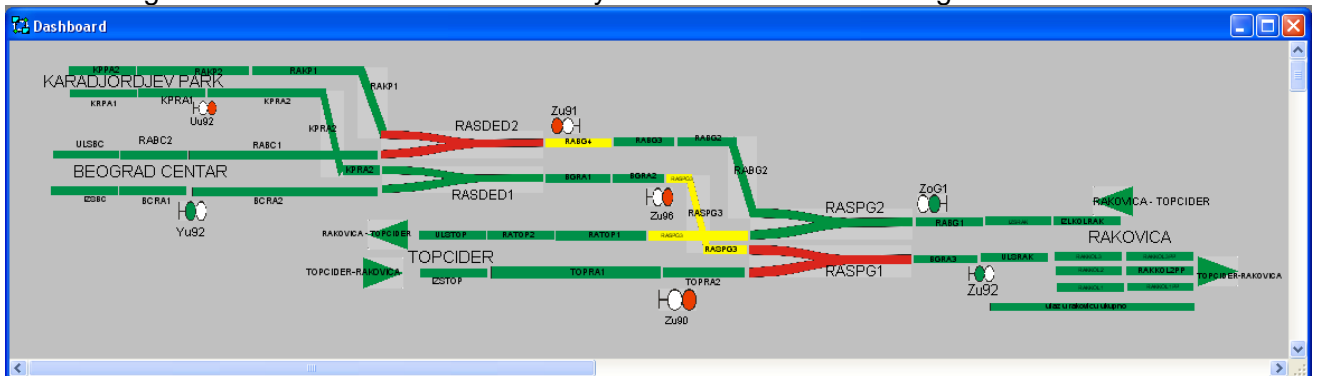

Figure 11 - Animation window indicating the states of the sections

The animation window is modelled to visually resemble the dispatcher interlocking control panel. Sections of the model are animated with section state data located in the storage.

During model development and testing, input data and results were compared with data from Čičak (1999), where the Belgrade railway node is modelled with analytical and simulation methods. The PN model was validated using comments received by railway personnel, such as train dispatchers, and data from train time – distance diagrams operating on the Belgrade node railway network model.

5.3 Results of the Petri Net model of junction G

The simulation program has tools for presenting simulation results; they are usually in the form of tables and graphs and are statistically processed (e.g., average train delay on a section). To obtain more detailed data analysis, the model exports information stored in section storage nodes and in tokens. Data are exported to the database when the system changes its state, which happens in a discreet time when a transition occurs, such as token generation and entering or leaving a section. The information sent from the token to the database includes the train number, time entering and leaving the section, section name and relation.

Simulation results can be classified and filtered for analysis. Data can be sorted by section (Figure 12), train number (Figure 13), train relation, or train category. Multiple queries can be used to generate reports. The reports are useful for the analyses of timetables and for train delays by train category or section. The database can generate reports that compare results from model experiments in which the timetable, section layout, or junction design was varied or new train operating policies were introduced.

	A	B	D	E	F	G	H	I
1	RELATION	TRAIN N	TRAIN Type	IN	DELAY	OUT	SECTION	DEPART
42	Topcider - Rakovica	105	passenger	27900	0	27972	IZSTOP	27900
120	Topcider - Rakovica	121	passenger	69900	0	69972	IZSTOP	69900
139	Topcider - Rakovica	125	passenger	78900	0	78972	IZSTOP	78900
140	Topcider - Rakovica	701	passenger	19899	94	20065	IZSTOP	19800
158	Topcider - Rakovica	403	passenger	34200	0	34272	IZSTOP	34200
177	Topcider - Rakovica	407	passenger	66600	0	66672	IZSTOP	66600
319	Topcider - Rakovica	707	passenger	64800	0	64872	IZSTOP	64800
341	Topcider - Rakovica	709	passenger	81000	0	81072	IZSTOP	81000
386	Topcider - Rakovica	809	passenger	27600	0	27672	IZSTOP	27600
413	Topcider - Rakovica	811	passenger	54900	0	54972	IZSTOP	54900
433	Topcider - Rakovica	815	passenger	69120	0	69192	IZSTOP	69120
452	Topcider - Rakovica	817	passenger	76620	0	76692	IZSTOP	76620
761	Topcider - Rakovica	3403	regional	25950	0	26022	IZSTOP	25950
783	Topcider - Rakovica	3407	regional	37933	0	38005	IZSTOP	37933
857	Topcider - Rakovica	3415	regional	58200	0	58272	IZSTOP	58200
908	Topcider - Rakovica	3419	regional	72650	0	72722	IZSTOP	72650
953	Topcider - Rakovica	3423	regional	79850	0	79922	IZSTOP	79850
2136	Topcider - Rakovica	51001	freight	3620	0	3699	IZSTOP	3620
2168	Topcider - Rakovica	51007	freight	6266	0	6345	IZSTOP	6266

Figure 12 - Simulation results report filtered by section

	A	B	D	E	F	G	H	I
1	RELATION	TRAIN	TRAIN Type	IN	DELAY	OUT	SECTION	DEPART
138	Topcider - Rakovica	125	passenger	0	0	78900	depart from Topcider	78900
139	Topcider - Rakovica	125	passenger	78900	0	78972	IZSTOP	78900
141	Topcider - Rakovica	125	passenger	78972	42	79071	TOPRA1	78900
142	Topcider - Rakovica	125	passenger	79071	0	79114	TOPRA2	78900
143	Topcider - Rakovica	125	passenger	79114	0	79130	RASPG1	78900
144	Topcider - Rakovica	125	passenger	79130	0	79174	BGRA3	78900
145	Topcider - Rakovica	125	passenger	79174	0	79209	ULSRAK	78900
146	Topcider - Rakovica	125	passenger	79209	174	79383	RAKKOL3	78900

Figure 13 - Simulation results report filtered by train

The fuzzy logic system for train delay is tested by experimenting with train delay data over a period of 30 days. The average delay of passenger trains is 4.9 min; for regional trains it is 1.7 min, and for freight trains, it is 61.1 min. The results from the fuzzy system are given in Table 2.

Table 2 - Statistical data for the fuzzy logic system

	All trains	Passenger trains	Regional trains	Freight trains
Average delay (min)	8.0	4.9	1.7	61.1
Standard deviation of delay (min)	17.7	4.9	1.0	11.1
Average deviation of delay (min)	10.4	4.5	0.7	9.6
Max delay (min)	80	13	6	80
Min delay (min)	0.0	0.0	0.0	41.6
Number of trains with delay	159	27	115	17
Percentage of trains with delay	87%	48%	94%	100%

The average section occupancy data can indicate possible bottlenecks of the system. The average rate of section occupancy by train movement is shown in Figure 14.
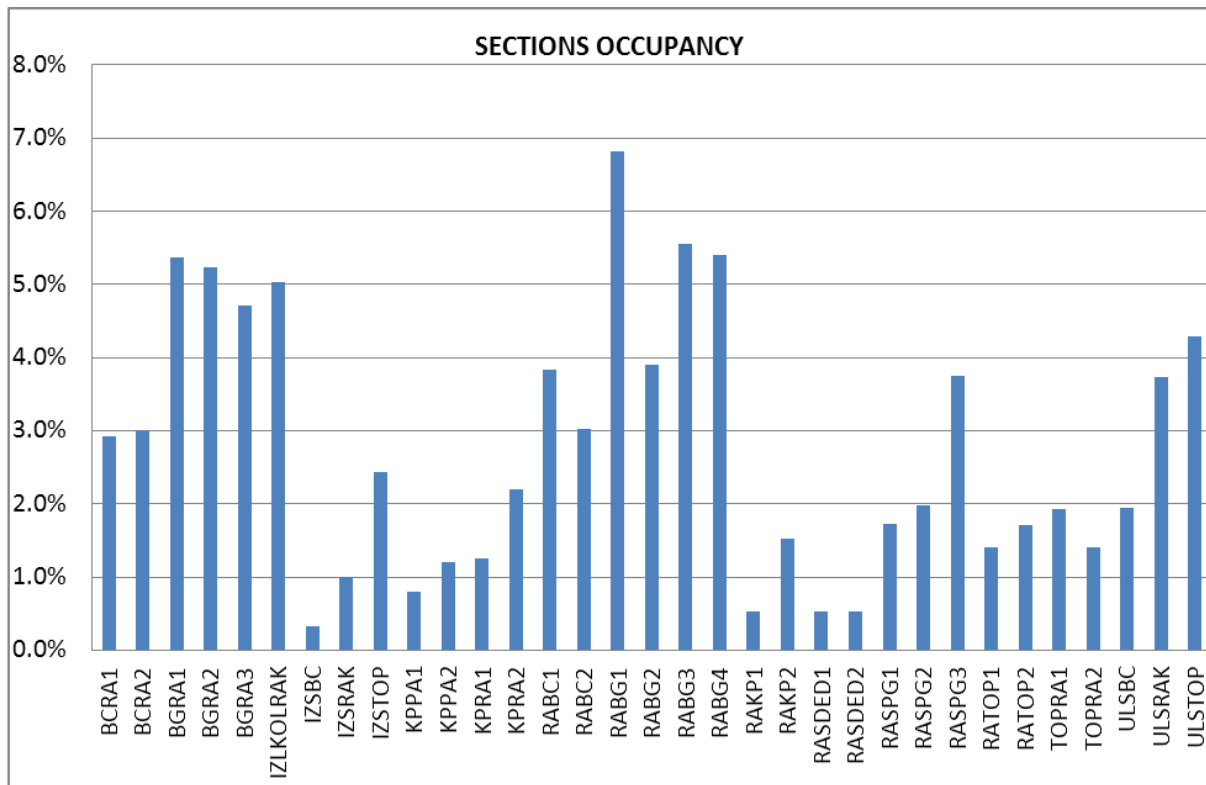
Figure 14 - Percentage occupancy of sections in the model

The sections with the highest percentages of physical occupancy are RABG1, RABG3, RABG4, BGRA1, BGRA2, and BGRA3. These are block sections between the junction and stations, and their occupancy is the highest because of their length. Section IZLKOLRAK also has a high occupancy rate, although it is a station track section in Rakovica. Trains accelerate on that section, and additional sections have train delays because their route is blocked by another train coming from the opposite direction. This delay is a secondary delay caused by disturbed train operation from a primary delay. The junction section occupied with a train coming from the opposite direction causes a signal that prevents the movement of trains from the Rakovica station. The total knock-on delay of this section is 476 sec. There are similar examples for the section adjacent to the junction.

Figure 15 presents a part of the train time – distance diagram for sections of the model. The dashed line represents train routes as a function of timetable, and the continuous line (colours represents different train categories) represents train routes with the supplemented primary delay calculated in the fuzzy logic system. Train 125 with no primary delay cannot depart because of conflicting routes with train 124. Train 125 generates 42 seconds of secondary delay on section TOPRA1 waiting for train 124 to release the junction section. Train 124 has a primary delay and disturbs train operation.
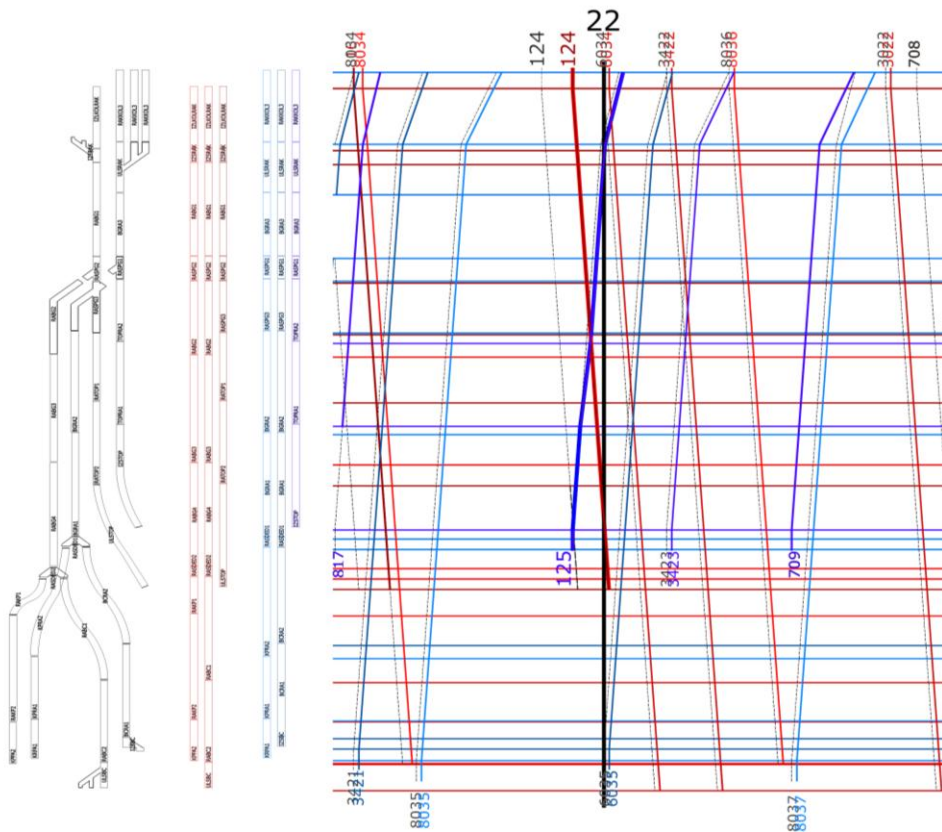
Figure 15 - Time - distance graph of junction G

6. CONCLUSION

The Petri Net model for the junction is based on a hierarchical structure with connected distinctive modules/subnets. Hierarchy in modelling makes it suitable for microscopic and mesoscopic infrastructure simulation. Connected modules that represent line and station sections can, with certain modifications, model different railway systems, including stations, nodes, and lines. Simulation results can be utilised for the following situations:

- decision making in investment projects,
- testing infrastructure or technological designs of junctions, stations, sidings, etc.,
- analysing effects from experimenting with train operation rules,
- analysing timetables,
- testing railway line capacity,
- analysing train delays.

The Petri Net model of the junction can be utilised in two ways. The first way is to experiment by varying input data that can be easily defined in a predefined database. Some of the input data are timetable information that can be defined as either stochastic or deterministic. Further, the deterministic timetable can be supplemented with train primary delays computed in a fuzzy logic system. The second method is to modify the Petri Net model in the following ways:

- changing the train operating rules (signal and safety level, optimal line section design);

- altering the infrastructure design (new track connections, new types of switches, dead-end tracks etc.);
- testing new grade separated solutions for junctions or railroad crossings.

The fuzzy logic system for primary delay computation can be applied on any similar railway system. Good knowledge of the system behaviour, experience and sufficient timetable and infrastructure data can be used to define the fuzzy system to produce quality results that are comparable to real system delays. We plan to focus future research on testing and fine-tuning the model and to introduce Fuzzy Petri Nets as a modelling tool for managing train operations in complex railway systems.

REFERENCES

van der Aalst W. M. P. and Odijk M. A. (1995), Analysis of railway stations by means of interval timed coloured Petri nets, Real-Time Systems 9, 241-263

Basten T., Roland B., Voorhoeve M. (1995). Simulating and Analysing Railway Interlockings in ExSpect, IEEE Parallel & Distributed Technology: Systems & Technology, 3 (3), 50-62,

Cheng, Y.-H. , & Yang, L.-A. (2008), A Fuzzy Petri Nets approach for railway traffic control in case of abnormality, Expert Systems with Applications doi:10.1016/j.eswa.2008.10.070

Čičak, M., (1999), Capacity of the Lines and Stations in the Railway Node Belgrade, Technical Report/ Study in Serbian, Institute of the Faculty of Transport And Traffic Engineering – University of Belgrade

Daamen, W., Goverde, R.M.P., Hansen, I.A. (2009). Non-discriminatory automatic registration of knock-on train delays, Networks and Spatial Economics, 9 (1), 47-61.

Fanti, M.P., Giua, A., Seatzu, C. (2006). Monitor design for colored Petri nets: An application to deadlock prevention in railway networks, Control Engineering Practice, 14 (10), 1231-1247.

Fay, A. (2000)., Fuzzy knowledge-based system for railway traffic control, Engineering Applications of Artificial Intelligence, 13 (6), 719-729.

Goverde, R., (2005). Punctuality of Railway Operations and Timetable Stability Analysis, PhD Thesis, TRAIL Thesis Series, Delft, the Netherlands

Hansen, I. A.; Pachl, J. (2008). Railway Timetable & Traffic. Analysis - Modeling – Simulation. Eurailpress, Hamburg,

Haas, P. J. (2002). Stochastic Petri nets: Modelling, stability, simulation, Springer-Verlag.

Higgins, A. and Kozan, E. (1998). Modeling train delays in urban networks. Transport. Sci. 32, 4, 346–357.

Huisman T. and Boucherie R., (2001), Running times on railway sections with heterogeneous train traffic, Transportation Research Part B: Methodological, Elsevier, vol. 35(3), 271-292,

Jensen K. (1991). Coloured Petri Nets: A High-Level Language for System Design and Analysis, Advances in Petri Nets 1990, Lecture Notes in Computer Science, 483, 342-416,

Landex, A., Kaas, A. H. and Hansen, S.,(2006). Railway Operation, Technical report at Centre for Traffic and Transport, Technical University of Denmark,

Mattsson, L.-G. (2007), Railway capacity and train delay relationships, 129-150, in Murray, A. and Grubesic, T.H. (eds), Critical Infrastructure: Reliability and Vulnerability, Springer-Verlag

Murata T. Petri nets: Properties, analysis and applications, Proceedings of the IEEE, Vol.77, No.4, 541-580

Pachl, J. (2002.). Railway Operation and Control, VTD Rail Publishing, Mountlake Terrace (USA)

Störrle, H. (1998), An evaluation of high-end tools for Petri-Nets, Technical Report/Bericht 9802. Ludwig – Maximilians - Universität München, Institut für Informatik.

Teodorovic, D. (1999). Fuzzy logic systems for transportation engineering: the state of the art. Transportation Research Part A, 33, 337-364

Vromans M. (2005). Reliability of Railway Systems, PhD Thessis, TRAIL Thesis Series, Delft, the Netherlands

Yuan J, Hansen I. (2007). Optimizing capacity utilization of stations by estimating knock-on train delays, Transportation Research Part B, 41, 202–217