Issues on Simulation of the Railway Rolling Stock Operation Process – A System and Literature Review

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Railway traffic simulation, taking into account operation and maintenance conditions, is not a new issue in the literature. External effects in such networks (e.g. level crossings) were not taken into account in studies. The used models do not take into account sufficiently the process of degradation and recovery of the network. From the technical side, currently carried out simulations are made using similar approaches and techniques as in the initial stage of research. Well-established work in this area could be the basis for evaluation of new solutions. However, the progress in simulation tools during the last years, especially in performance and programming architecture, attempts to create a modern simulation tool. In the paper were presented the main assumptions for the evaluated event-based simulation method, with application to stiff-track transportation networks.

Keywords: railway traffic simulation, railway rolling stock, traffic management, train crew management.

1. OPERATION OF RAILWAY ROLLING STOCK – IMPORTANCE AND BOUNDARY CONDITIONS

Operation and maintenance of technical systems is connected to the need of timely application of preventive maintenance as well as to the way of reacting during unwanted situations in an appropriate manner [17], [18], [52]. If such a system consists of components located in an area where unexpected interactions with the environment may occur, the complexity of the issue increases. Such a situation occurs in case of railway transportation.

The main problems of scheduling carrier's tasks are: planning of rolling stock circulations, crew scheduling and train interchanges.

The train travel time is a key element of the transport offer and, frequently, one of the main reasons why the client chooses the given mean of transport. It is the time from the moment the train leaves the place of departure until it reaches its destination, taking into consideration foreseeable and unforeseeable events which can interrupt the train's journey [37]. The travel time should be calculated in such a way that it would be possible to benefit from the technical parameters of the line, as well as the possibilities resulting from technical properties of the rolling stock used by licensed carriers [2], [20], [43]. In practice, there are situations in which trains do not arrive to stations in accordance with the timetable. In [49], an inventory of sources of disruptions in railway traffic was done, indicating incorrect planning of the traffic (errors in the structure of timetables) as a basic problem causing delays. In the works [34], [41], the organisation of railway traffic was identified as another possible reason for disruption. In this aspect, it was noticed that the use of channel capacity (resulting from the timetable) affect the punctuality of trains.

The aim of the article is to present main assumptions of a new simulation tool. It is under development at The Wroclaw University of Science and Technology.

2. SIMULATION TOOLS USED FOR THE RAILWAY SYSTEM

Among many issues concerning railway transportation system management the issue of the use of its resources is of a special importance as it allows for implementation of the carrier's tasks. Optimisation works are conducted within this scope, aiming at reduction of costs related to the process. Savings can be made by adopting more rational management of the fleet. Many railway carriers use simple methods of planning their rolling stock and train crew operation. It is time-consuming on the one hand and may lead to undetected errors on the other. Effective management of such processes demand appropriate algorithms and an appropriate IT tools. The issue of railway operation process planning includes timetables, rolling stock circulation and train crew planning [38].

Simulation models used in Practice usually include mapping of rail networks. The main goal is related to traffic policy and traffic management investigation. Degradation phenomena of the rolling stock and infrastructure are skipped. In [39]it was looked for a compromise between the service level and network capacity. Two complementary simulators were used. There is a main difference between these simulators (RTC and RailSys). RailSys bases on timetables, while RTC uses departure times and conflict solving algorithms for train traffic

In [12] the authors reject a few known simulation platforms (Open Track Bahn, RailSys, PTV VisSim, QuadstoneParamics) due to being uneconomical or ignoring of passenger flows. They propose an own model, is based on rolling stock operation. It ignores infrastructure network operation.

The paper [29] shows modelling of networks with high-intensity traffic. Train traffic is represented as stochastic process, while passenger activities base on a constant schedule. The arriving times of trains are modelled by the Poisson distribution.

In [48] is a method presented for scheduling of railway rolling stock maintenance. It was supported with use of computer simulations in Arena. The aim of the simulation is to determine the appropriate conditions to increase the efficiency of such facilities.

3. PARAMETERS AND CHARACTERISTICS RELATED TO RAILWAY VEHICLES

3.1. TRAIN AS BASIC OBJECT IN THE SIMULATION

The rail vehicle is a part of an entire transport system. It interacts with the environment, infrastructure and its operators. Passengers or cargo have also an effect on its operations. In this aspect, it is possible to describe the system as vehicles riding on the infrastructure, which in some places have contact with the environment. Infrastructure and environment influence will be described in a separate article.

Regardless of the type of rail transport system (underground, tram, train, etc.) a common element can be introduced, which is a train. The train is an operation chain, which consists of three sets: train crew (drivers and managers with assistants), the vehicle (or vehicles) and passengers (or cargo):

$$Tr = <O, R, K>$$

where:
Tr–operation chain (train)
O –set of train crew
R–set of rolling stock belonging to the train,
K – set of transportation subjects (passenger or cargo).

The set of vehicles consists of technical objects which are fitted with a power train, an energy supply system, wheel sets and bogies, and other necessary parts to move passengers or cargo.

Reliability of a train is a function of many factors that quantitatively and qualitatively change during operation. The following parameters have influence on its reliability:
– train category and type of moved goods,
– traction type,
– rolling stock type,
– lifetime of vehicles belonging to the train,
– time and mileage since last main repair,
– season.

Another element of the operation chain is transportation subject. The subject will affect random events that may cause disruptions in the

train ride. Type of cargo or culture of passengers depend on the train category.

3.2. OPERATION PARAMETERS AND TRAFFIC MANAGEMENT

According to the international literature, passenger rail traffic is described on the basis of timetables (detailed operation plans) [5], [13], [15], [40]. Timetables usually take delays into consideration. At the time of railway traffic planning, deterministic travel times are assumed. In case of any disruptions on a railway line, buffering time is added in order to compensate for the delays. The probability of suppressing delays is directly related to the issue of the so-called robust timetables [9], [13], [28]) and an ability of a system to regain its functionality after an event (resilience) [11]. The use of procedures on the basis of a fully deterministic nature of information results in high inconsistencies in the railway traffic management [27], [35]. However, in the majority of cases, disruptions in traffic are of a random nature and are far from being determined.

Development of methods to prevent occurrence or reduce occurred delays is an important issue. Advanced models and algorithms of reacting inconsistencies with timetables in complicated railway networks were presented in [7], [8], [13], [30], [42]. In [44], an approach related to cyclical character of the railway traffic was used. It described a mathematical model for the so-called Periodic Event Scheduling Problem (PESP). In PESP, an event can mean an arrival or a departure of a train. Those events are planned in one cycle which repeats regularly. Periodical limitations may include fulfilment of safety requirements, especially for each pair of trains using the same track, such as maintenance of a minimal time interval. In [3], robust timetable modelling was summed up. The following approaches to the issue were distinguished:

− ordinary designing of a cyclical and a non-cyclical timetable,
− stochastic programming,
− light robustness,
− recoverable robustness,
− delay management,
− bi-criteria Lagrangian approaches.

Modelling of a train timetable may be connected to the issue of modelling mass service systems. In the work by [50] those issues were resolved with time reserves needed in timetables. If the relative value of an initial delay is known, it is possible to determine the number of time reserves needed to eliminate the effects of the initial delay. Railway junctions' capacity is a similar issue which is examined in terms of critical points in infrastructure. A more detailed description can be found in an analysis of the results of events as initial defects and secondary defects which result from them (excluding the influence on the traffic) [43], [50].

Another group of works from the railway industry concerns dispatch activities in case of disruptions. One of the approaches assumes controlling the speed of trains in order to minimise unplanned stoppages (which affect the passengers) and lower power consumption [10]. This approach does not propose any structural changes in the process, but only changing its parameters (for example by lowering the speed of trains which are in conflict with a delayed train). Generally speaking, those issues are related to reorganisation of traffic after disruptions occur and they are aiming at minimisation of the risk of further propagation of the disruptions [4], [46], [47].

Wendler [51] used Markov's semi-processes model in order to indicate time intervals between trains of various speeds.

Kroon et. al. [26] proposed a model supporting management of disrupted railway traffic. The model is based on costs of reorganisation of the train traffic and cancellation of trains. It was assumed that the most important resources which demand reorganisation are train crews (drivers and traffic services). In [1] a model of support in a process of making decisions during disrupted traffic management was presented. The influence of the infrastructure on the propagation of disturbances was shown. The deciding variables were the moment of commencement of such an event and disturbances caused by it. The remaining variables are: the value of the delay, which is a result of the event, and binary variables.

Decisions made may be divided into two groups: an immediate and strategic one. Immediate solutions cover mainly the current usage of the system that is traffic management, while strategic ones focus on technical service works. The service models depend on the profile of a given organisational unit of a company. The models were collected and described in detail in publications such as [32], [33].

3.3. TRAIN CREW MANAGEMENT

In [6], the so-called tabu search algorithm was presented, which is a tool supporting the process of designing circuits. An important advantage of the algorithm is its simplicity which allows for easy application of this solution. Taking into account boundary conditions, single events are combined into series, which finally form circuits. In the algorithm, there are no random events which would disrupt the process.

In [38] was proposed the solution based on mixed integer linear programming (MIP) models. The approach is based on combining all carriers' tasks in circuits and then dividing them between drivers. Due to the complexity of the issue, Lagrangian's relaxation approach was proposed. The approach adopted has one significant disadvantage which is narrowing the issue of scheduling the train crew to the driver. In practice, the crew consists of conductors and employees responsible for manoeuvres. This method does not take into consideration random events disrupting circuits as well. Development of circuits was directly combined with development of a timetable. However, the time of work of a train crew and the aspects or reliability were omitted. The problem was solved using the ant colony algorithm. Such a combination of a biomimetic algorithm and a heuristic algorithm is based on the ability of ants to find the shortest path to food by submitting information between units. Two approaches were described. In the first, the classical one, there was one big circuit which was then divided into smaller parts. However, attention was paid to the fact that it was a relatively non-effective algorithm and that is why its modification was proposed. It was based on a search for appropriate circuits.

The authors of [16] widened the issue of circuits and scheduling of bus drivers with aspects of dynamic resources management. Its aim is mainly to fulfil tasks in a timely manner, and that means it focuses on passengers. It was assumed that rolling stock and human resources are unlimited. The paper was dived into two parts containing a static and a dynamic solution. The approach assumed a very high flexibility and even though it is useful in bus traffic, it is hard to apply it to railway transportation.

In case there is a high number of routes, the problem of static scheduling of driver crews leads to the need of choosing between the speed of the solution and the quality of the algorithm's results.

In [19], a decomposition of the task area into regions was proposed. The tasks of a train crew are assigned to regions on the basis of the criterion of the lowest costs. In the set of heuristic algorithms for solving the shown problem [14], also genetic algorithms are used [45].

In publications on scheduling work of aircraft crews there were numerous algorithms proposed [21], [22], [23], [24], [31], [36], [53]. Even though the boundary conditions are similar, the conditions related to the transport offer are less flexible in case of the railway, and this is why it is not possible to use those methods directly.

A train crew consists of two subgroups, a train driver and a train manager with assistants. Scheduling of train manager's work is a little easier than train driver's scheduling, because drivers must have separate admissions for each driven line. The most important factor is returning of train managers and drivers to their home stations. Such a solution is preferred for domestic courses due to financial reasons. Therefore, train crews change during a train ride and the planning issue is going to be more complex. Daily working time for train crews has a length from 8 to 12 hours.

A train manager is responsible for a train ride on a designated section. A manager is a superior of all personnel operating a train, except supervisory and control. Manager's assistants perform the duties of commercial transport (sales and ticket control, the action related to start-up of a train, monitoring order on a train).

In the case of drivers, in addition to compliance with working time, a train driver must have knowledge on the route, type of vehicle, type of traction (petrol, electricity), permission to ride abroad, and, depending on the speed limit, the number of drivers varies (one or two). Another issue is related to validity period of certificates. For formal reasons it is also required to establish working hours in the context of salary. The number of train crews should be greater than the number of scheduled shifts. In practice, the reserve is about 22%. There are no methodologies and tools to resolve such a complex issue.

According to the regulations, any change of an employee may not cover third consecutive night (23.00-05.00), the third Sunday in line, or does not start on the day of previous shift. The rest must last for 12 hours.

4. EXISTING IMPLEMENTATIONS OF SIMULATION MODELS

Most often, the simulation models used in practice include mapping of track network for checking the traffic strategy, or the supervision of traffic in the network. The analysis of phenomena related to degradation and renewal of the rail network technical infrastructure is excluded.

Railway traffic simulations taking into account operational conditions have been implemented since the very beginning of the availability of computer simulation techniques. They were concerned with motion engineering [54] or even took into account some randomness of events occurring in the railway traffic [55].

At present, the question of the capacity of railway lines is still subject of research. In [39], the authors seek a compromise between the level of service and the network capacity. Two complementary simulators were used. There is results interchange between them. These simulators (RTCs, RailSys) differ mainly in that RailSys is based on scheduled timetables and the RTC allows to plan on a specific departure time and it has conflict resolution algorithms.

Today's simulations are characterized by significantly improved and more complex detailing of technical objects, covering many issues simultaneously.

The infrastructure simulation model used for the analysis of the rail network presented by Wales and Marinov [56] is a typical example found in literature. It takes into account the operation and maintenance process. This model has been implemented in SIMUL8 software. It is used to validate strategies for reducing delays in Tyan and Wear Metro Network. Concentrated on the control of primary and secondary delays, it completely omits the phenomena associated with infrastructure degradation.

In [57], the authors use their own solution (SimDimMetro) to examine the traffic strategy that takes into account the flow of passengers. They rejected all known simulation platforms: Open Track, Bahn, RailSys, PTV Vissim, QuadstoneParamics. In their opinion, the platforms are non-economic or do not take into account passenger flows. The model omits the operation and maintenance of the network infrastructure. The model has been implemented in C # and is compatible with programs written in MATLAB.

In [58] modelling of traffic networks with high traffic intensity is presented. Finding future needs of the network is the main goal. Train traffic is represented by a stochastic process. Passenger traffic is based on a fixed schedule. It is assumed that most trains arrive in accordance with the Poisson distribution. Both passenger and freight traffic are included. The model was implemented in the original solution using the SLAM II Simulation Language.

A simulation solution dedicated to freight transport was presented in [59].In this work, the location of the service stations and parking spaces was determined in relation to the location of the transport work. After rejecting the typical simulators of the national carriers (North America, Germany, the Netherlands), the model was implemented in the author's solution written in SIMUL8.

Another issue discussed in the context of rail networks is the simultaneous operation of normal and high speed trains. In [60], station sections are analyzed, taking into account the rolling stock. The model was implemented in the Arena simulation environment.

An important issue is the occurrence and propagation of network interference. In [62], the authors propose a model in which delays result from interruptions in network operation. Like Wales and Marinov [56], the authors distinguish between primary and secondary delays. Interference is generated throughout the network and delays are recorded at the measuring points. Algorithm for calibration of disturbance parameters was also introduced. The model was implemented in RailSys and DoSim (Yong Cui).

Railroad network simulations should enable [61]: traffic management, timetables, power management, on-line control. In this article, the authors review the available simulation solutions in these areas of the rail network.

In the literature models can be found which cover development of timetables, take into account detailed reflection of the infrastructure. In [63]a simulation method implemented in SIMARAIL software was presented. This system takes into account the closures of the sections resulting from the timetable for operating the infrastructure when creating timetables. The model was implemented on Enterprise Dynamics (INCONTROL Simulation Solutions) in 4DScript.

Among the works related to the simulation of rail transport systems, this study deals with optimization of energy consumption on the route.

An example of such an elaboration for simplified terms of one line is [64]. A very important issue, but it is becoming too difficult to implement due to technical reasons.

Simulations related to the maintenance of the technical infrastructure of track networks are generally conducted without direct relation to the current network traffic schedule but are related to its operating parameters. In [65], an infrastructure maintenance model is presented and implemented in the simulation.

Among the elements of the track system, the next areas of application of simulation techniques are rolling stock facilities. In [48] a method of scheduling support using computer simulation techniques in the Arena environment was presented. The purpose of the simulation is to determine the appropriate conditions for increasing the efficiency of such objects.

As it is evident from the recognition of available solutions, there are many simulation platforms used to model rail networks. However, none of them is suitable for in-service track systems surveying both track infrastructure and traffic organization.

5. IMPLEMENTATION OF THE SIMULATION MODEL

The main goal of this research is to make a set of objects for simulation of guided transit operation systems to be implemented in programming language. To achieve this, a python reference library is created.

Therefore our goal is to describe both: data model for guided transit operation systems (DMS) and its software reference implementation library (SRL). Data model consists of network object definitions.

Implementation of the model consists of dedicated code modules:
a) modules that define the behaviour of the model objects,
b) modules that implement the logic and functionality of the model,
c) modules defining the runtime environment and how to cooperate with other software,
d) modules that allow the data logging and reporting for later analysis.

Objects can be implemented in a single or multiple processes. Large load during simulation can also be the cause of a simulation run on a cluster. To ensure communication during simulation between objects regardless of differences in:
a) architecture
b) runtime environment
and to allow parallel processing, a dedicated module is introduced.

The simulation consists of establishing all the events in a certain period of time. The events are mainly related to the routes of vehicles. There are two main types of routes (fig. 1):
– a route with closed loop (A)
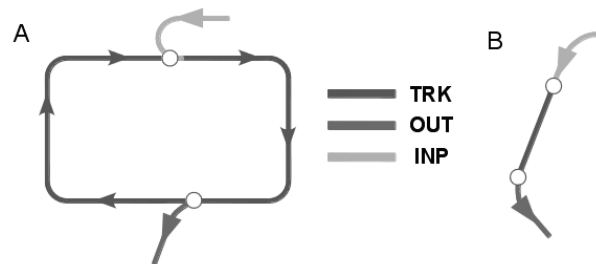– a simple route between two points (B)

Fig. 1. Route of a vehicle.

Each of these types consists of three stages (fig. 1):
– introduction to the network (INP),
– the movement on main route (TRK),
– leaving the network(OUT).

The point of entry to the network may be different from the place where a vehicle leaves the network. Sometimes you have to take into account the earlier movement between points of entry / exit nodes before a vehicle sets off on a route. To start moving vehicles, all network objects must be pre-initialized in the correct order. It is a task of a network initiation module, consisting of:
– enabling the introduction of load distribution between nodes of a computing cluster,
– enabling the introduction of load distribution between processor cores,
– creating all network objects,
– performing configuration of network objects based on the class of these objects,
– enabling the distribution of objects on remote hosts, and ensuring the operation synchronization with the root computing node,
– supervising and executing all other tasks related to the preparation of the network to be simulated.

After completing all the tasks on the preparation of a simulation network, a definition module gives control over the simulation back to simulation execution module.

The basic types of events in the simulation are (fig. 2):

- events associated with the entry on the module (EA) and leaving it (EB)
- change of the operating parameters on the network section (with its lock included) - static: (EDD)
- section reservation for the moving vehicle (sometimes including the consequent locking of the whole module) – dynamic (EEE)
- events at a point - static: (EC):
  - stop
  - checkpoint

- TracMod (A) - is a transit sector with FIFO queue
- BufrMod (B) - is a buffer sector, with algorithmically generated leaving order
- InOuMod (C) - is a enter/exit sector, for introducing to or leaving a vehicle the network

In addition to these basic types of modules, it is possible to distinguish the network modules with fixed or variable direction movement.

Events that define the behaviour of the network are assigned to each sector (module).

We can distinguish the following basic types of events on modules which generate the data as result of related events (fig. 4):
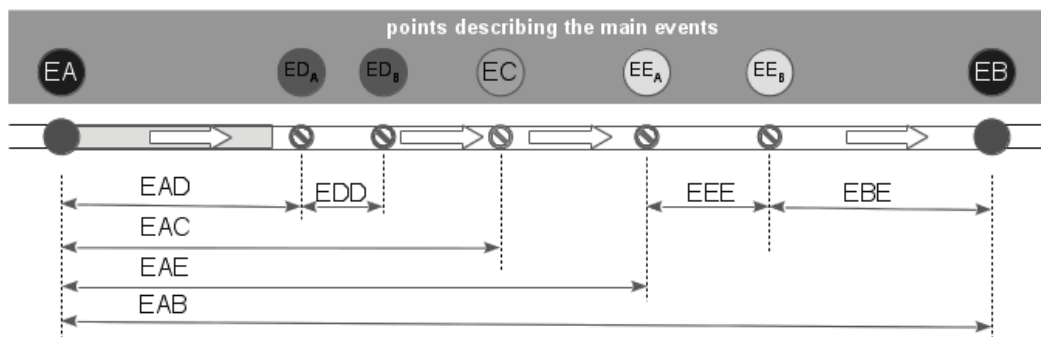
- vehicle entry to the network section (MA)

Fig. 2. Types of events occurring on the module.

Event times decide when the network status updates during the simulation.

Static events are calculated at the beginning of the simulation or during time-step initialization.

Dynamic events are updated on a regular basis during the simulation.

So the cause of the event can be a vehicle and infrastructure (e.g. as a result of the module EFECTS) or current simulation itself (e.g. to allow monitoring).

Generally, events are logged by network modules but logging through network nodes or vehicles is also allowed.

A dedicated module defines global objects for representation of network's sectors between its nods or allows you to enter and exit the vehicle from the network (fig. 3):

- vehicle exit from the network section (MB)
- occupation section of the network to enter (MA + MAC)
- stop on the route (MS_X)
- checkpoint on the route (MS)
- damage of section (MS_2 – MS_1)
- blocking section by a damaged vehicle (MS_2 - MS_1)
- blocking section by a moving vehicle (MS_2 - MS_1)
- change the operating parameters (e.g. slowing) of track section (MS_2 - MS_1)

Some of these events are logged by the vehicle and some by the section of the track (module).
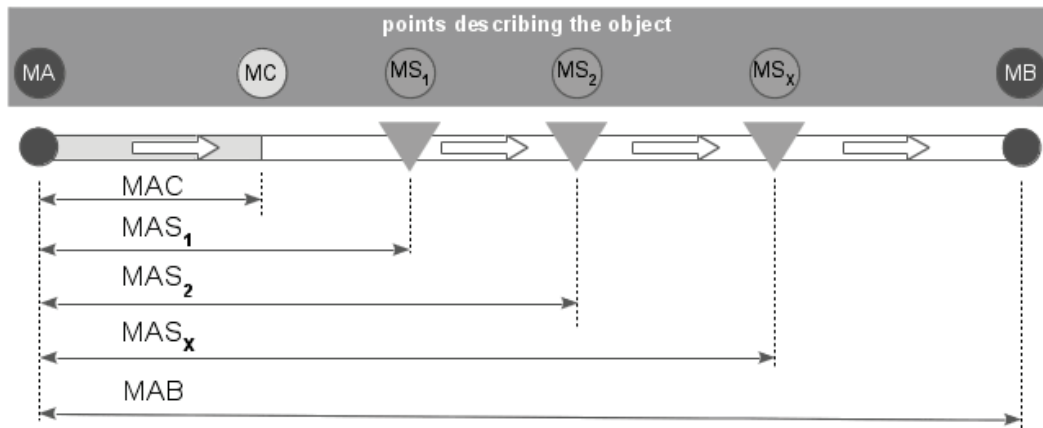

Fig. 3. Types of model modules.

Fig. 4. The main elements of the module which generates the data as a result of related events.

If it is necessary to introduce track sections where only one vehicle can enter at a given time, and that may be achieved by establishing a permanent MC = MB. Sometimes the next module is shorter than the vehicle, and then the vehicle is moved once a reservation on succeeding module is done, where the vehicle fits in its entirety. Then intermediate modules and nodes on the route are also blocked.

The entrance to the module can be blocked as a result of:
– blocking MAC section,
– events in the section,
– setting the lock on a net section.

The name of the module consists of three parts: the first node, the intermediate module, the second node. The characteristics are described separately for each direction and the direction is determined by the starting node, e.g.: module generally [10, 23, 11], the module with the selected direction [10, 23, =].

A special nodes module is introduced to the network nodes. There are three main cases to insert a node to the network:
– the intersection with a road(to show the influence of the environment),
– splits the route into sections which can occupy only one vehicle (including MAB = MAC),
– the mapping of switches in the network.

For all other cases, insertion of a node must be very cautious, since the node affects the network traffic. In many cases it is more appropriate to place events on the module with the same consequences for the behaviour of a particular piece of the network.

The model allows the use of only two kinds of physical node:
– DiffNod (A) - node dividing section into two modules,
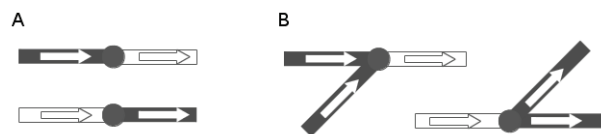– TracNod (B) - node between three modules.

Fig. 5. Types of model nodes.

The vehicle, reaching to the node asks for further route even if it has saved the whole route. The node decides whether or not to pass the vehicle.

The network node knows only its direct neighbours. However, its neighbouring node can recommend its further neighbour to answer a request. The network node can be blocked. Putting a lock on the node stops the vehicle despite the fact that the node is only a point on the route.

Network nodes decide on network traffic. All the mechanisms that determine the conduct of network traffic are introduced in the network nodes.

The vehicle moves in a well-defined track. Therefore, the representation simplifies to the section of the route.

Due to the fact that the network has a number of vehicles and the fact that they move on the network a vehicle is not a one simple determined segment (VAB) (fig. 6).
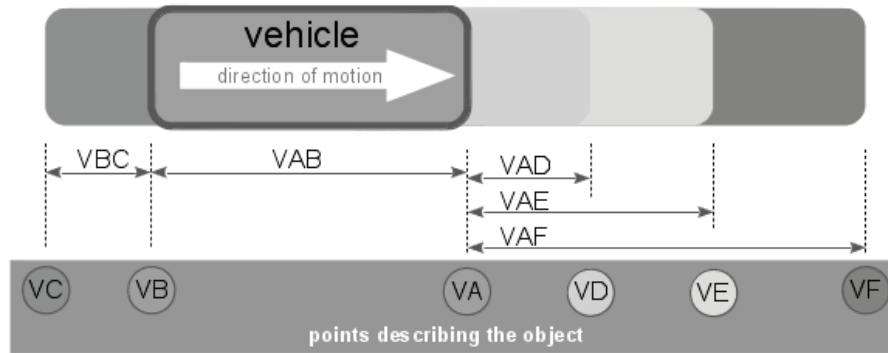
Fig. 6. Points defining vehicle.

For safety, when the vehicle does not move, we take into account the additional distance before (VAD) and after it (VBC).These sections should not be affected by any other vehicle. If the vehicle moves, two additional distances in the direction of the movement are taken into account (VAE, VAF).

Two points of the vehicle are always tracked: the beginning (VA) and the end (VB).This is due to the fact that some events are initiated by the start point of the vehicle and some by its end point. These points are therefore recorded on a regular basis. If the vehicle is moving additional points (VE) and (VF) can occur as source of events. The particular event may be related to only one point of the vehicle.

Various types of vehicles may be present in the network. Each one may have different characteristics.

Vehicles can move at different speeds. The value of the average speed on a section is always taken into account. Acceleration and braking are not recorded. Instead, the value of the average speed over some distance is revised (therefore it is important to track the (VF) point). This procedure is sufficient even if one vehicle catches up with another.

Distances VAD and VBC are fixed and determined at the beginning of the simulation. Distances VAE and VAF are determined and updated on a regular basis. They depend, inter alia, on the vehicle type and current speed.

6. SUMMARY

It was found that there can be observed the lack of a solution that allows for a methodical solving of the problem of travel time planning with regard to linear disturbances. There can be distinguished models that focus on solving the already existing problem, i.e. a delayed train. This is an attempt to cope with the effects of the phenomenon, not to counteract it. Surprisingly, there is a modest number of literature entries that seek to build a reliable timetable. There is no full classification of the causes of delays at random. Often, the classification of railway traffic factors is limited to the indicators to which they have values without conducting further research. In carrying out the recognition in the world literature it seems that this area needs to be developed.

The presented method can be used without huge computing resources. It allows verifying potential collisions within the timetable. It shows how the interference generated in this way is propagated in the transport network. This is due to the original model of the system as well as the use of currently available new information technologies and programming techniques.

The scope of the article discussed in this paper is much broader and the article presents only selected aspects that are important for further research to implement the method as a simulation platform. The purpose of the article is primarily to justify the work in the described area. At present, the work is focused on defining and parametrizing the main simulation objects. As a consequence of these works, the typical values of these parameters will also be estimated. The knowledge will allow beginning the simulation with a fully defined topology of the rigid grid.

The method envisages the use of the same simulation platform throughout the analytical workflow: from the planning of the measurements to the generation of the final reports from the analysis.

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