# SCALABLE SIMULATION MODELS OF RAILWAY TRAFFIC

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**ABSTRACT**
This contribution deals with the methodology of building scalable simulation models reflecting railway traffic. Those models apply different level of abstraction (granularity) to diverse parts of a simulating system. The areas of a railway system that are supposed to be studied in detail are typically modelled on a microscopic level. The sections of infrastructure, which require just rough traffic evaluations, are investigated on a macroscopic level. The resulting methodology contains a variety of functionalities supporting the construction of variant configurations related to a scalable simulator of railway traffic for the needs of different simulation scenarios.

Keywords: scalable simulation model, hybrid model, railway traffic

## 1. INTRODUCTION
Modelling a railway infrastructure and corresponding railway traffic represents an important part of the research focused on railway system optimizations. For such purposes the researchers use the experimental method of computer simulation within the frame of which the applied level of *abstraction*/*granularity* plays an important role. The mentioned granularity defines the level of details which are observed in the simulating system. On the basis of the required granularity level different simulating systems are supposed to be utilized. Traffic simulations can be classified according to the applied level of details.
Generally, concerning transport simulations we can classify models according to their applied level of detail as *microscopic*, *mesoscopic*, and *macroscopic*. Microscopic simulation models are characterized by examination with great level of resolution. Individual mobile entities (rolling stock) and their interaction are observed. For these reasons it is necessary to include detailed information about particular sub-systems (*fixed subsystem* - typically consisting of infrastructure, *mobile subsystem* - consisting of mobile objects, and *management subsystem* - specifies technological processes) in the simulation model. Utilizing microscopic simulation models is suitable for examining small segments of railway (e.g. for an operational check of a railway station after its infrastructure or its graphical timetable of rail transport have been changed, or after the handling technology has been changed, etc.) mainly because of their high demands for detail and computational demand.
While the listed types of investigation are typical for their detailed examination of interactions of individual mobile entities, for evaluating, for example, track or station capacities, it is sufficient to examine only rough characteristics of transport flows (individual rolling stock is not examined). For the purposes of examination we advantageously use macroscopic simulation models, which enable to simplify individual subsystems and thus conduct simulation experiments even above extensive segments of a railway network, but all of that at the expense of the level of detail. However, there is a compromise in the for of mesoscopic simulation models which are trying to balance the level of detail and computational demand.
Considering the concrete aim of the examination (e.g. investigating the throughput or the influence of delay), it is important to select the level of detail for each individual subsystem of the simulating system. (Krivy and Kindler 2003; Burghout 2004).
Traditional approaches apply the same granularity level for the entire simulator. Such a homogenous approach does not enable to combine for example microscopic and macroscopic levels of details within one simulator. Designers of traffic simulations are motivated to use methodologies for building scalable traffic simulators in order to be able to combine and interconnect various submodels of infrastructure constructed on different levels of details (Hansen and Pachl 2008). Then, different traffic models are applied to the mentioned 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. CURRENT STATE
Typical contemporary solutions use the same granularity within the whole railway simulating system. Certain scalability can be enabled by applying different level of details for diverse parts of input data. For example, in the simulation tools *Villon* (Simcon 2014) and *OpenTrack* (Huerlimann and Nash 2010) a larger area of a railway network can be modelled. Border railway stations of that area are not supposed to be investigated on a detailed level because the primary attention is paid to central parts of the mentioned area. Thus, those border stations can be specified by means of

simplified processes and skeletonized layouts of tracks. However, the trains and their driving dynamics are modelled on a unified level of abstraction within all parts of the studied network.

There are various approaches of building scalable simulation models focused on railway traffic. The published concept of simulation model (Burghout 2004; Cui, and Martin 2011) features the option to change the level of detail dynamically during the simulation experiment aimed on the operation of the whole railway network (*scalable simulation model with continuous changeover*). Changing the level of detail from microscopic to macroscopic (*bottom-up*) or vice versa (*top-down*) can be applied by, for example, mere executed change of an appropriate graphic zoom. In the mentioned concept of the scalable model, we can use a uniform graphic visualization of selected rolling objects for various levels of zoom within the infrastructure – *Figure 1*). Concerning the level of detail, the interconnection of different infrastructure submodels can be achieved by model aggregation, in which each node or edge on a higher level can be considered a set of nodes or edges of a lower level. However, there is no uniform approach in the field of traffic simulations which would deal with the consistency of (railway) traffic dynamics in relation to various submodels within the entire simulator.

An approach based on paralelly conducting both, microscopic and macroscopic simulation (of the entire investigated system) can be used for the change of level of detail in traffic simulation - the person conducting the experiment will only see the switch between levels. However, computational demand is a rather inconvenient disadvantage. We are trying to reduce such high demand by introducing scalable simulation models.

Another approach is the combination of submodels with different level of detail within one simulator, which is created statically before starting the simulation (*hybrid model*). Within the simulation experiment conducted above the hybrid model it is possible to, for example, to focus on detailed examination only of narrow operational areas and to manage with only rough operational characteristics in adjacent areas (Magne, Rabut, and Gabard 2000; Gille, Klemenz, and Siefer 2008).

Current solutions of a hybrid model are characterized by the utilization of cooperation of several simulation tools. A possible approach is to use a microscopic simulator for the area of a railway network of high importance and to use a macroscopic simulator for all other areas. The railway network is then divided into areas in which an inevstigation of traffic is investigated using different simulation tools (Casas, Perarnau, and Torday 2011).

A different approach, which is considered a borderline hybrid model, is using the cooperation of simulation tools in a scenario in which each tool solves its own constituent task above the whole area of a railway network. The base of such approach is a microscopic simulator which includes detailed information of individual subsystems and which conducts detailed simulation of train movement dynamics and with it connected investigation, results of which (e.g. aggregated infrastructure model) are subsequently used for, for example, evaluating station throughput or for finding optimal (the shortest) train routes, etc., in a macroscopic simulator (Montero, Codina, and Barcelo 2001). RailSys microscopic tool (Radtke and Bendfeldt 2011) and the macroscopic tool NEMO (Sewcyk and Kettner 2001; Kettner, Sewcyk, and Eickmann, 2003) are both examples of simulators utilizing such approach.

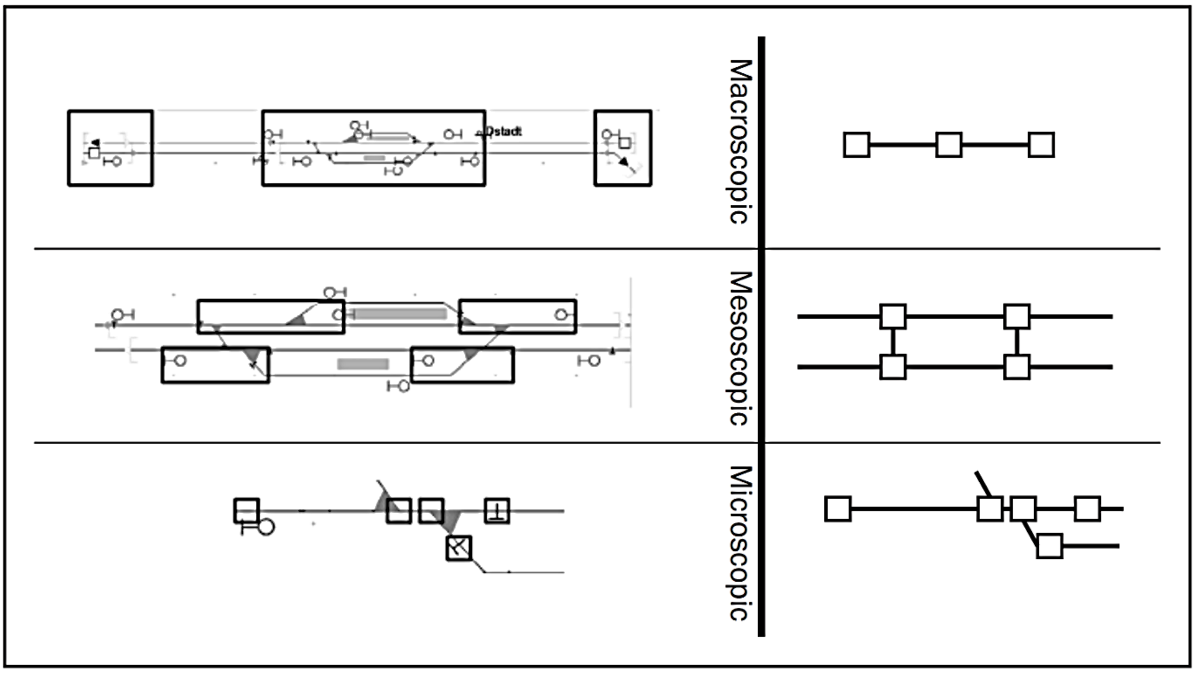


Figure 1: Visualization of infrastructure for different level of abstraction (Cui and Martin 2011)

## 3. APPROACH OF HYBRID MODEL

On the other hand, our presented methodology is based on a hybrid 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 typically connected to particular areas, within the frame of which detailed traffic indicators are essential for an experimenter. On the contrary, macroscopic simulation is applied within those simulator's parts where only rough operational indicators are requested. Unitary hybrid model enables to adjust the *granularity* of a part of a simulator, i.e. operational submodels for individual infrastructure submodels, thanks to the nature of the simulation. Overall computational demands of a unitary hybrid model are certainly lower than relevant demands related to a corresponding model executing pure microscopic simulation.

To create a unitary hybrid model it is necessary to manage solutions to the following problems concerning the submodels applying different level of detail: (i) construction of inhomogenous infrastructure submodels, their suitable interconnection and visualization, (ii) construction of different submodels of traffic, (iii) transformation of traffic flows on interfaces of different traffic sumbodels.

## 4. MICROSCOPIC INFRASTRUCTURE MODEL

The methodology of building unitary hybrid models focuses primarily on the construction of a track infrastructure submodel (*Figure 2*). 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 of an undirected graph in which each node contains not only the position in a schematic plan, but also real kilometric position within the railway network.

Within the editor it is possible to define topological, metric and slope characteristics related to all tracks or their parts. Those characteristics accurately reflect either an existing situation on the spot or a planned infrastructure from the project documentation. Hence, it is possible to carry out realistic calculations (during simulation trials) concerning the dynamics of train rides. The created microscopic 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).

In the *TrackEd* editor we can use a variety of sophisticated functionalities which help to automate some stages of a design. For example, it includes a semi-automatic calculation of a complete set of primary and alternative train routes for all possible train transfers within the investigated track layout or an automatic calculation of useful lengths of station tracks in the station which affect technologic processes in the station, etc.

## 5. DOUBLE-LAYER CONCEPT

The resulting *hybrid submodel/layer of infrastructure* is built over a *micro-layer*, which corresponds to the above mentioned microscopic submodel. The *hybrid layer* combines infrastructure areas applying different level of abstraction (*Figure 3*). The introduced *hybrid-layer* is composed of *micro-segments* and *macro-segments*. *Micro-segments* are represented by sub-graphs directly taken from the micro-layer. *Macro-segments* lower granularity of relevant disjoint connected sub-graphs from the micro-layer.

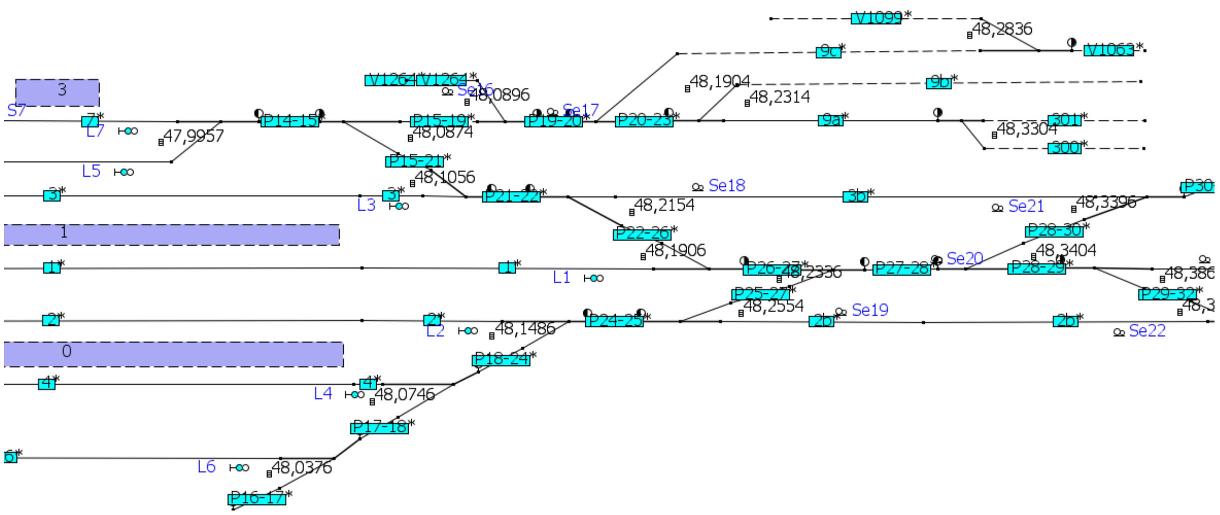

Figure 2: Schematic plan of track infrastructure in the *TrackEd* (Novotny and Kavicka 2015)

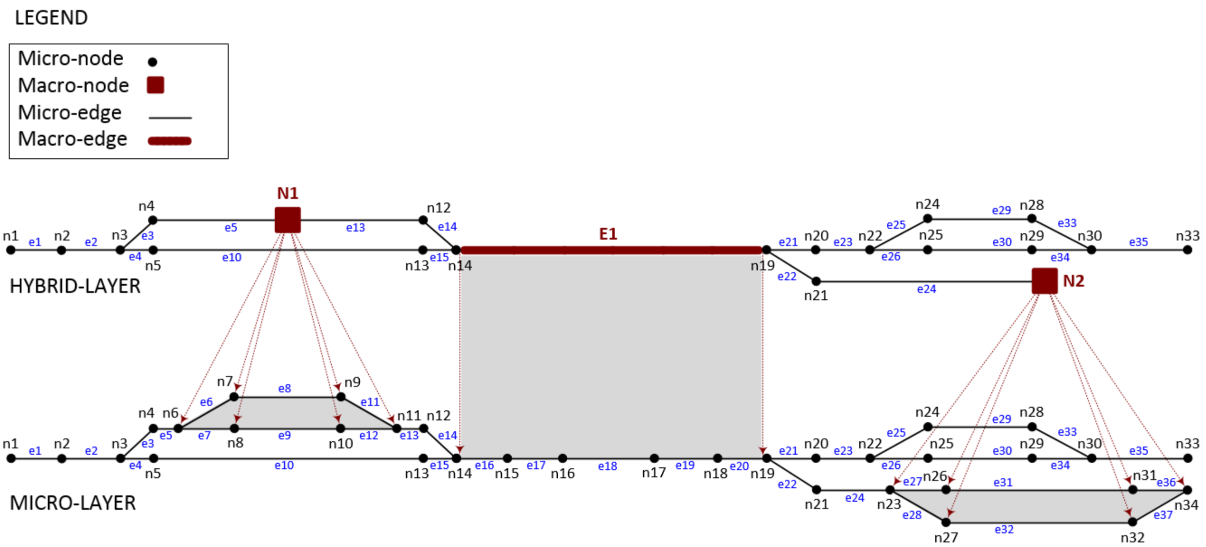


Figure 3: Double layer concept of infrastructure model

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.

As it has already been said, a data structure in a form of a graph implemented in the operational memory and composed of two types of object (*nodes* and *edges*) is used to represent a railway network. From the viewpoint of the implementation of the unitary hybrid model, this means two different (co-existing) instances of such data structure: (i) a graph representing the primary micro-layer, and (ii) a graph representing the resulting hybrid layer of the track infrastructure (*Figure 3*). As a general rule, the edges or nodes in the graph of the hybrid layer can represent individual edges or nodes of the micro-layer or their aggregated area (macro-segments). When creating such objects in the hybrid layer of the infrastructure, it is necessary to first set attributes (by deriving them from appropriate encapsulated objects in the micro-layer) needed mainly for calculations within the macroscopic areas. We can thus find within the macroscopic area, for example, the average speed, the number of isolated circuits, the set of train routes defined by a technologist, etc.

When creating a hybrid model of the railway infrastructure, we must always base our model on a detailed infrastructure model, which contains detailed information (attributes) necessary for mainly the microscopic simulation and which can be then easily aggregated for the needs of the macroscopic simulation.

An reverse approach, in which we only have the aggregated (macroscopic) model of the track infrastructure at our disposal, is not considered as it mainly derives detailed information about the infrastructure for the needs of the microscopic simulation rather inaccurately. An example of such inaccuracy can be a railway stations for which we know only the coordinates of their real positions within the railway network, but we do not know the detailed information about their track layout which is important for, e.g. finding the capacity/throughput of the station, etc.

## 6. SEGMENTS

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 micro-layer (*Figure 3*). A typical example of an infrastructure that can be represented by rougher granularity is a railway station. Within one experiment it can be realistically specified with all basic elements (tracks, platforms, signals). Another experiment, which does not pay attention to bottlenecks of infrastructure and/or internal station processes, can interpret that station as a point element (a macro-node). A double layer concept related to infrastructure model provides making various configurations of a hybrid layer with a fixed connection to real topological, metric and slope properties defined in the invariable micro-layer.

Concerning visual representation of the hybrid layer it is important to take into account certain visual deformations of rail elements in comparison with the original visual forms in the microscopic layer. It is caused by different graphic connections of microscopic elements to macro-segments with regard to the "native" connections within the micro-layer.

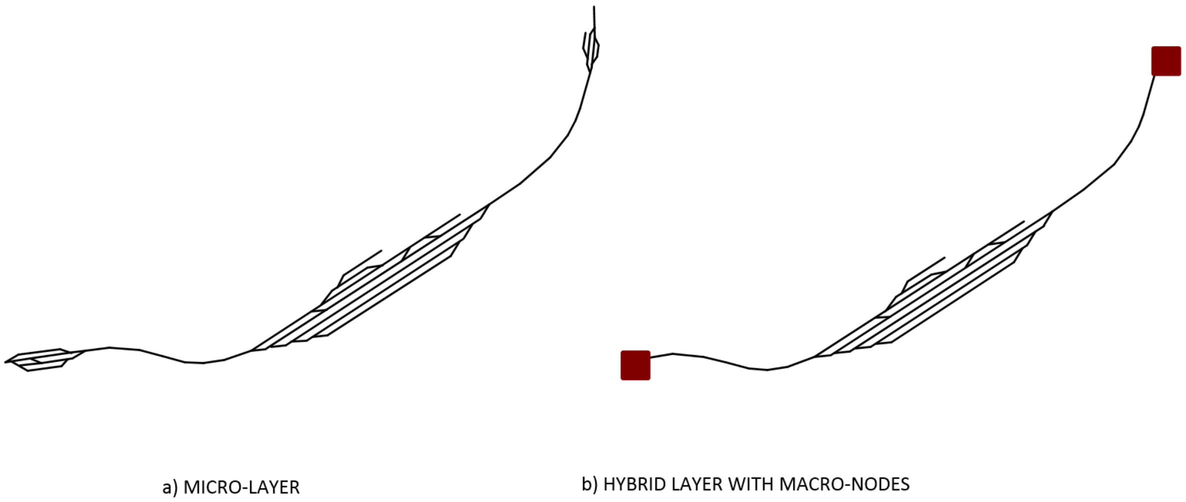


Figure 4: Macro-node illustration

## 7. CONSTRUCTION OF MACRO-NODE

Macro-node corresponds to the encapsulation of selected nodes and their interlocutory edges of the micro-layer into a single node of the hybrid layer. As it has been said, a typical example of a macro-node can be a railway station *(Figure 4*) which can be represented on a rougher layer of granularity and thus its detailed operational verification is not necessary.

The introduced methodology of creating a hybrid model of a track infrastructure enables to select any area of the micro-layer and its subsequent aggregation into a macro-node (and it is thus to create more of these macroscopic areas within a station *Figure 3*). An advantage of such approach then can be the detailed investigation of railway traffic only on selected station tracks, development of switches, or in a selected part of the investigated station.

Graphic position of the created macro-node in the visual schematic hybrid model of track infrastructure is always located in the middle of the selected area and thus can create visual deformation as in result. In the *TrackEd* editor it is then possible to change graphic position not only of nodes taken from the micro-nodes, but also of these macro-nodes.

## 8. CONSTRUCTION OF MACRO-EDGE

In the railway network there are parts of tracks where there is no track crossing, convergence into one or divarication into more tracks. Such parts of tracks are called an open track and it connects two traffic landmarks (places with special significance). In other words, it is a route between two adjacent stations which can usually be modelled using several smaller edges with component nodes. Within simulation modes focused mostly on operational verification of stations, such open tracks do not have to be principal for the experimentator, thus it is not necessary to conduct any microscopic traffic simulation in this part of the railway network. For these reasons it is important to enable the encapsulation of such component edges along with their border nodes into a single, so called, *macro-edge* *(Figure 5)* and to conduct above it only macroscopic traffic simulations, when applying the described methodology. A macro-edge is then used to encapsulate a liner connection of edges in the micro-layer, or rather the sub-graph, in which each inner node is interlocutory only with two edges (a liner sub-graph).

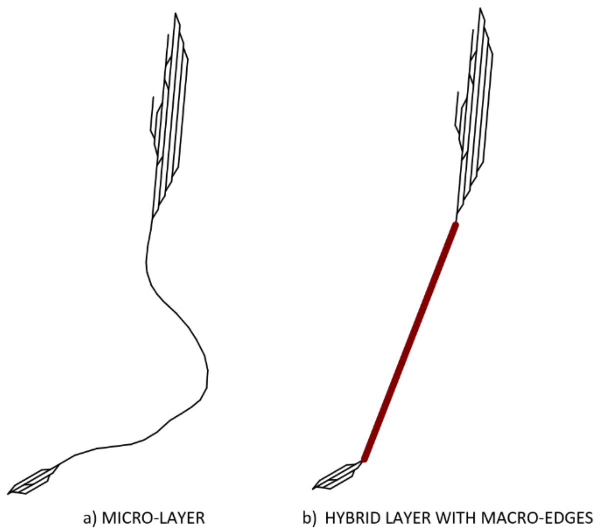


Figure 5: Macro-edge illustration

If we are considering a single track, it can be for the macro-segments modelled as one macro-edge. If we are considering a multitrack and at the same time there is no crossing, convergence or divergence of tracks, it is necessary to model each track individually (i.e. encapsulate each track into one macro-edge). If a multitrack is represented as macro-edges, it is necessary to manage their graphic representation so no visual overlay occurs in case of the same intial or end node.

Generally, we can use the macro-edge in any part of the railway network not only for open tracks, but it also has to be represented as encapsualtion of a liner subgraph. In this way we can treat all station tracks, which is not evaluated in detail in the aim of the investigation within the station, and only information about the traffic density is sufficient.

## 9. HYBRID INFRASTRUCTURE MODEL

When creating a hybrid track model by applying macro-edges or macro-nodes above the defined areas (while respecting the abovementioned rules), one must also consider suitable setting of borders of the selected macro-segment while considering switches, crossings, platforms, isolated circuits, and other traffic landmarks (places with special traffic significance). Generally, creating a hybrid model means that creating macro-segments above the defined infrastructure segment is limited not only by its track layout, but also by other subsystems (e.g. security devices system, etc.)

Combining any macro-segments is allowed when creating a hybrid track layer *(Figure 6*). It is then possible to connect macro-nodes with macro-edges. However, such connections always have only one common microscopic element (node) within their encapsulated infrastructure submodels. That means that it is not possible for two border nodes of one edge of the micro-layer encapsulated into a macro-layer to also occur in a macro-node.

It is presupposed a static configuration of all macro-segments before an execution of simulation experiments. Thus, dynamic changes of levels of details related to track layouts are not supported during simulation trials. The resulting track model can also have the characteristics of a microscopic model when it does not include any area encapsulated into a macro-segment. And thus the resulting hybrid layer is identical with the input micro-layer. The resulting model can be entirely macroscopic if each edge or node of the micro-layer also belongs into any of the defined macro-segments. However, for the resulting hybrid infrastructure model it is typical to combine the areas applying different levels of detail.

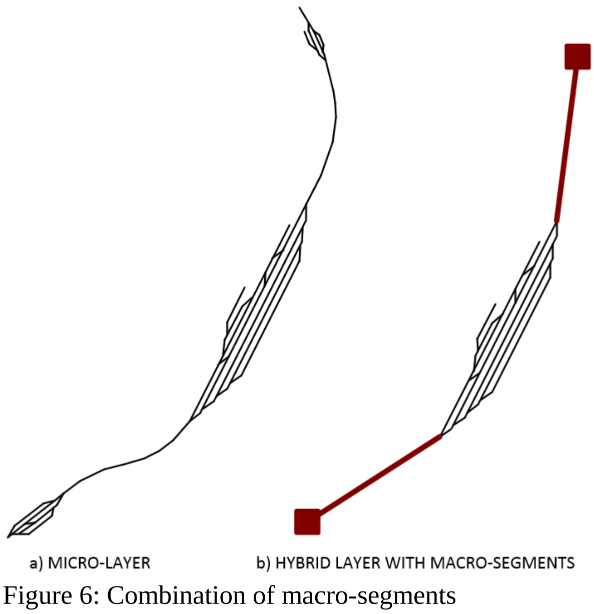

Figure 6: Combination of macro-segments

For the needs of repeated use of the defined configuration of the hybrid layer, the *TrackEd* editor enables saving such configuration into a predefined template and the use it again in the future.

## 10. TRAFFIC MODEL

Because of combining macro-segments with areas composed of microscopic elements within the hybrid layer, it is necessary to apply different traffic models (implementing various levels of abstraction). Diverse traffic models are connected with different traffic indicators - e.g. detailed riding features of individual rail vehicles or average rates of traffic flows within the observed areas (Cenek 2004), etc. As an example can be mentioned a macroscopic traffic model, which observes individual vehicles on a high level of abstraction (applying constant average speeds etc.). Another approach can be based on the theory of traffic flow exploiting the analogy with the flows of liquids (Krivy and Kindler 2003).

Because several different submodels coexist within a hybrid model, it is necessary to solve the transformation of traffic flows, i.e. it is necessary to unambiguously define the information about railway traffic on the interface of microscopic and macroscopic submodels in order to maintain information consistency. The main problems is the loss of a large amount of information when switching the rolling stock from the microscopic to the macroscopic submodel. The result is absence of detailed information about individual rolling stock which later switches from the macroscopic area back into the microscopic one. These attributes must be unambiguously defined for the microscopic simulation from aggregated information (e.g. average speed or the intensity of the traffic flow) and thus establish the current speed, the acceleration, the occupancy of insolated circuits, and intervals between trains. Of course, the current status of traffic and traffic situation in the relevant surroundings must be considered.

When the rolling stock switches to or from the macroscopic submodel, it is necessary to decide if the switching is even feasible based the occupancy of the area to which the train is switching. If the switch is directed onto the microscopic rolling element, the vacancy is evaluated based on the occupancy of the relevant isolated circuit. In the switch is directed onto the macroscopic area, such situation is ambiguous and in some extent it depends on the traffic model applied for macro-segments, i.e. it can depend on the intensity of the traffic flow, vacant capacity of the segment, etc.

For rolling stock within macroscopic areas and mainly to maintain consistency of traffic simulation, it will be necessary to select a mechanism of derivating aggregating information. An example of such can be attributing to rolling stock average speed which can consider maximal allowed speed within all rolling elements encapsulated in a macro-segment or just in those in which the train will be moving.

## 11. PERSPECTIVE OF DEVELOPMENT

The next stage of development related to a scalable railway traffic simulator (based on the unitary hybrid model) will be focused on a selection and advancement of traffic models utilized within microscopic and macroscopic parts of a hybrid infrastructure model. Special attention must be paid to transformations of traffic flows when they transit from the microscopic to the macroscopic elements and vice versa (Burghout 2004). It is presumed that series of simulation experiments will be carried out over the created hybrid infrastructure model within an integrated development environment belonging to *TrackEd* tool.

Prospects of further development can be extending the editor by functionality, thanks to which macro-edges created above a multi open track are encapsulated into one aggregated macro-edge.

Other prospective option of development can be extending the unitary hybrid model by mesoscopic areas enabling more detailed traffic simulation than it is possible in macroscopic areas, but above more detailed infrastructure model.

## 12. CONCLUSION

The article deals mainly with the explanation of basic phrases of methodical approach to the construction of a scalable infrastructure model.

Unitary hybrid model (currently in development in the *TrackEd* editor) combines areas constructed on different levels of detail (microscopic and macroscopic) and thus differentiates between a micro-layer and a hybrid layer. To create a hybrid layer, the approach of decreasing the level of detail for specified areas of the micro-layer (macro-segments) is applied. Two types of macro-segments, used to encapsulate various areas of a microscopic model of track infrastructure and thanks to which it is possible to create variant configurations of a scalable simulation model, are introduced.

The scope of future development also considers the selection of traffic models for microscopic and macroscopic parts of the hybrid model and transformation of traffic flows on their interface.

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