UTILIZATION OF RAILWAY NETWORK MODEL FOR DYNAMIC CALCULATION OF TRAIN DELAYS

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ABSTRACT

This article deals with the proposal for dynamic calculation of train delays using the rail network model and satellite navigation. Attention is focused on the description of the location of trains in the designed model of railway network. Further attention is aimed on the design of the dynamic calculation of train delays with utilization of reduced track profile and using computer simulation for experiments.

Keywords: Railway infrastructure models, train positioning, web services

1. INTRODUCTION

Precise dynamic calculation of train delay is not exactly trivial and includes a wide variety of aspects affecting the resulting journey time. Such are both, technical parameters of (i) a train set (e.g. train acceleration or overall train set weight) and (ii) railway infrastructure (character of the line, velocity limits), and (ii) external influences like weather (e.g. temperature, weather conditions, visibility). Delay calculation is always dependant on the current train location in the railway network in given time, thus current information about location is an inseparable part of dynamic calculation of delay. In this case, it is not necessary to demand such accuracy as for safety systems to determine location and thus it is possible to use satellite navigation (GNSS – Global Navigation Satellite System) for finding the current location of a train.

2. POSSIBLE TYPES OF LOCALIZATION

Generally, localisation is prone to a wide range of approaches on how to identify the position of trains on a track. Put simply, localisation may be divided into the following three groups:

- Localization without the use of GNSS,
- GNSS using localization,
- GNSS-based, involving further support systems.

2.1. Trains localization without the use of GNSS

This type of trains localization often requires complementing the rail network infrastructure with additional construction elements, which entails higher costs of the actual implementation. On the other hand, this type of localization shows a high accuracy and reliability and is often used in the railway signalling technology. Essentially, it relates to the system of:

- ETCS (Ghazel 2104; Lieskovský and Myslivec 2010),
- Automatic train control (Chudacek and Lochman 1998; Lieskovský 2004),
- Track circuits (Dorazil 2008),
- RFID.

2.2. Trains localization using GNSS

When using GNSS for various application levels, it is necessary to take an indicated position error into consideration. Indicated position error is generally based on the nature of the satellite navigation. If we use systems that operate with the position information on an informative level only, we can tolerate a certain error; however, such inaccuracy is unacceptable in the railway signalling technology. However, various additional systems can be implemented to eliminate the error (completely or at least partially), thus making the position of the tracked object more accurate. The following systems can be listed in this group:

- EGNOS (Senesi 2012),
- Differential GPS (O'Connor 1997).

2.3. GNSS based localization involving additional support systems

As mentioned above, precise localization of trains using GNSS, especially for the needs of signalling technology, is a priori impossible. Nevertheless, the position of a rail vehicle can be determined significantly more precisely with the use of additional systems. This concern especially solutions using inertial systems (Standlmann 2006), but also less known systems such as those based on GNSS and contactless eddy current measurement (Becker and Poliak 2008).

3. RAILWAY NETWORK MODEL

Undirected graph, as defined graph theory, is a natural candidate for a railway network model. Based on an analysis of data provided by the company SŽDC-TUDC (consisting of service regulations, passports, and codebooks), sets of algorithms were subsequently created, with which it was possible to generate a three-layer model of the rail network (Fikejz and Kavička, 2011). Roughly speaking, the track can be divided into individual so called supertracks, which consist of definition supra-sections (TDNU), where each supra-section contains track definition sections (TUDU) with mileposts (in hectometres). Basic aspects of the description of the rail network are collectively shown in Figure 1.
Mileposts (in hectometres) are shown in Figure with the distance in kilometres and are graphically represented using gray points. TUDU is recorded using a six-digit code (163105, 163106, 16307, 173202) and are graphically represented using solid lines (red, black, orange, brown). Individual supra-sections (CLS 007, CLS008, REG023) are shown in light blue and supertracks (B421021 1 and B421021 1A) are shown in dashed lines. A place significant in terms of transportation (branch line) is symbolized by a green square.

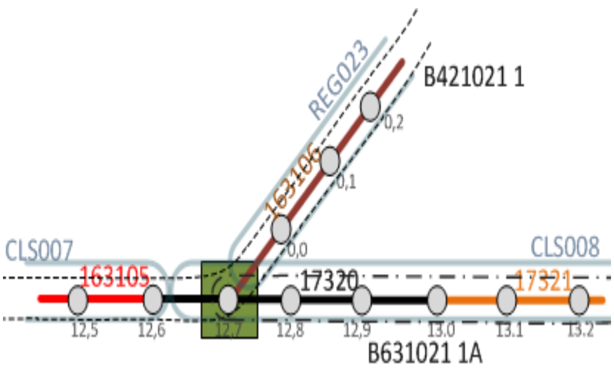


Figure 1: Basic aspects of the description of the rail network

The algorithm of railway network model (Fikejz and Kavička, 2011; Fikejz and Řezanina 2014.) was implemented directly on the database level using PL/SQL language. However, the algorithm had to be adjusted and generalized several times since there are various nonstandard conditions in the data, such as jumps in the mileposts (nonlinear growth of the kilometre succession between the mileposts) or change of an increasing kilometre sequence into a decreasing one and vice versa. The final model includes three data layers:

- **Data-Micro**, consisting of vertices and edges,
- **Data-Mezo**, include mezo-vertices and mezo-edges
- **Data-Macro**, containing super-vertices and super-edges.

Figure 2 presents the overall concept of a complete three-layer railway network model.

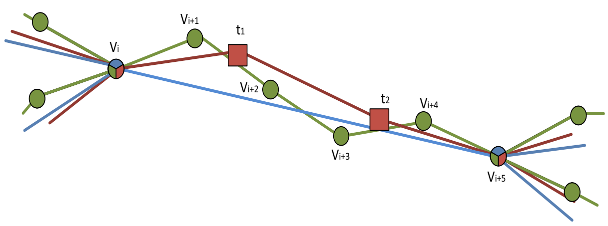


Figure 2: Illustration overall concept of a three-layer module

The data structure non-oriented graph was finally implemented directly in the ORCLE database using the ORACLE Spatial Network Data Model (Kothuri et al. 2007) technology. This technology enables the user to build a various network representation, involving also the object scheme and the communication interface API.

The objects scheme includes metadata and network tables. The interface contains on the server side PL/SQL API (an SDO_NET packet) for the creation, control and analysis of the database network, and a middle layer Java API (on client´s side) for the network analysis. The actual network is then defined by means of two compulsory tables:

- Node table,
- Link table.

For the work with spatial data, ORACLE with Spatial technology defines a special object data type SDO_GEOMETRY, which enables its user to store a number of spatial information and geometric types, such as various points, arcs, linear chains or polygons.

4. LOCALIZATION

The idea of trains localisation access to tracks is based on the correct pairing up of GPS information on position, provided by communication terminals, with the nearest vertex or edge of the graph. The discovered vertex/hectometre post disposes not only of a multi-dimensional key in the form of a GPS coordinate, it is also linked, through definition sections, to further information concerning the railway network infrastructure.
View of the situation that the model of railway infrastructure is stored in the database Oracle we can use the native database functions and operators. The `SDO_NN` (*nearest neighbor*) operator was selected in view of realising this unique trains localisation approach. The aforementioned operator searches for a geometric object that is closest to the object entered (like a point,

for example). In other words, it is possible to find the nearest vertex, or more precisely edge in a model, from the current position trains, Figure 3.

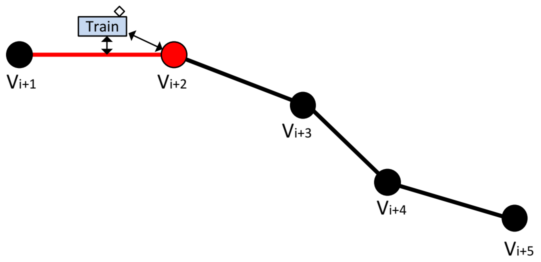


Figure 3: Main concept of localization

The actual detection of the current position of the trains can be divided into the following steps:

1. **Finding the nearest vertex and edge of the graph** – from the current position of the trains given the three-layer railway network model
2. **Assessment of the relevancy of incoming GPS information from the communication terminal** – verification whether the current position is not burdened by a disproportionate error (like, for example, that the distance of the trains from the nearest vertex/edge is a mere few meters or tens of metres, or that the trains is still assigned to the same super-edge, provided that it should still be located on it)
3. **Calculation of the exact position of the trains on the edge of the model** – using perpendicular projection of the point (current trains position) onto the line

The trains position data are collected from the communication terminals. These communication terminals sent position information to the central database every 30 second, Figure 4

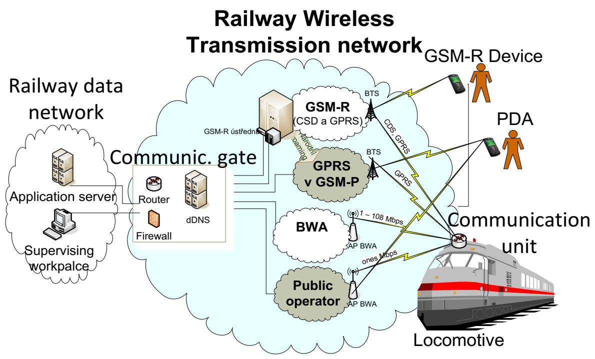


Figure 4 : Communication between the rail vehicle and dispatching centre

4.1. **Search algorithm of previous or next railway station**

Searching for the previous and next railway station utilises of iterations algorithm to Data-Micro layer. This algorithm allows finding the nearest railway station despite the fact that within the one TUDU there exists more stations, Figure 5.

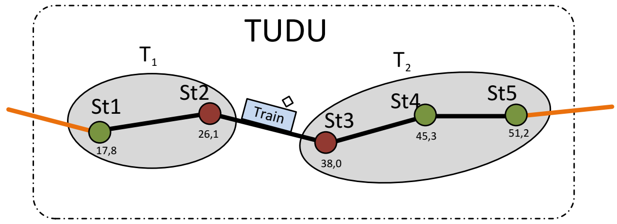


Figure 5: Finding nearest station

Concept of search algorithm consists of the following steps:

1. Sort the railway stations within the same TUDU considering the kilometric values
2. Divide the sorted railway stations to two separated subsets T1 and T2 by current position of rail vehicle
3. Select the first railway station from the subset T1 with the highest value of kilometre and the second railway station from the subset T2 with the lowest value of kilometre

As a next step, there is used the shortest path algorithm for finding the real distance from current train position to the both already found railway stations and according to the civil timetable we are able to calculate the actual time of arrival to the next railway station and actual train delay.

5. REDUCED TRACK PROFILE

Railway infrastructure is rather varied and contains many areas affecting the train dynamic (Bandžuch 2006). For common traction calculations, it is possible to substitute the real track profile by a reduced set of substitute gradients, so called line resistance, which includes:

- gradient resistance
- curve resistance
- tunnel resistance

Curve resistance $\boldsymbol{sl_c}$ is substituted by fictive incline, for which the curve radius R<300 m for secondary and regional lines is defined by:

$$sl_c = \frac{500}{R-30}\ [‰] \tag{1}$$

Reduced incline $\boldsymbol{sl_r}$ is then defined by:

$$sl_r = \frac{sl_1 l_1 + sl_2 l_2 + sl_3 l_3 + \cdots + sl_k l_k + sl_{c1} l_{c1} + \cdots + sl_{cm} l_{cm}}{l_1 + l_2 + \cdots + l_k}\ [‰] \tag{2}$$

where:

- $\boldsymbol{sl_1}$**to** $\boldsymbol{sl_k}$ -actual gradient in per mille (incline „+“, decline „-“)
- $\boldsymbol{sl_{c1}}$ **to** $\boldsymbol{sl_{cm}}$ -fictive gradient, substituting set of curves
- $\boldsymbol{l_1}$**to** $\boldsymbol{l_k}$ -length of gradients $s_1$to s_k in meters
- $\boldsymbol{l_{c1}}$**to** $\boldsymbol{l_{cm}}$ -curve lengths 1 to m

While condition
$(l_1 + l_2 + \cdots + l_k) \leq 2{,}5\ (l_{c1} + l_{c2} + \cdots + l_{cm})$ must be valid

An example of a reduced track profile is illustrated on the following Figure 6, in which arrows show the intended direction of movement of the train. The data in tables then depict:

- **kilometric position** of a change in profile $[km]$
- **the direction** where:
  - „+“ expresses change in direction
  - „−“ expresses change opposite the direction
- **track resistance** [‰] where:
  - positive value expresses track incline
  - negative value expresses track decline

6. TRAIN ACCELERATION

Train acceleration is influenced mainly by

- technical parameters of a locomotive (acceleration)
- overall weight of the train set

Using a special software tool for simulation train dynamics developed at University of Pardubice (Diviš and Kavička 2015), a set of measuring simulations focused on acceleration and breaking deceleration of trains was conducted for selected trains for the following track resistances:

- 0.5 %
- 1.0 %
- 1.5 %
- 2.0 %

Assessment of data from individual measurings has shown that data can be approximated by a linear equation for other calculations.
If we consider a train set with the following parameters:

- Acceleration: 0,6497725 m/s^2
- Length: 96 m
- Weight: 234 t

then individual measured values of acceleration can be reflected in a graph on Figure 7.

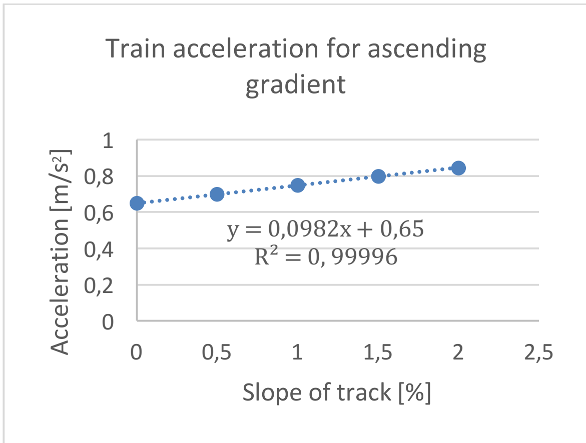
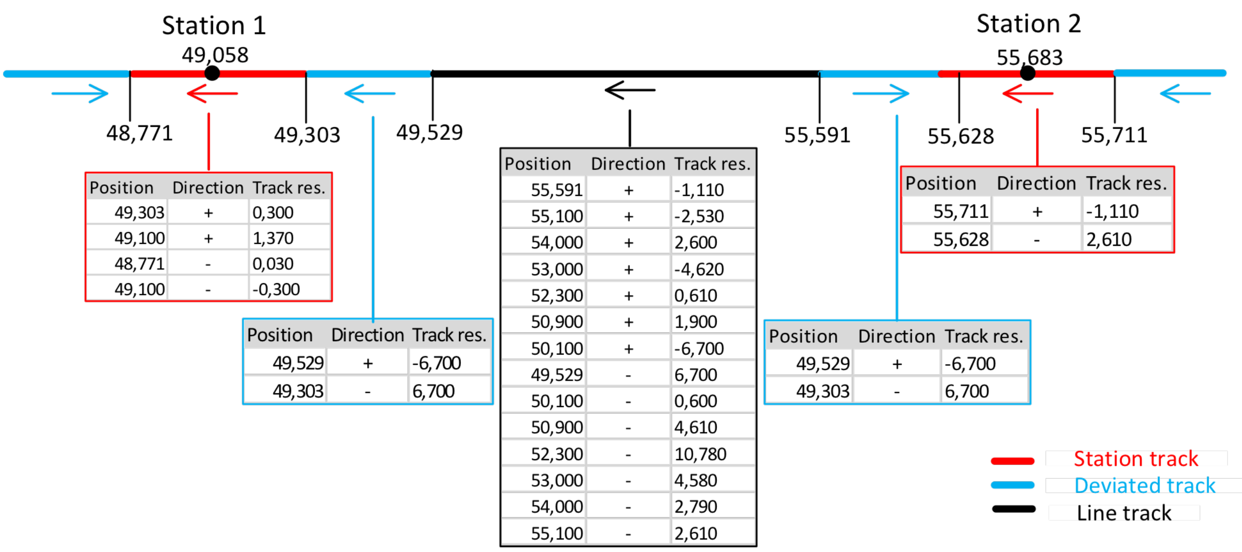


Figure 7: Example of train acceleration

From the graph above, it is clear that measured acceleration for incline can be approximated by a linear equation



Position	Direction	Track res.
49,303	+	0,300
49,100	+	1,370
48,771	-	0,030
49,100	-	-0,300

Position	Direction	Track res.
49,529	+	-6,700
49,303	-	6,700

Position	Direction	Track res.
55,591	+	-1,110
55,100	+	-2,530
54,000	+	2,600
53,000	+	-4,620
52,300	+	0,610
50,900	+	1,900
50,100	+	-6,700
49,529	-	6,700
50,100	-	0,600
50,900	-	4,610
52,300	-	10,780
53,000	-	4,580
54,000	-	2,790
55,100	-	2,610

Position	Direction	Track res.
55,711	+	-1,110
55,628	-	2,610

Position	Direction	Track res.
49,529	+	-6,700
49,303	-	6,700

Figure 6 : Example of reduced track profile

$$y = 0{,}0982x + 0{,}65 \quad (3)$$

for reliability $R^2 = 0{,}99996$.

When data from measured acceleration for a declining track are applied, then through approximation we can achieve linear equation

$$y = -0{,}1044x + 0{,}6511 \quad (4)$$

for reliability $R^2 = 0{,}99974$.

7. CALCULATING DELAY

For dynamic calculation of delay, it is possible to base the calculation on a simplified model, in which the overall journey time between two stations is given by adding their three parts (Figure 8):

- acceleration period to set velocity
- journey period in set velocity
- breaking period from set velocity to zero velocity

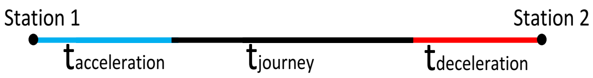


Figure 8: Concept of calculation

$$t_{total} = t_{accel.} + t_{\text{journey}} + t_{decel.} \quad (5)$$

while it is supposed that acceleration and breaking are affected by track profile, however, the train has sufficient performance power to keep required velocity on route between the two track segments.

7.1.1. Calculation algorithm

Delay calculation algorithm uses general formulae for evenly accelerated linear movement, i.e. relations based on:

$$v = v_0 + at \implies t = \frac{v - v_0}{a} \quad (6)$$

$$s = v_0 t + \frac{1}{2}at^2 \implies v^2 = 2as + {v_0}^2 \quad (7)$$

The algorithm itself is divided into 5 parts.

1. iterative calculation calculates the time $t_{acceleration}$ and path $s_{acceleration}$ needed to reach the required velocity v_{max}
2. iterative calculation calculates the time $t_{deceleration}$ and path $s_{deceleration}$ needed to reach zero velocity from velocity v_{max}
3. path of train movement in velocity v_{max} is calculated based on the difference between the overall path s_{total} and path for acceleration $s_{acceleration}$ and breaking $s_{deceleration}$, i.e.

$$s_{\text{journey}} = s_{total} - s_{accel.} - s_{decel.} \quad (8)$$

4. the time t_{journey} of train movement in set velocity v_{max} is calculated
5. overall time t_{total} is calculated from formula 5

So, if we consider maximal velocity of a train on a regional line v_{max} (for example $65\frac{km}{h}$) and track according to figure 9, then the first part of the algorithm (for calculating $t_{acceleration}$ and $s_{acceleration}$) will conduct individual iterative calculations in points of gradient change on the track sl_i [‰] defined by kilometric location d_i [km]. If the current velocity of the train v_i is higher or equal to the required velocity v_{max}, then the iterative calculation is terminated and subsequently the exact time t_{last} and path s_{last}, when the train reached the required velocity v_{max} are calculated. For starting the calculation, a corresponding railway station $d_{station}$, kilometric location of which is given, is considered.

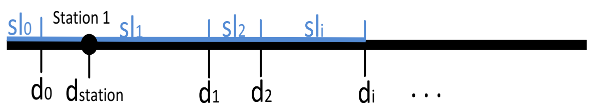


Figure 9: Concept of the acceleration algorithm

Concept of the algorithm for train acceleration to the required velocity v_{max}

1. $i = 1; v_0 = 0$
2. **if** $i = 1$
   then $s_i = d_i - d_{station}$
   else $s_i = d_i - d_{i-1}$
3. **if** $sl_i > 0$
   then $a_i = 0{,}0982sl_{i-1} + 0{,}65$ (eq. 3)
   else $a_i = -0{,}1044sl_{i-1} + 0{,}6511$(eq. 4)
4. $v_i = \sqrt{v_{i-1} + 2a_i + s_i}$
5. **if** $v_i < v_{max}$
   then $i = i + 1$ and go to step 2
6. $s_{last} = \frac{{v_{max}}^2 - {v_i}^2}{2a_i}$
7. $t_{last} = \frac{v_{max} - v_i}{a}$
8. $t_{toVmax} = \sum_{k=1}^{i-1} t_k + t_{last}$
9. $s_{toVmax} = \sum_{k=1}^{i-1} s_k + s_{last}$

Analogously, the breaking time $t_{deceleration}$ and the path $s_{deceleration}$ needed to stop the train at the station are calculated accordingly. The relation 8 determines the length of the line on which the train moves at a constant velocity and consequently from the relation

$$t = \frac{v}{s} \quad (9)$$

the journey length t_{journey} is calculated. Overall journey time t_{total} is then given by the sum of the partial times per the relation 5.

From the times between the individual railway stations t_{total}. and the time needed for the train to be serviced in the station $t_{service}$, it is then possible to calculate the total time of the journey to the required station.

For dynamic calculation of the delay of a moving train on the track, it is possible to calculate the time of journey/delay to the next railway station or to the selected station on the track from the knowledge of its current position (from the railway network model).

Complete calculations for the dynamic calculation of the delay were subsequently implemented in the *infraRail* software tool, and further variants of delayed trains were subsequently checked using the discrete simulation, both based on historical data and data generated. The running application captures the current position of the train on the track with a set of information related to its position including the calculation of the current arrival delay to the next railway station, Figure 10.

CONCLUSION

The focus was on the proposal for dynamic calculation of train delays using the rail network model and satellite navigation. A multi-layered model of the railway network was designed reflecting the non-oriented graph. In addition, the algorithm was used to identify the position of trains in the railway network. This algorithm includes the search of the previous or next railway station. The article was also focused on description of the reduced track profile which was used for designs of the algorithm for dynamic calculation of train delays. Proposed algorithms have been implemented in the InfraRail software tool. Discrete simulation was used to test other variants of delayed trains, both based on historical and generated data.

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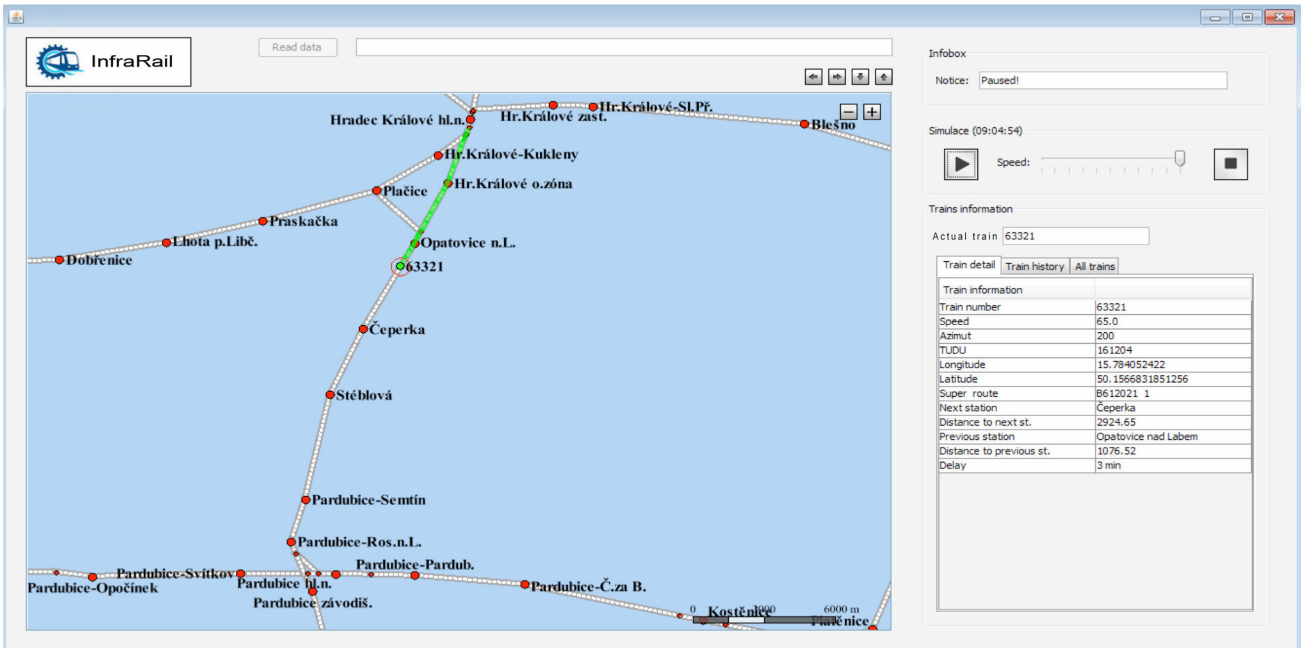

Figure 10: Running application

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