UNITARY HYBRID MODEL OF RAILWAY TRAFFIC

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The contribution deals with the methodology of building unitary hybrid simulation models reflecting railway traffic. Those models apply different level of abstraction (granularity) to diverse parts of a simulating system. Special attention is paid to different traffic models applied to microscopic and macroscopic elements of hybrid model. Because several different submodels coexist within a hybrid model, which are connected to different traffic indicators, it is necessary to solve the transformation of traffic flows on the interface of microscopic and macroscopic submodels.

Keywords: scalable simulation model, hybrid model, railway traffic, transformations of traffic flows

1. INTRODUCTION

Modelling a railway infrastructure and a corresponding railway traffic represents an important part of the research focused on railway system optimizations. For such purposes the researchers use the experimental research method of computer simulation in which the level of *granularity* (applied within simulators) plays an important role. It defines the level of details considered within an examined simulating system. The different levels of details required for investigating the railway traffic, can determine various simulation models utilizing different granularity. Thus, simulations can be classified according to their granularities as *microscopic, mesoscopic*, and *macroscopic* (Krivy and Kindler 2003; Burghout 2004).

For the needs of simulation studies with defined goals, it is essential to have at disposal appropriate specifications of simulating systems. It means that an appropriate level of details for the needs of relevant examinations has to be selected. Traditional approaches apply the same level of details for the entire simulator – i.e. that homogenous approach does not allow to combine microscopic and mesoscopic levels of details within one simulator. While applying investigations on the microscopic level, it is typical to explore in detail the interactions among individual mobile entities. On the other hand, the macroscopic level of details typically provides only rough features of traffic flows. There is a strong motivation for designers of traffic simulations to use methodologies for building scalable simulation models of railway traffic. Those models enable to combine and interconnect:

- various submodels of infrastructure built on different levels of details (Hansen and Pachl 2008; Cui, and Martin 2011; Novotny and Kavicka 2016) and
- different traffic submodels reflecting granularities of relevant infrastructural submodels – certainly relevant transformations of traffic flows are supposed to be carried out on the boundary between corresponding submodels.

The mentioned approach has to be supported by appropriate software tools (e.g. infrastructure editors and integrated simulation environments etc.).

2. UNITARY HYBRID SIMULATION MODEL

Our presented methodology is based on a hybrid simulation model implemented within one simulation tool (*unitary hybrid model*). That methodology supports combining submodels exploiting the microscopic and macroscopic levels of details. Microscopic simulation is connected to particular areas, within the frame of which important details about traffic (and infrastructure) are important for the experimenter. On the other hand, macroscopic simulation is utilized within those parts of the simulator for which rough operational/traffic observations are sufficient. Unitary hybrid model enables to adjust the *granularity* of selected parts of a simulator. The mentioned parts are connected to relevant traffic submodels operating over corresponding infrastructure submodels.

Overall computational demands of a unitary hybrid model are certainly lower than demands related to a corresponding model executing pure microscopic simulation (Novotny and Kavicka 2016).

3. MICROSCOPIC INFRASTRUCTURE MODEL

The methodology of building unitary hybrid models focuses primarily on the construction of a track infrastructure submodel. That submodel applies the highest level of details which can be required for the given part of the railway network. Within this context the editing tool *TrackEd* (Novotny and Kavicka 2015) can be utilized. The mentioned software is specialized in (i) quick constructions of track layouts with the help of prearranged prototypes of rail objects and (ii) subsequent schematic visualizations depicting track infrastructures. The resulting submodel is then represented by a data structure depicting a mathematical model based on an undirected graph. Each graph node encapsulates not only the position in a schematic plan, but also real geographic (kilometric) position/coordinates within the railway network. Within the editor it is possible to define topological, metric and slope characteristics related to all tracks or their parts. Hence, it is possible to carry out realistic calculations (during simulation trials) concerning the dynamics of train rides. The created microscopic infrastructure submodel considers: (i) tracks, (ii) switches, (iii) crossings, (iv) signal devices, (v) limit signs for train positions on tracks, (vi) platforms, (vii) isolated circuits, (viii) electrification and useful lengths of tracks, and finally (ix) speed limits valid for individual rail elements (Kubat 1999; Jirsak 1979).

4. HYBRID INFRASTRUCTURE MODEL

From the viewpoint of the resulting *hybrid submodel/layer of infrastructure* (e.g. built in editing tool *TrackEd*) it is necessary to distinguish between *micro-layer*, which corresponds to the above mentioned microscopic submodel and *hybrid-layer* composed of *micro-segments* and *macro-segments*. *Micro-segments* are represented by sub-graphs directly taken from the micro-layer. *Macro-segments* apply higher degree of granularity (i.e. lower level of details) to relevant disjoint connected sub-graphs from the *micro-layer* (Novotny and Kavicka 2016). Two types of macro-segments (*macro-nodes* and *macro-edges*) are distinguished within the presented methodology. *Macro-edges* typically encapsulate line sequences of edges from micro-layer. *Macro-nodes* can enclose a general connected sub-graph from the micro-layer. Constructions of *macro-segments* support creating variant configurations of hybrid submodels of railway infrastructure. It means in fact that different scenarios of simulation experiments can apply various levels of details (micro- or macroscopic) within an infrastructure submodel.

5. HYBRID TRAFFIC MODEL

Because of combining macro-segments with areas including microscopic elements within the hybrid infrastructure model, it is necessary to apply different traffic models implementing various levels of abstraction, which are connected to different traffic indicators (Cenek 2004). From the viewpoint of the implementation of the unitary hybrid model (Figure 1) it is necessary to distinguish between traffic models applied to microscopic and macroscopic infrastructure segments of hybrid model. *Microscopic traffic submodels* observe detailed riding features of individual trains. *Macroscopic traffic submodels* utilize the theory of traffic flow based on the analogy of flowing of liquids within the macroscopic areas.

Because several different traffic submodels coexist within a hybrid model, it is necessary to solve transformations of traffic flows, i.e. it is necessary to unambiguously define the information about railway traffic on the interface between each microscopic and macroscopic submodel in order to maintain consistency of data.

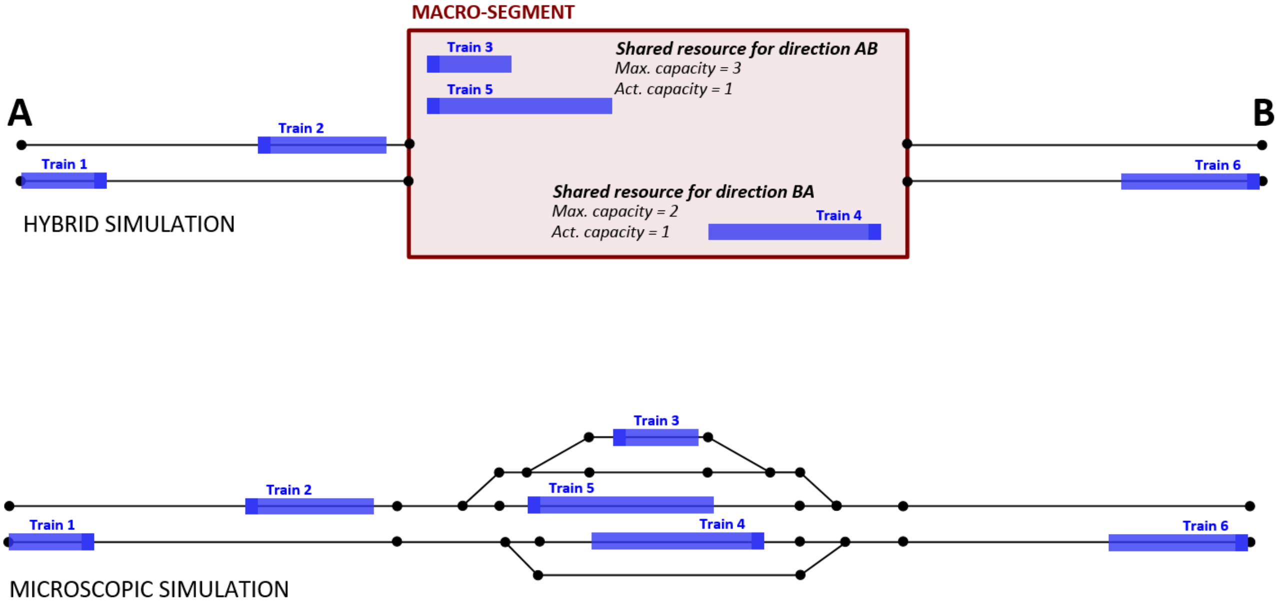

Figure 1 – Hybrid simulation model (analogy based on competition for shared resources)

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From the implementation perspective, the transformations of traffic flows must distinguish between microscopic $\rightarrow$ macroscopic transformations and macroscopic $\rightarrow$ microscopic ones. When transferring the rolling stock from the microscopic to the macroscopic submodel, the main problem is the loss of a large amount of data items. Those items must be unambiguously defined for individual rolling stock which is later transferred from the macroscopic submodel back into the microscopic one (Burghout 2004; Novotny and Kavicka 2016). When transferring the rolling stock, the current status of traffic in the relevant surroundings must be considered.

6. MICROSCOPIC TRAFFIC SUBMODEL

Microscopic traffic submodel is based on applying realistic calculations connected with the train ride dynamics and train interactions (Divis and Kavicka 2015). Train rides computations use detailed information about railway infrastructure (real topology/metric and slope properties) defined in *micro*-layer of infrastructure model (Novotny and Kavicka 2015). For trains, it is necessary to maintain the traction characteristics, resistance, breaking and other train parameters. Some other parameters are abstracted (wind resistance in a tunnel or effects of transition curve on the train ride). Defining such parameters would prolong creating a hybrid simulation model in comparison with the insignificant effect on the riding time of trains.

The calculation of train driving dynamics is performed by numerical integration with an intermediate step of calculation for greater accuracy repeatedly according to a defined time frame due to the changing train position and track charakteristicks. In other words, the movement of trains on the infrastructure reflects the real driving characteristics with respect to the train and tracks properties. Within the above presented microscopic traffic submodel, which apply higher levels of abstraction to some aspects, is possible to achieve reliable results from simulation experiments without any significant loss of their informative value.

Within the integrated development environment of *TrackEd* is implemented simulation engine based on the method of discrete events planning using agent-oriented architecture. This method uses a calendar of events, from which events are removed in the correct chronological order and executed. *TrackEd* features online animation for easy and clear overview of the progress of a simulation and monitoring train position and speed during the simulation, especially in microscopic submodels. The simulator is capable of setting the speed of animation based on the user's needs or to pause the animation if a detailed inspection of the simulation status is needed.

7. MACROSCOPIC TRAFFIC SUBMODEL

According to the existence of *macro-segments* differences due to the encapsulation of different parts of microscopic infrastructure model (railway stations, tracks, etc.) within a hybrid model, there are different realizations of the traffic models in these macroscopic submodels.

7.1. Analogy of flowing of liquids

Movements of rolling stock through macroscopic submodels can be described analogously to the formalisms defining fluid flows. As well as the motion of fluid particles is affected by the movements of surrounding particles of liquid, the movements of individual pieces of rolling stock within *macro-segments* depend on surrounding train rides. This approach is directly taken from the domain of road traffic simulation (Daiheng 2011). Some of the original principles are not considered, because different variability of the rolling stock movement along the infrastructure exists (mainly determined by the train path and the assigned timetable). The proposed approach of transformation of traffic flow (characterized by a certain intensity φ) assumes an assignment of average speed $\overline{v}$ to each individual train entering into the macroscopic submodel. Assigned current average speed $\overline{v}(\rho_C)$ depends on the current density (ρ_C) of traffic flow in *macro-segment*. That density is determined for every *macro-segment* from the attributes (the number of isolated circuits, average length of train routes, etc.) defined in relevant part of *micro*-layer and the current number of trains being inside the relevant segment. According to the mathematical formula can be the average speed assigned to each train in *macro-segment* expressed determined by the maximum allowable speed v_{max}, the current density ρ and maximum density ρ_{max} (maximum number of trains in macro-segment):

$$\overline{v}_{(\rho)} = v_{max}(1 - \frac{\rho}{\rho_{max}})$$

Certainly, the average speeds of all trains in *macro-segment* are always recalculated (when a train approaches/leaves the segment) in order to maintain traffic consistency.

From the viewpoint of macroscopic traffic submodel discussed above, if the average speeds are known in the instants of time when the trains leave the macro-segment be pre-calculated (it is not necessary to observe individual trains during their temporary stay in the macroscopic submodel). It is essential convenient to consider a relevant time table as well (Burghout, Koutsopoulos and Andreasson 2006).

On the other hand, depending on the different characteristics of the *macro-segments* and maintaining consistency of information about traffic, it is also include to calculation information about train stopping on some of the encapsulated microscopic elements by the timetable (for example, station tracks).

7.2. Analogy based on competition for shared resources

Different approaches to modelling traffic within macro-segments are to be imagined as a shared resource. In which can be only a certain number of rolling stock.

The maximum number of trains within the submodel can be given by attributes defined in relevant part of micro-layer. A similar parallel can be seen in real railway traffic where the number of station tracks can be the factor determining the maximum number of trains allowed in the railway station the same time. Other trains are not allowed to enter the station and have to wait for the leaving of some station tracks.
The basic difference from the previous concept is that trains do not interactions on each other (i.e. trains do not change the density of traffic flow in submodel and it does not have an effect on the average speed assigned to the next entering train).
In other words, if the train can enter to the macroscopic submodel (from the rules defined above), it is defined the simulation time for individually train, when the current submodel leaves. Simulation time is calculated from the attributes of the microscopic elements, which consists of a train path through the submodel.
An important factor is the right simulation time to be added if the train stops in the macro-segment. This is the reason of braking or acceleration of the train in the case of microscopic simulation traffic.

7.3. Extension of competition for shared resources

In the case of a selected traffic model for macroscopic submodels based on competition for shared resource, the macro-segment can be blocked by train arriving from only one direction. Of course, leads to an increase the delay of trains in the opposite direction and the inconsistency of the hybrid simulation model compared with only microscopic one. In real traffic (in a railway station) a set of station tracks is always assigned to each direction. If we neglect the unusual situation of real traffic, when the station uses the same station tracks for different directions (dispatcher-controlled methodology), we can use a group of shared resources within each macro-segment. The advantage is the trains coming from different directions will affect each other only in cases, e.g. if railway stations use the same station tracks for different directions.

7.4. Summary

From approaches to modelling a macroscopic traffic submodel, it is not possible to use one global traffic model for all types of macro-segments. A general assumption is use a macroscopic traffic submodel based on competition for shared resources for macro-nodes (encapsulating railways station etc.) and for macro-edges (encapsulating open tracks etc.) traffic model based on the analogy of flowing of liquids.
In order to accept this fact, all presented concepts of macroscopic traffic models for both types of macro-segments must be implemented and validated by a series of simulation experiments.

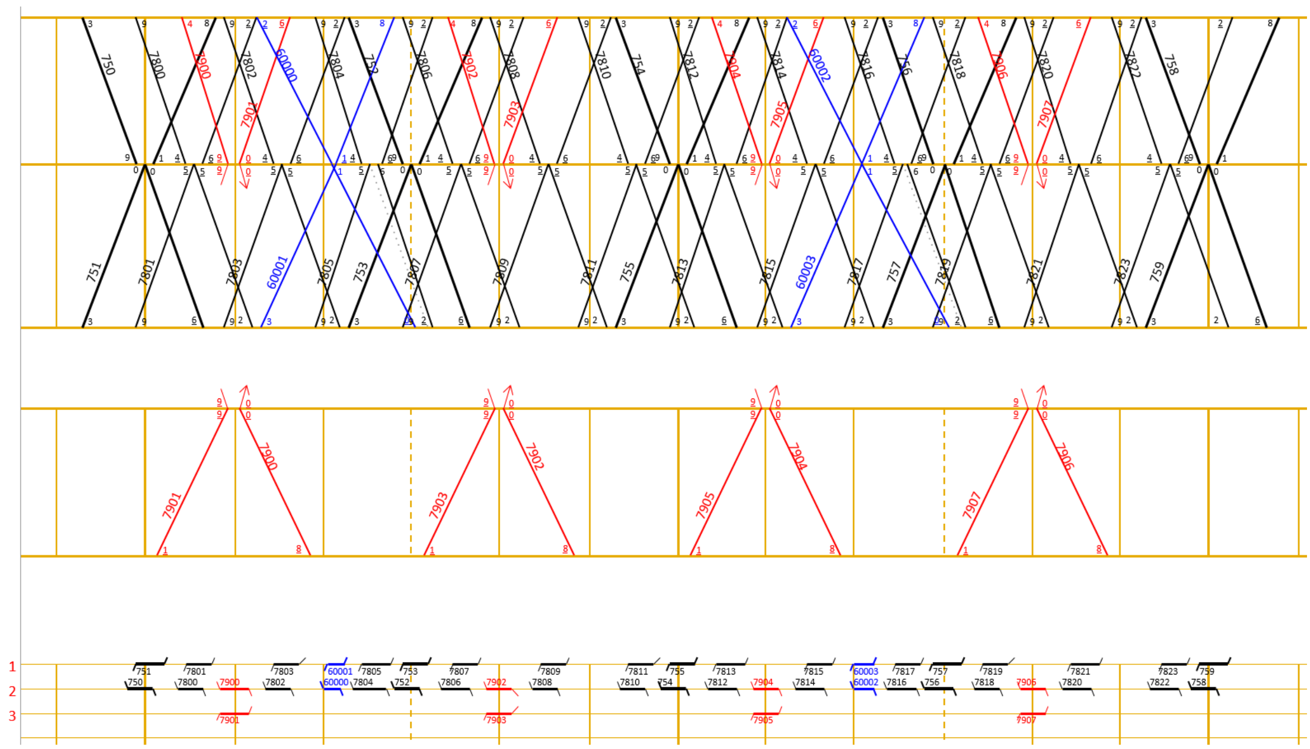

Figure 2 - Timetable of prototype station

8. VERIFICATION AND VALIDATION

In order for the unitary hybrid model of railway traffic (applying different level of abstraction to diverse parts of simulation system) to be used in practice, it is necessary for simulation results to be correct and real. To verify the correct functionality of hybrid simulation model, it is possible to identify validation methodology:

- deterministic simulation over the microscopic simulation model of railway traffic
- deterministic simulation over the hybrid simulation model of railway traffic
- hybrid simulation of railway traffic with various delays (stochastic simulation)

It was necessary to verify the microscopic model of railway traffic focused primarily on the proper implementation of the train driving dynamics in the initial phase. In other words, comparison of a tachogram obtained from the simulation results with a similar tachogram obtained from a real environment or other simulation tool (Divis and Kavicka 2015). Next, the series of simulation experiments were carried out on the case study of the railway traffic an appropriate area of the official railway network in Czech Republic used by *The Railway Infrastructure Administration* (SZDC). Other, more complex verification was compared with the results from the simulator Villon (representing a validated simulation tool widely accepted by experts from railway practice).

9. CASE STUDY

As a part of the initial testing, an infrastructure, which consists of a prototype station and several adjancent border stations. According to the real timetable of the prototype station (*Figure 2*), containing several trains in both directions, a series of deterministic simulation experiments was carried out. These steps have been replicated in the simulation tool Villon. Next, a series of simulation experiments was conducted. After the experiments were performed, statistical evaluations of the results were done and the differences in driving characteristics were compared. The difference of measured values is in the matter of units of percent and it is expected due to the apply higher levels of abstraction to some aspects of microscopic simulation. Implemented microscopic traffic submodel was accepted from the viewpoint of the deterministic simulation experiments.
Due to validation of the macroscopic traffic submodel, the prototype station was encapsulated into macro-node. Variant of hybrid traffic model was created, which apply different level of granularity in the simulator. The results of the deterministic simulation experiments of the hybrid model of railway traffic were compared with the results, when microscopic traffic submodel was used for the entire infrastructure. Verification of the correctness of the hybrid traffic model focused primarily on deviations of the train delays moves through the macro-node. In other words, the transformation of traffic flows on the interface between microscopic and macroscopic submodels of the hybrid model must have a minimal effect on the final train delay.
In the case of macro-node, a macroscopic traffic submodel based on analogy of flowing of liquids was tested. An increase in train delays in the order of tens of percent was detected. The reason may be that the prescribed timetable of the prototype station did not include, for example, train waiting at the station tracks in macro-node. The evaluation of macroscopic traffic submodel based on shared resource was better. Train delays showed little deviation according to the results of the microscopic simulation traffic.
Next step is implementation of other predefined macroscopic traffic submodels for defined hybrid model of infrastructure with macro-node. Similarly, the validation will proceed for hybrid model of infrastructure containing macro-edge. The results of simulation experiments will then determine the usability of macroscopic traffic submodels for different macro-segments and also to determine the complex validation of variant configurations of the unitary hybrid model.

10. PERSPECTIVES OF DEVELOPMENT

The next stage of development related to an implementation of traffic models for *macro*-edges and their evaluation. From the viewpoint of preserving consistency of traffic information, it will be necessary to clearly identify the implementation of macroscopic traffic models for *macro*-nodes and *macro*-edges. In the case of different macroscopic traffic submodels used for two types of macro-segments, to solve the transformation of traffic flows on their interfaces. In respect to the use of unitary hybrid model of railway traffic in practice.
Prospective option of further development can be propose a methodology of a general macroscopic traffic model applicable to any defined *macro-segments*.
Other prospective option of further development can be related to an extension of the unitary hybrid simulation model supporting constructions of mesoscopic segments/areas. Mesoscopic segments would enable more detailed traffic simulation than it is carried out within macroscopic areas. Or extending the editor by functionality, thanks to which macro-edges created above a multi open track are encapsulated into one aggregated macro-edge.

11. CONCLUSION

The article deals mainly with the explanation of basic phases of methodical approach to the construction of a hybrid model of railway traffic.
Hybrid model of railway traffic combining submodels applying different level of abstraction (microscopic and macroscopic). It is distinguished between *microscopic traffic submodel* applied to the microscopic elements of the hybrid model and *macroscopic traffic submodel* used in the case of macro-segments. Special attention is paid to explaining the methodology related to

transformation of traffic flows on the interface between microscopic and macroscopic submodel.

Microscopic traffic submodel is based on applying realistic calculations connected with the train ride dynamics. On the other side, apply higher levels of abstraction to some aspects, but still enables to achieve reliable results from simulation experiments without any significant loss of their informative value. There are two approaches to modelling railway traffic within macroscopic submodels (ie. analogy of flowing of liquids and analogy based on competition for shared resources) and their extended variants.

Within simulation experiments a hybrid model of infrastructure (containing macro-node) has been built over a real microscopic model of infrastructure. Both basic versions of the macroscopic traffic models have been implemented. Finally, the possibility of using them in a particular hybrid model was discussed. In addition, a validation methodology was proposed to evaluate the accuracy of the simulation results.

The scope of future development (in editor *TrackEd*) also considers the implementation of traffic models for macro-edges and their evaluation.

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