DOI: https://doi.org/10.14256/JCE.2067.2017

Građevinar 2/2018

Primljen / Received: 8.4.2017.
Ispravljen / Corrected: 26.8.2017.
Prihvaćen / Accepted: 6.11.2017.
Dostupno online / Available online: 10.3.2018.

Analysis of vehicle/track interaction measurement data using the V/TI Monitor system

Authors:

Predrag Tešić, MCE
"Tangram projekt" d.o.o., Novi Sad
tesic1989@gmail.com

Assist.Prof. Stanislav Jovanović, PhD. CE
University of Novi Sad
Faculty of Technical Sciences
stasha.jovanovic@gmail.com
Corresponding author

Matthew Dick, MME
Ensco Inc., USA
dick.matthew@ensco.com

Professional paper

Predrag Tešić, Stanislav Jovanović, Matthew Dick

Analysis of vehicle/track interaction measurement data using the V/TI Monitor system

The Vehicle / Track Interaction Monitor (V/TI Monitor) is one of the latest-generation systems for measuring quality of railway infrastructure elements which, with the help of accelerometers, measures and describes dynamic behavior of vehicles in interaction with the track. The VTI-TQI software was developed as a means to discover and interpret a considerable number of typical situations on railways involving simultaneous occurrence of various irregularities. The possibility for forecasting future development and growth of such irregularities was established through generation of appropriate deterioration trends.

Key words:
railway infrastructure, vehicle/track interaction, condition monitoring, segmentation, V/TI Monitor

Stručni rad

Predrag Tešić, Stanislav Jovanović, Matthew Dick

Analiza mjernih podataka sustava "V/TI Monitor" baziranog na međudjelovanju vozila i kolosijeka

V/TI Monitor (Vehicle/Track Interaction Monitor) jedan je od najnovijih sustava za mjerenje kvalitete elemenata željezničke infrastrukture, koji uz pomoć akcelerometara mjeri i opisuje dinamičko ponašanje vozila u interakciji s kolosijekom. Razvijen je računalni program VTI-TQI pomoću kojeg je otkriven i protumačen velik broj karakterističnih situacija na prugama, s istodobnom pojavom različitih nepravilnosti i uspostavljena mogućnost predviđanja njihovog rasta u budućnosti generiranjem odgovarajućih trendova propadanja.

Ključne riječi:
željeznička infrastruktura, međudjelovanje vozila i kolosijeka, segmentacija, V/TI Monitor

Fachbericht

Predrag Tešić, Stanislav Jovanović, Matthew Dick

Analyse der Messdaten des System "V/TI Monitor" basierend auf der Interaktion von Fahrzeugen und Gleisen

Vehicle/Track Interaction Monitor (V/TI Monitor) ist eines der neuesten Systeme für die Messung der Qualität der Elemente der Eisenbahninfrastruktur, das mithilfe eines Beschleunigungsmessers das dynamische Verhalten der Fahrzeuge in Interaktion mit den Gleisen misst und beschreibt. Entwickelt wurde die Software VTI-TQI, mit deren Hilfe eine große Anzahl an charakteristischen Situationen auf dem Schienenweg entdeckt und gedeutet wurde, mit gleichzeitigem Auftreten unterschiedlicher Unregelmäßigkeiten, und mit der Möglichkeit deren Wachstum in Zukunft durch Generierung entsprechender Trends des Verfalls vorherzusagen.

Schlüsselwörter:
Eisenbahninfrastruktur, Interaktion Fahrzeug – Gleis, Zustandsüberwachung, Segmentierung, V/TI Monitor

1. Introduction

Advances in technology, environmental changes and ever increasing demands by the users, are placing railways in a position that requires constant improvement of their various operational activities. The primary requirement is to provide a safe and reliable railway network, featuring an appropriate capacity and availability. However, the fulfilment of this condition is becoming increasingly difficult due to the continuing increase in speed, axle load and traffic volume, where the latter additionally reduces the availability of infrastructure for the track condition measuring and monitoring purposes, as well as for performing maintenance and renewal (M&R) works. It is clear that track condition is bound to deteriorate during its service life, i.e. it will never be able to reach its initial level of quality. Therefore, the railway track performance will largely depend on the decisions that are taken in terms of M&R works during its lifetime. The only effective manner of reaching adequate condition of railway infrastructure elements (RIE) is to implement the so-called *Condition-based* approach (which relies on systematic measurement and analysis of RIE condition) within the M&R planning process [2-4]. According to the condition-based approach, M&R activities will be carried out strictly in accordance with the needs observed through the RIE condition-monitoring and analysis. At the same time, the "mission" of the condition-based approach is to make progress and changes within the current M&R management approach, which has traditionally been primarily remedial, rigidly prescribed and cyclical, and to adopt the modern approach that has to be preventive, and as predictive as possible.

The data collected using one of the most advanced systems currently available on the market, the *Vehicle/Track Interaction Monitor* (*V/TI Monitor*), were used for the purposes of RIE analysis described in this paper. Unlike traditional measurement systems, which are primarily based on track geometry (TG) measurements, the *V/TI Monitor* is based on an entirely different concept, i.e. with the help of accelerometers, it measures vertical and horizontal (lateral) acceleration of different vehicle parts, namely the wheelset, bogies, and carbody. The tendency of increasing trains speeds and axle loads has contributed to the fact that these accelerations measured by V/TI *Monitor*, which occur as a result of vehicle/track interaction, are now gaining in importance. The focus is primarily placed on local defects (shelling, rail corrugation, battered joints, loose/missing bolts, switches and crossing (S&C) defects, etc.). These defects, which are often overlooked by railroad personnel, in combination with the aforementioned increasing speeds and loads, could produce extremely high impact forces, which could lead – due to passage of a large number of vehicles - to accelerated deterioration of all RIE, with unforeseeable consequences, Figure 1 [5]. As it is often explicitly stated, impact forces that occur as a result of local irregularities at the wheel/rail contact are often the main cause of track deterioration [6, 7]. On the other hand, these defects precisely indicate the *target group* or, more specifically, the origin of the motives for creation and utilization of the *V/TI Monitor* system, whose data will be analysed in the context of this article, and based on which, in accordance with the basic principles of vehicle dynamics, certain mechanisms leading to creation of various defects will be defined.

The use of the *V/TI Monitor* system should also be associated with the track geometry (TG), as well as with traditional systems and vehicles for the TG measurement. The TG quality greatly influences the level of dynamic forces between the vehicle and the track and, consequently, the deterioration of both the track and rolling stock. Because of this, the rail systems (railways, tramways, metros, etc.) around the world have been paying for decades a significant attention to the TG and its change over time as a result of railway use (e.g. tonnage carried). The TG problem, and its correlation with dynamic forces, is very similar to the appearance and development of potholes on roads. Namely, as the first deviations from the designed geometry occur in a track

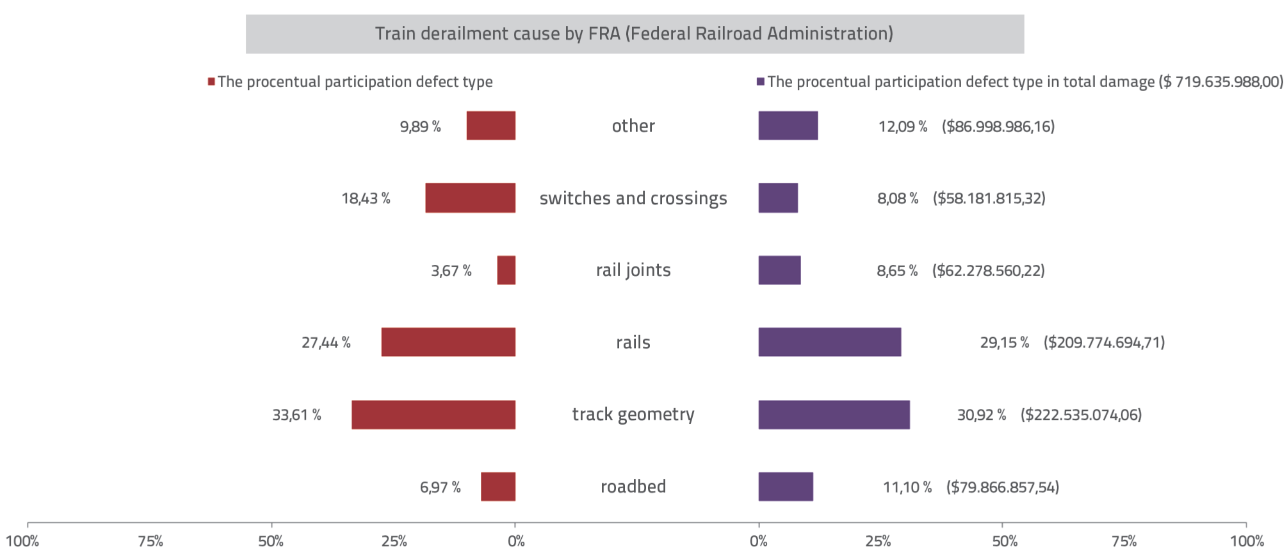


Figure 1. Relative contribution of particular defect types to the total number of railway accidents in the USA (01.01.2010. - 31.12.2015), [5]

(which may be caused by both dynamic forces at the wheel/rail (W/R) contact point, and external influences, e.g. differential settlements due to problems in the subgrade or due to inadequate drainage, poor weld/joints geometry, etc.), they provoke an increase in dynamic forces which, in turn, negatively affect the TG, thus initiating a *vicious circle* where the TG and dynamic forces exert mutually accelerating deteriorating effects. Due to this mechanism, even the seemingly small TG irregularities can rapidly develop into a problem of serious proportions, the correction of which may prove to be very expensive and time-consuming. Knowledge of locations with impaired geometry (both track and rail) is essential for any rail system, so that appropriate actions can be taken before these irregularities grow and cause large and expensive damage to the track and vehicles.

The TG has regularly been measured for many decades by means of specific track recording vehicles (TRV). However, high cost of TRVs (millions of €) has always prevented railway authorities from having larger fleets of such recording vehicles. For this reason, TRV fleets are normally dimensioned to measure the railway network condition at least twice a year, usually in spring and autumn, while for the high-speed lines (HSL) and heavy-haul (HH) lines, such measurements are normally taken more frequently (e.g. usually once a week in Europe for HSLs, or 16 times a year in the USA). In recent years, again due to increasing speeds and axle-loads, many railway authorities have concluded that this measurement frequency is insufficient. In fact, due to the mutually accelerating negative effects of geometric imperfections and dynamic forces, longer time between measurements allows greater development of geometrical irregularities between two consecutive measuring runs. The problem is that this greater development of geometrical irregularities remains undetected due to longer periods between consecutive measurements, and thus the problem may evolve to the point where potentially unforeseeable consequences may be experienced. Therefore, present day railway authorities have been looking for solutions that would enable more frequent measurements, but without extreme investments and disruption of normal train operation timetables. Even with the acquisition of expensive TRVs and higher frequency of their use, the timetable compromising problem still remains unsolved because, when a TRV is run, no revenue trains can be operated. The solution was found in the use of the so-called "unattended" measuring systems that can be installed on all vehicles (locomotives, passenger and freight wagons), rather than solely on specialized recording vehicles, such as TRVs. These unattended systems can constantly measure track condition and send the collected data automatically to the central database over a wireless connection, regardless of where the vehicle is heading to. Also, cheaper versions of measurement systems that only measure vertical and lateral accelerations, such as the *V/TI Monitor*, have been selected for this purpose. Due to their low cost, these systems can be installed on a larger numbers of vehicles, thus increasing the measurement frequency and network coverage. For example, in the US, there are currently 435+ of these systems that measure 107.000 km daily and send the data to the central database. A concise description of main aspects of the *V/TI Monitor* system, parameters it measures, and typical track defects it can identify, are provided in Section 2. The structure and working principle of the "VTI-TQI" software, developed specifically for the analysis of the *V/TI Monitor* data, are explained in Section 3. Section 4 provides a more detailed description of the data-analysis performed using the VTI-TQI software, and an analysis of several characteristic situations that were discovered during this study. In Section 4, a special emphasis is also placed on the influence of switches and crossings (S&C), and on the possibility of generating and using trends in the VTI-TQI software for the prediction of parameters in future *V/TI Monitor* measurements.

2. Vehicle/Track Interaction Monitor system

The primary objective in the use of this relatively simple and inexpensive system is to measure the parameters explained in Section 2.1, and to identify network points with higher acceleration levels that produce higher dynamic forces, which can lead, due to rapid deterioration over time, to serious and costly damage to infrastructure and rolling stock. Unlike in traditional TG measurements, here the intention is not to collect absolutely precise TG values, but to survey the entire rail network - usually extending over many thousands of kilometers - in an objective, simple and inexpensive way, in order to identify ten to twenty percent of the most critical locations that deserve highest priority. It is important to understand that the *V/TI Monitor* and TRV both inspect track geometry (TG), but from different perspectives that can be regarded as mutually complementary. TRV TG measurements are direct and objective. On the other hand, *V/TI Monitor* uses vehicle response to TG as a measure/indication of track condition. A full picture of track condition can be obtained using both TRV and *V/TI Monitor* data.

In addition to identifying problematic locations within the network, the secondary goal of the *V/TI Monitor* system is to define, based on the analysis of measurement data, appropriate track M&R activities that will enable adequate improvement of track condition and prevent its further deterioration, while also reducing detrimental impacts on the rolling stock. For this reason, the expected results of the *V/TI Monitor* application and data analysis simply include:

- Generation of the list and exact location of places along the railway network with track/rail geometry problems and increased levels of dynamical forces at the wheel/rail contact,
- Definition of urgency levels of the identified problematic locations, with indication of further deterioration tendencies,
- Proposal of M&R measures that should be taken in order to eliminate or remedy the problems, with their prioritization according to the severity and urgency levels.

2.1. The *V/TI Monitor*

The *Vehicle/Track Interaction Monitor* (*V/TI Monitor*) originated as a US Federal Railroad Administration (FRA) research and development (R&D) project, and evolved into a joint R&D partnership between ENSCO, Inc., the FRA and Amtrak (corporation that provides middle and long distance passenger railway transport services in the USA) in the late 1990s. This system uses an array of sensors to accurately measure dynamic response of a rail vehicle in interaction with the underlying track. The standard *V/TI* onboard monitoring unit (computer) (Figure 2) can be installed on both passenger and freight vehicles, and its equipment consists of the main housing, which contains all necessary electronics, five accelerometers, and an externally mounted dual-purpose antenna for GPS and cellular communications [8].

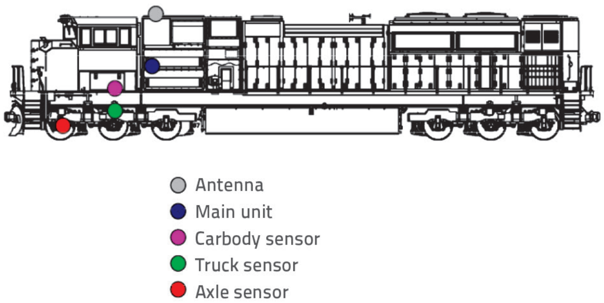


Figure 2. V/TI Monitor Component Layout [8]

Each accelerometer performs its measurements continuously and, an exception is created when a value exceeding a predetermined threshold is encountered (defined by the railway authority). This exception includes:
- Exception time,
- GPS (*Latitude/Longitude*) coordinates,
- Exception value,
- 4 seconds of continuous data of all the accelerometers (2 seconds before the event and 2 seconds after the event).

The exception value is used to evaluate the severity level. There are three severity levels:
- Urgent*:* a detailed inspection must be conducted within 24 hours
- Near Urgent: the inspection needs to be conducted within 7 days
- Priority*:* the inspection is normally conducted within the ensuing 30 days, or the data are used to anticipate future behaviour of the track.

One channel of the *V/TI Monitor* system, and one field in the database, is reserved for each of the 5 accelerometers. Each accelerometer measures a specific type of exception:
- CarBody Vertical: *CBV* accelerations,
- CarBody Lateral: *CBL* accelerations,
- Truck Lateral: *TRL* accelerations,
- Axle vertical impact: AXV_1, AXV_2 (axle accelerations measured individually for the left and right side of the axle box; these acceleration values serve as the basis for calculating dynamic forces at the wheel/rail contact, based on a specific real-time data processing algorithm and known axle-loads and unspung masses)
- Mid-chord Offset: MCO_1, MCO_2 - vertical geometry of the track for both the left and right rails

A summary of the *V/TI Monitor* exception types and their potential causes can be found in Table 1 [9, 10].

The key information is that a carbody sensor measures vertical and lateral accelerations near the left/right centerline of the locomotive cab floor. The Carbody Vertical (CBV) and Carbody Lateral (CBL) exceptions are the maximum *peak-to-peak* (*Figure 3*) accelerations within one second. These exception types are typically associated with irregularities in vertical geometry (top) and horizontal geometry (alignment) of the track, respectively.

A truck (bogie) sensor measures lateral accelerations of the truck frame. The Truck Lateral (TRL) exceptions represent the root-mean square (RMS) of measured accelerations in a 2-seconds interval. TRL exceptions are generally caused by sustained oscillations caused by truck hunting.

Two axle sensors are installed on a single wheelset with each sensor installed on the left and right side bearing axle boxes. These axle sensors measure acceleration in the vertical direction. The Axle Vertical Impact (AXV1 & AXV2) exceptions calculate the W/R impact force using the accelerations, static wheel load, and unsprung mass value.

It should be noted that this is a simplified interpretation because - for impact peaks of very short duration (less than 1/100th of a second) - it is most likely that the effective mass will be lower, because both axle bending and the resulting wheel plate flexure will act as "springs" to isolate the traction motor from impact accelerations, which are measured on journal boxes at each end of the axle. On the other hand, for impact peaks with longer duration, the real force will most likely be higher due to the additional inertial response from the bogie (truck) frame and the vehicle car body itself. Depending on the stiffness of primary suspension and duration of the impact, the values may vary from one case to another.

Finally, the same two axle-sensors are used to calculate the vertical track profile using a 10 foot (~3m) mid-chord offset (MCO). This is a novel approach aimed at utilizing the same sensors for an additional purpose. It was first used by the Union Pacific Railway [10].

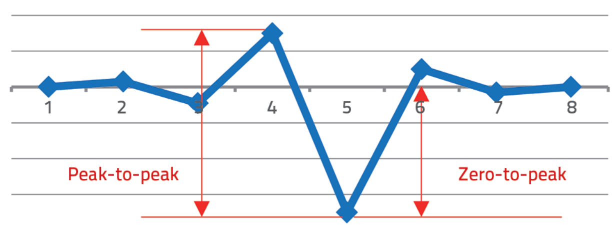
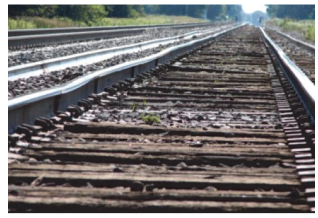
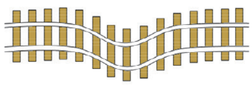
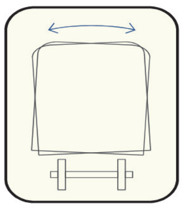
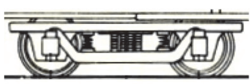
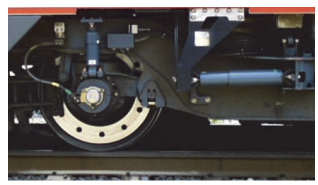
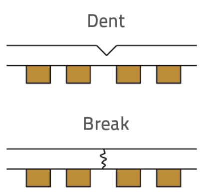


Figure 3. Peak-to-peak and zero-to-peak signal processing

Table 1. V/TI Monitor Exception Types Summary [9]

Exception type	Look for:		Examples
CBV Carbody Vertical		• Look for repeated vertical profile dips in track • Look for mud and pumping conditions	
CBL Carbody Lateral		• Look for lateral alignment irregularity in track	
CBR Carbody Roll		• Look for staggered joints or repeated crosslevel irregularities • Only associated with coal car V/TI Monitors	
TRL Truck Lateral		• Indicates truck hunting. • Look for worn wheel profiles, degraded dampers, worn gibs	
AXV1 i AXV2 Axle Vertical Impact		• Look for broken rail, broken joint, broken frog, battered joint, engine burn, crushed rail head, loose/missing bolts	
MCO1 i MCO2 10-Foot Mid-Chord Offset Vertical Profile		• Look for mud and pumping conditions. • Look for pumping joints	

2.2. Vehicle Track Interaction - Track Quality Index ("VTI-TQI") software

In North America, for example, a large number of *V/TI Monitor* systems produce huge quantities of data (especially if observed over a long period of time). Such quantities of data may be challenging to process without an appropriate software. This kind of software is especially necessary in case the knowledge of long-term behaviour of measured parameters is required, e.g. in terms of defining future trends, which is a basic prerequisite for condition-based management of M&R works. Since over three million *V/TI Monitor* defects - recorded over a period of more than 3 years – had to be processed in the scope of the analysis described in this paper, a special software tool called *Vehicle Track Interaction - Track Quality Index* (*VTI-TQI*) was developed for conducting these analyses involving such a large

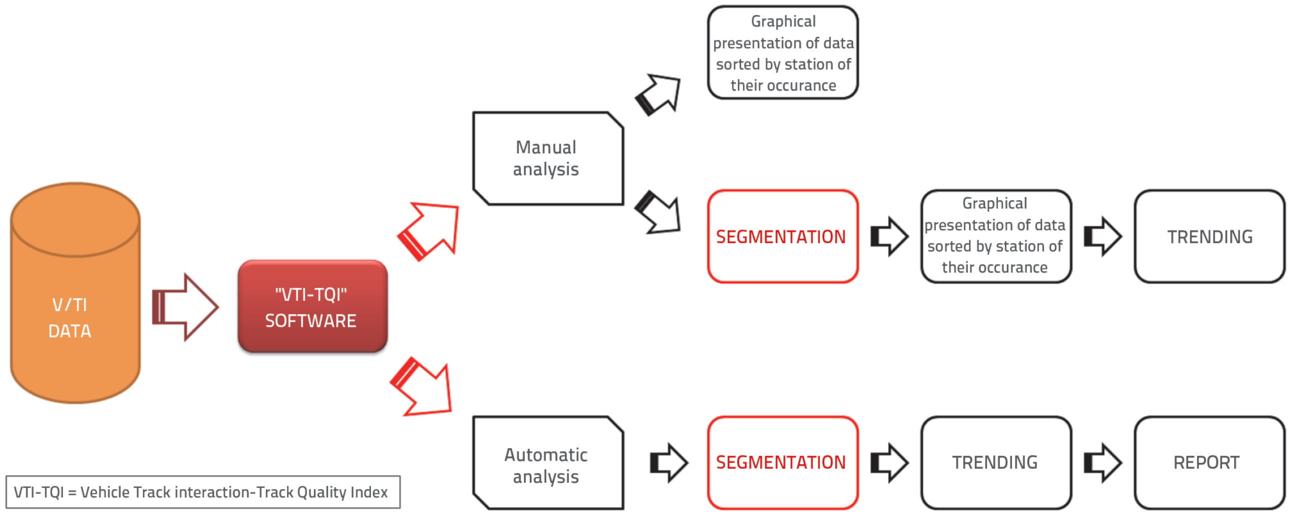


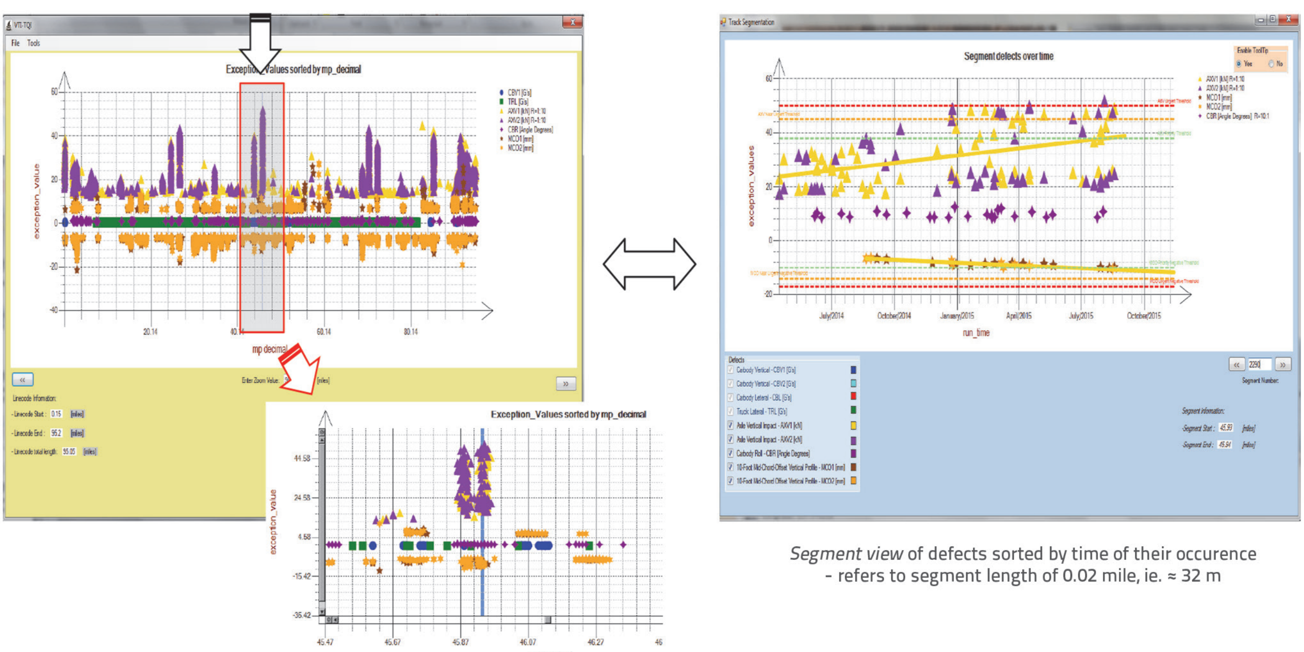
Figure 4. VTI-TQI software concept [1]

amount of data, Figure 4. This software was developed using Visual Basic 2010, which is currently one of the most popular programming languages for the development of *Windows* and *Web* applications. Thus the entire software code is based on the latest-generation programming technique, the so-called *Object-oriented Programming* (OOP). *Microsoft Access*, as a part of the *Microsoft Office Suite*, was used as the database, which was supposed to host the above-mentioned quantity of approximately 3.000.000 records. These records are related to the total of 25 subdivisions (network regions), spreading over 1,700 miles (or approximately 3,000 km) in Australia. The *MS Chart* control was used as a support for data-visualization. This extremely powerful tool, integrated with the *VB.Net* platform, provides excellent opportunities in terms of data manipulation. Proper preconditions for the implementation of detailed analysis were obtained thanks to a wide range of functions offered by this control.

VTI-TQI software (Figure 4) contains two characteristic modes:

- manual
- automatic.

The segment position within the observed track - total length of presented track ≈ 100 mile, ie. ≈ 160 km



Segment view of defects sorted by time of their occurence - refers to segment length of 0.02 mile, ie. ≈ 32 m

The zoom view of segment within the observed track - total length of presented track ≈ 1 mile, ie. ≈ 1,60 km

Figure 5. Visualization of data within VTI-TQI software [1]

The manual analysis is mandatory and is carried out separately for each section. Its end-result should be the defined track deterioration model and the optimal track-segment-length that is used for further automatic analyses. The analysis is further divided into two phases:

- First phase: For the selected track, the user gets a graphical representation of defects sorted by their chainage (stationage/km posts), Figure 5 (left)
- The second phase: Segmentation [11] of the data related to the selected track and display of defects recorded within the segments, where the defects are sorted by the time of their registration – the so called "segmental approach", Figure 5 (right)

Track segmentation is the "cornerstone" of the *condition-based* approach in terms of automatic analyses of railway networks of large proportions. The segmentation process concept is explained in detail in papers [2-4, 11, 12]. For the sake of this study and explanation of the *V/TI Monitor* data analysis, it is sufficient to state that segmentation is basically a *discretization* process of linear/spatial Railway Infrastructure Elements (RIE) and their conversion into singular, discrete objects, with the finite (short) lengths suitable for automated analyses. Although this definition seems quite simple, the very concept of segmentation – regarded in its full extent - is highly complex. The need for segmentation arises from the fact that it is impossible to conduct adequate, automatic and systematic analysis of linear/spatial objects (e.g. rails, ballast, contact line wire, etc.) in their entirety because of their considerable length. The problem is that distinct parts of such objects are in a different state, i.e. they exhibit differing behaviour, and so demand separate consideration, which is why none of these objects can be analysed in their entirety. Therefore, the objects need to be divided into pieces, "segments" (hence the term "segmentation") presenting – as much as possible – uniform behaviour. This allows further sequential analysis of the track, segment by segment, but in an identical manner, which is the basic precondition of every automatic analysis.

Such an objective clearly implies division of linear objects into segments with uniform properties, as uniform properties/characteristics generally result in uniform behaviour. The problem, however, arises as the sheer number of linear objects, as well as the number and diversity of their characteristics, is huge, which seriously complicates the process of segmentation. The so-called *flexible uniform segmentation* is applied in modern *Railway Infrastructure Asset Management Systems* (RI-AMS) [2-4, 11, 12]. In this type of segmentation the segment length is variable/flexible, so that segment characteristics can be as uniform as possible. However, for the sake of analysis of *V/TI Monitor* data, this approach could not be applied because, unlike conventional TRVs, which continuously measure and record values, a *V/TI Monitor* produces data only for the locations with identified anomalies, while it does not record any values for the remaining locations. Therefore, the application of the flexible uniform segmentation on *V/TI Monitor* data would produce an excessive number of "empty" segments, i.e. segments without any measured values, while at locations with identified defects, the usual minimum length of flexible uniform segments used by RI-AMS (about 200 m) would contain too many *V/TI Monitor* defects, which would thus be averaged-out, causing the analysis to lose its "edge" and wasting many benefits of the highly accurate *V/TI Monitor* measurements.

For this reason, the segment length for the analysis of *V/TI Monitor* parameters was reduced so as to be shorter than

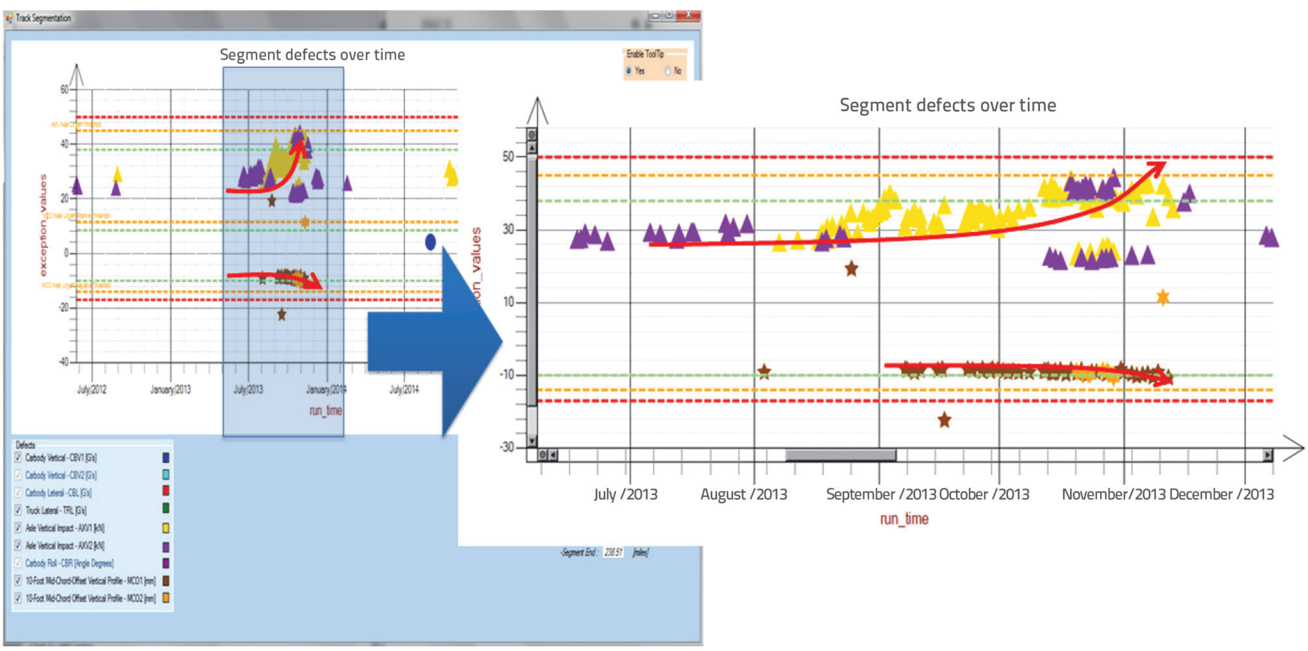
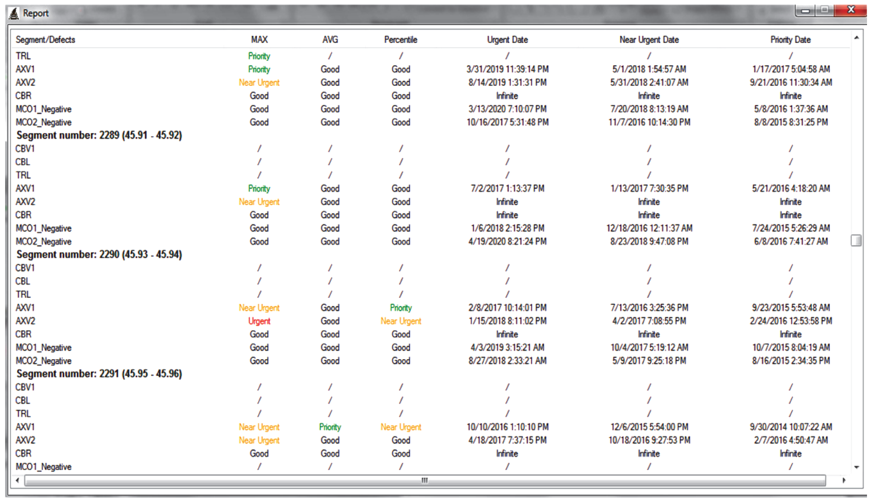


Figure 6. Extremely rapid growth of impact forces in a very short period of time of approximately 4 months [1]

the minimum length usually used by the RI-AMS system, and the final segment length of ~32 m (0.02 miles) was also adopted based on the results and experience coming from previous analyses of the *V/TI Monitor* data [8]. Furthermore, the locational recording accuracy of the *V/TI Monitor* system itself was fixed to 0.01 miles (~16 m), so that the most logical length enabling easy manipulation of data within the database would be an integer of 0.01 miles, which directly suggests the segment length of ~32 m (2 x 0.01 = 0.02 mile).

The track condition analysis based on the so-called "Track View", i.e. representation of defects as per their chainage, would prove quite unreliable for the purposes of defining the deterioration model. The main point of such representation is to allow users to orient themselves in space and identify the most critical track locations, while the actual causes of deterioration can only be investigated and determined through the earlier-mentioned *Segment View,* which focuses on the time-and-value-progression of defects found on a particular segment. Only then could their deterioration model be adequately defined and their future behaviour predicted, along with definition of the moment when the behaviour will become such that it necessitates appropriate M&R interventions. In this respect, the software allows drawing trends and thresholds for certain urgent levels as defined by competent railway personnel, (Figure 5 - top right and Figure 6). The change of values of each of the parameters as a function of time has been monitored using basic principles of trend-type selection. In so doing, it was noted that, in most cases, the linear trend approximates parameter behaviour – or their growth over time - quite well (Figure 5 - top right). Although in most situations this approach enables proper establishment of the dependence between the given data, it is important to stress that certain deviations implying much faster changes in defect values between consecutive measurements were also observed. This certainly points to a non-linear trend, and hence requires additional attention and caution (*Figure 6*). This aspect is to be more thoroughly analysed in subsequent studies/research.

The situation shown in *Figure 6*, where a rapid increase of AXV and MCO defects can be observed, highlights quite appropriately the advantages of the *V/TI Monitor* system, and the wealth of measurement data it produces. As can be seen, impact forces have grown from the values that were below the level of priority maintenance, to the values that exceed the limit of emergency maintenance, in a very short period of time (July - November 2013). Although not a large number of segments with similar behaviour was observed during the analyses, it should be noted that such situations are clearly possible, which certainly require high level of attention and special treatment by competent staff in charge of railway infrastructure M&R.


Report

Segment/Defects	MAX	AVG	Percentile	Urgent Date	Near Urgent Date	Priority Date
TRL	Priority	/	/	/	/	/
AXV1	Priority	Good	Good	3/31/2019 11:39:14 PM	5/1/2018 1:54:57 AM	1/17/2017 5:04:58 AM
AXV2	Near Urgent	Good	Good	8/14/2019 1:31:31 PM	5/31/2018 2:41:07 AM	9/21/2016 11:30:34 AM
CBR	Good	Good	Good	Infinite	Infinite	Infinite
MCO1_Negative	Good	Good	Good	3/13/2020 7:10:07 PM	7/20/2018 8:13:19 AM	5/8/2016 1:37:36 AM
MCO2_Negative	Good	Good	Good	10/16/2017 5:31:48 PM	11/7/2016 10:14:30 PM	8/8/2015 8:31:25 PM
Segment number: 2289 (45.91 - 45.92)						
CBV1	/	/	/	/	/	/
CBL	/	/	/	/	/	/
TRL	/	/	/	/	/	/
AXV1	Priority	Good	Good	7/2/2017 1:13:37 PM	1/13/2017 7:30:35 PM	5/21/2016 4:18:20 AM
AXV2	Near Urgent	Good	Good	Infinite	Infinite	Infinite
CBR	Good	Good	Good	Infinite	Infinite	Infinite
MCO1_Negative	Good	Good	Good	1/6/2018 2:15:28 PM	12/18/2016 12:11:37 AM	7/24/2015 5:26:29 AM
MCO2_Negative	Good	Good	Good	4/19/2020 8:21:24 PM	8/23/2018 9:47:08 PM	6/8/2016 7:41:27 AM
Segment number: 2290 (45.93 - 45.94)						
CBV1	/	/	/	/	/	/
CBL	/	/	/	/	/	/
TRL	/	/	/	/	/	/
AXV1	Near Urgent	Good	Priority	2/8/2017 10:14:01 PM	7/13/2016 3:25:36 PM	9/23/2015 5:53:48 AM
AXV2	Urgent	Good	Near Urgent	1/15/2018 8:11:02 PM	4/2/2017 7:08:55 PM	2/24/2016 12:53:58 PM
CBR	Good	Good	Good	Infinite	Infinite	Infinite
MCO1_Negative	Good	Good	Good	4/3/2019 3:15:21 AM	10/4/2017 5:19:12 AM	10/7/2015 8:04:19 AM
MCO2_Negative	Good	Good	Good	8/27/2018 2:33:21 AM	5/9/2017 9:25:18 PM	8/16/2015 2:34:35 PM
Segment number: 2291 (45.95 - 45.96)						
CBV1	/	/	/	/	/	/
CBL	/	/	/	/	/	/
TRL	/	/	/	/	/	/
AXV1	Near Urgent	Priority	Near Urgent	10/10/2016 1:10:10 PM	12/6/2015 5:54:00 PM	9/30/2014 10:07:22 AM
AXV2	Near Urgent	Good	Good	4/18/2017 7:37:15 PM	10/18/2016 9:27:53 PM	2/7/2016 4:50:47 AM
CBR	Good	Good	Good	Infinite	Infinite	Infinite
MCO1_Negative	/	/	/	/	/	/

Figure 7. Report generated through VTI-TQI automatic analysis [1]

The automatic analysis algorithm is conceptually identical to the previously described manual analysis where a linear trend is generated during the observed period of time based on the defects identified on a given railway segment. The algorithm is used to calculate the moment when this trend will reach an appropriate threshold value (defined by the railway authority in charge of the network where the *V/TI Monitor* measurements take place). It is understood that the user has acquainted himself during manual analysis with a given track condition, and is only expected to define the segment length (with 0.01 mile being offered by default), the threshold values for each and all *V/TI Monitor* parameters and, finally, certain *decision-making rules* to be used in track condition analysis. The results of the automatic analysis are automatically reported in tabular form (Figure 7), and this information can be used for planning future M&R activities.

3. V/TI Monitor data analysis using VTI-TQI software

The analysis revealed a number of situations along the analysed 3,000 km of tracks that demand further and more detailed consideration. For the purposes of this article, only those deemed most representative will be discussed, and the focus will primarily be placed on those defects that are of greatest interest for railways, namely the dynamic impact forces. These forces, marked as AXV defects (vertical axle accelerations and associated dynamic forces at the vehicle/track contact), within the *V/TI Monitor* system, and the derived MCO defects (vertical track geometry "top", with the chord length of 3m), represent "*absolute measurements*" that are independent of the characteristics of the vehicle, i.e. of its primary and secondary suspension. For that reason, the greatest attention was paid to this relationship. Specifically, AXV defects relate primarily to unsprung masses, and therefore indicate local, isolated locations and short-wave irregularities, such as rail joints (mechanical and welded), or rail breakages, shelling, squats or wheel burns, as well as periodical rail surface defects, such as rail corrugation. On the other hand, both MCO defects and obtained values of wheel/rail (W/R) contact forces are calculated from the AXV acceleration. Of course, this does not mean that AXV defects must necessary be accompanied by MCO defects, although MCO defects are derived from the AXV accelerations. As indicated earlier, AXV accelerations defects, AXV W/R dynamic forces defects, and the MCO defects, all originate from the same original AXV signal. Unlike MCO defects that are obtained by double integration, the AXV defects are identified by peak-to-peak processing of the AXV signal, while maximum "zero-to-peak" values are used for the calculation of AXV impact forces at the wheel/rail contact (Figure 3).

3.1. Generation and use of *VTI-TQI* trends

For deeper explanation and better understanding of characteristic problems identified using the VTI-TQI software, it is necessary to explain one of its important characteristics, and that is the possibility of calculating and using trends. Based on Section 1.2 with the description of the VTI-TQI software, and Section 3.2 with individual analyses of different types of defects, it can easily be concluded that the largest contribution of the *VTI-TQI* software is its ability to model and present the track segment behaviour in the past, via any of the *V/TI Monitor* parameters (or their combination), and to predict (project) their future behaviour. This is why an emphasis is placed in this section on the concept according to which the trends for each and every *V/TI Monitor* parameter are defined.

Based on this concept, a special procedure (*routine*) is formed within the *VTI-TQI* software, which performs, within every segment, the grouping of defects according to their type and their sorting as per the date of measurement. Afterwards, the software calculates linear trend coefficients for each of the mentioned groups. Using maintenance level thresholds defined by competent railway officials, which basically represent limit-values on the y-axis, and with the obtained linear trend equation, the system simply calculates the moment when the respective thresholds will be reached.

In that context, the VTI-TQI software will be used to simulate a situation in which irregularities in the first year of measurement will be observed for a particular segment, and the corresponding trend will be generated (Figure 9 and Figure 10). In order to check reliability of the linear trend, the values shown by the trend line will be compared with real values measured in the next year using the V/TI Monitor system. The irregularities/defects concerning the segment shown in Figure 8, for measurements conducted until the end of 2014, are presented in Figure 9.

As can be noticed, the predicted and measured values differ very little in the observed time-span of a few years. The parametric form of the trend equation, and the true (measured) value of this defect after one year, can be seen within the tooltip shown in *Figure 9* (grey window in the centre). This information can of course be easily obtained at any time by simply hovering the mouse over the desired trend line. The defect value registered after one year amounts to 41.86 kN (or 418.6 kN as the defects

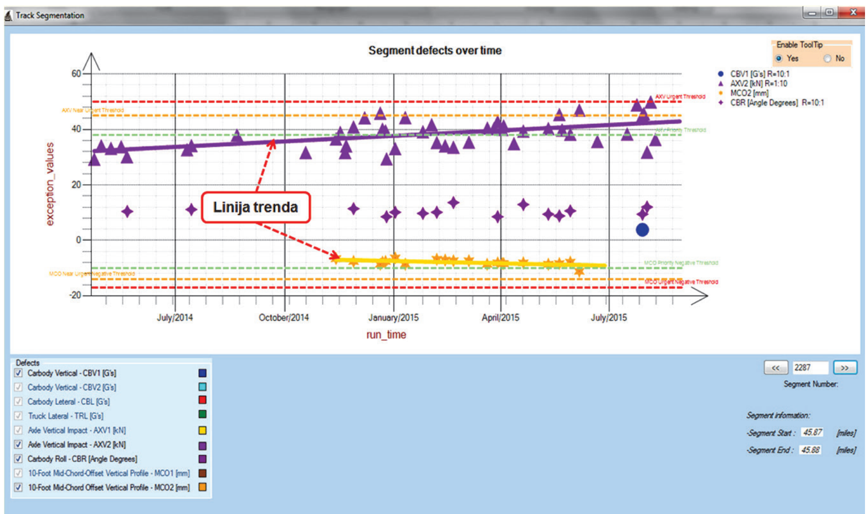


Figure 8. VTI-TQI "Segment View" with trend-line [1]

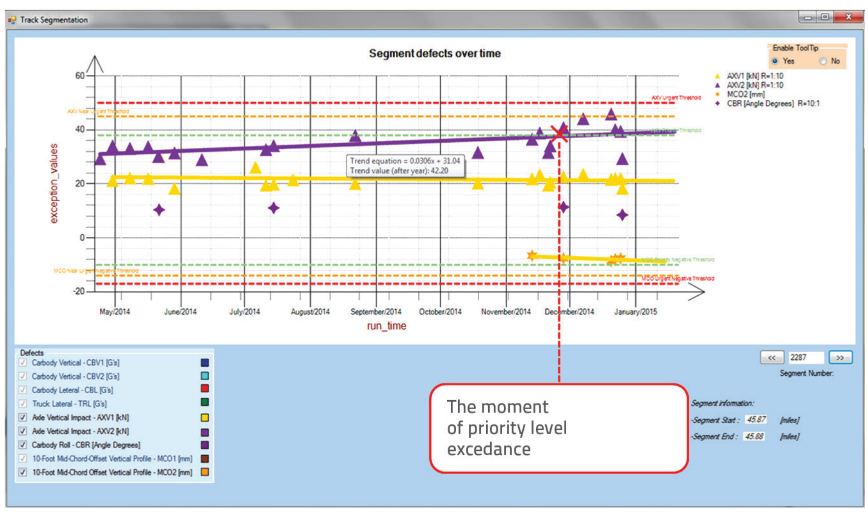


Figure 9. "Segment View" - the same segment as in Figure 8, but this time the defects are limited to those registered in 2014 [1]

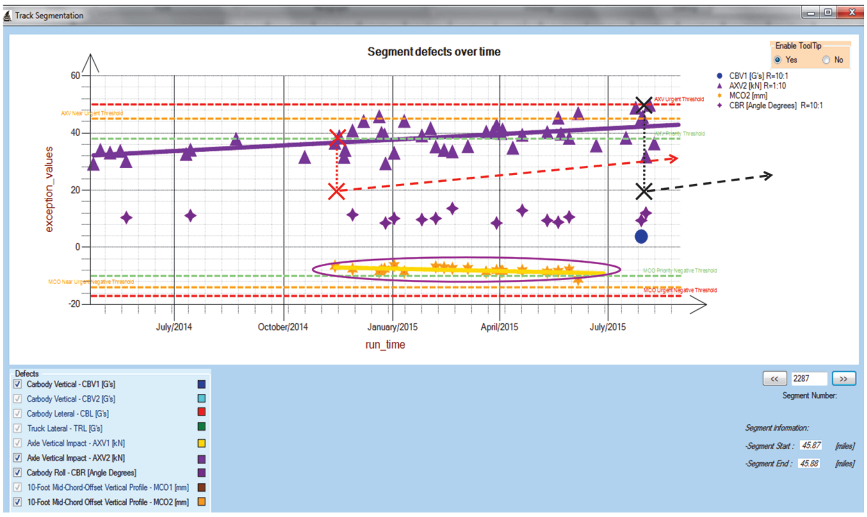


Figure 10. Segment-based deterioration modelling with VTI-TQI software [1]

3.2. Characteristic situations and problems discovered by V/TI Monitor and VTI-TQI software

The first situation refers to the relationship between the MCO and AXV defects that were discussed in the introductory part of Section 3. Namely, the parts of the track that are characterized by small subgrade irregularities can cause the occurrence of MCO defects, but the AXV defects (i.e. the AXV accelerations that exceed threshold values) might not necessarily be generated. As opposed to that, a vehicle passing over sharp irregularities in the W/R profile can cause large AXV forces at the W/R contact but, in this case, MCO defects might not be registered due to very small deviations in the vertical track geometry (TG). This can be expected in situations where only AXV issues of strictly local character are present. These defects can initiate very large dynamic forces, but their length is not sufficient to enable their recording as MCO defects (Table 1). However, if such AXV defects would remain in track for a sufficient time period, then, it might be realistic to expect that this problem would spread and get worse at a later stage due to rapid accumulation of (constantly increasing) dynamic forces, which would eventually also manifest itself through vertical TG irregularities, i.e. MCO defects that occur as a direct result. The mentioned mechanism is shown in the situation presented in Figure 11.

The deterioration of the segment shown in Figure 11 can be divided into three periods. The first one, marked with green line, clearly indicates the increasing trend of AXV defects (purple triangles). After a while, they reach the priority maintenance limit (upper horizontal dashed green line) for AXV defects (this moment is marked with vertical red line). This also exactly coincides with the moment of first registration of TG irregularities or MCO defects at a given segment (orange stars in the lower part of the chart, with yellow trend - here it is perhaps also necessary to clarify that the maximum values in absolute terms are of primary importance for the *V/TI Monitor* defects, so that in this case the sign has no importance; this is why all AXV values are shown with positive sign, while the MCO values are shown with negative sign, i.e. only for better visualization purposes). This is also the moment when the new (second) period starts, which is evidently characterized by an increase in both AXV and MCO defects. However, the CBR defects (dark purple diamonds), indicating lateral tilting of the vehicle body, also start emerging in this period. Analysing the segments similar to the one displayed in Figure 11, an identical mechanism of CBR defect appearance could also be discerned. It can

representing W/R impact forces are shown on the scale of 1:10, as noted in the legend). Based on this fact, it can be concluded that these values indeed correspond to the values actually recorded later on by the *V/TI Monitor*.

Had the *VTI-TQI* software support been available at the time of recording the first defect in this segment, the situation could have developed in a completely different direction, depending on the decisions that the responsible infrastructure manager would have made using the *VTI-TQI* software. Namely, in *Figure 10*, the red dashed line represents hypothetical deterioration of the track on a given segment in case the *VTI-TQI* software is used. Here the analysis would show that appropriate maintenance activities have to be conducted. As can be seen, the situation would differ significantly in case this approach is used, because such intervention - conducted at the moment the priority maintenance level is exceeded - would avoid reaching the level of "urgent maintenance" involving W/R impact forces. In fact, realisation of such works, as a direct consequence of VTI-TQI software analysis, would also avoid occurrence of defects in vertical geometry of the track (marked by large pink oval at the bottom), as well as the occurrence of CBR defects (purple diamonds in the centre). It is therefore quite clear that the benefits of the correct and timely use of software tools like VTI-TQI is not only visible and valuable but also manifold and multidimensional.

Another option, much more demanding in terms of necessary interventions, is represented by the black dashed line. In this case, although fully aware of the consequences of such decisions, but still sure of their ability to control the situation using a software tool like *VTI-TQI*, track managers could let the segment/track deteriorate for a little while longer, and the intervention would be scheduled to take place just before the very moment the "urgent maintenance level" is approached. Taking this possibility into account, it can easily be concluded how beneficial the VTI-TQI and the V/TI Monitor measurement system can be to railway maintenance operators.

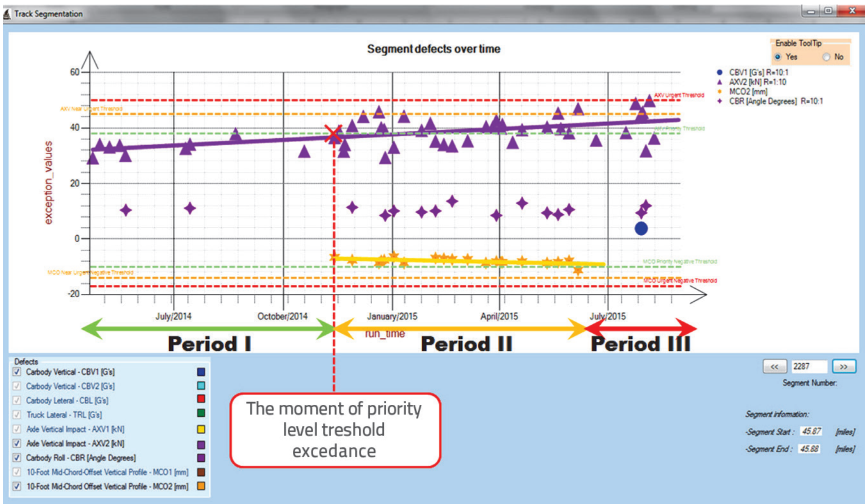


Figure 11. Influence of dynamic forces on vertical track geometry deterioration [1]

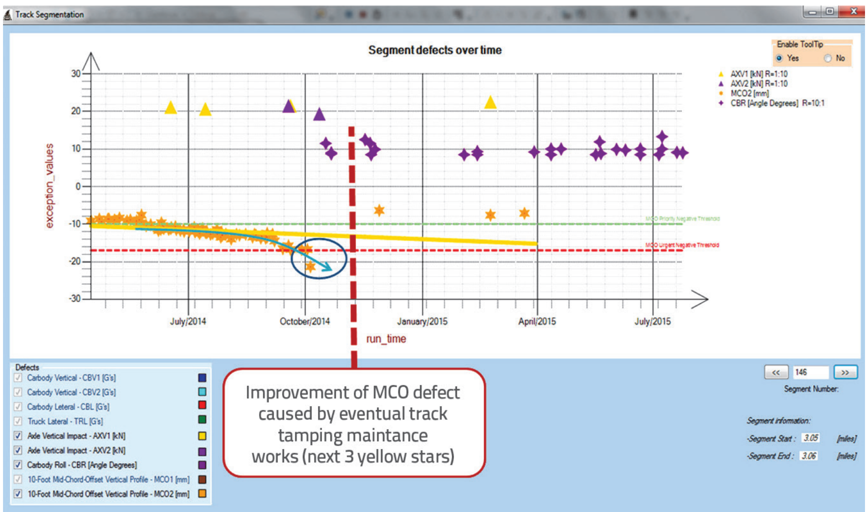


Figure 12. Unexpectedly rapid growth of MCO defects in a very short period of time [1]

therefore be concluded that in situations with synchronized appearance of AXV and MCO defects on one side of the track, there is a considerable chance that the CBR defects would also consequently develop/occur. This is actually a very logical sequence of events, which occurs as a result of different W/R contact heights (on a sufficiently large scale) between left and right side of the track, i.e. left and right rail.
Based on situations considered during analysis of *V/TI Monitor* defects, it could be concluded that, in most cases, an increase in dynamical forces at the W/R contact in the 1-2 year period does not lead to serious vertical TG problems. Therefore, certain safety factors definitely exist, but it is still necessary to approach every situation with great deal of caution, regardless of conclusions derived from certain statistical data. This assertion is supported by situation displayed in Figure 12.
The trend of negative values displayed in Figure 12 predicts that the limit for urgent maintenance will be exceeded almost a year later in comparison to what really happened (large blue oval at the bottom). This situation, where an increase in MCO defect values points to the need of using a non-linear trend type, was also encountered on other segments. More specifically, it can be said that a non-linear trend type becomes relevant at the moment when MCO defect values exceed the "near urgent" limit. Up to that moment, the approximation of increase in MCO defect values involving linear trend has proven to be sufficiently reliable. During the analysis, this kind of MCO defect progression was rarely encountered, but it is still desirable to keep in mind that these situations are certainly possible, as well as realistically achievable, and that is what makes this topic interesting for some further research. Another possible explanation for slower linear trend indicated by the final three MCO measurements could be that track tamping took place on that segment in the period right before the measuring was performed, as hypothetically shown in Figure 12.
When considering TRL (*truck lateral*) defects, which are detected as lateral accelerations of the bogie (truck), it is necessary to consider the position of the sensor in charge of measuring these particular irregularities, as this particular sensor is affected by primary suspensions (Figure 2). For this reason, TRL sensor will primarily register problems of vehicle sinusoidal movement (hunting), the excitation of which is typically caused by irregularities described in Table 1 (worn wheel profiles, damaged dampers, etc.). This is why these defects are typically of lowest interest for infrastructure problems.
In contrast to AXV and TRL defects, CBV, CBL and CBR defects are related to carbody acceleration measurements, which are affected by both primary and secondary suspension. As can also be seen in Table 1, CBL (*CarBody Lateral*) defects, *Figure 2*, are related to horizontal TG, i.e. to geometrical irregularities of longer wavelengths. Therefore, sensors intended for CBL defects measure carbody oscillations, and they will, because of vehicle suspension, react "late" in comparison to the real track geometry imperfections. Vehicle suspension will "filter" the effects of high-frequency geometrical imperfections, i.e. short wavelengths, caused by irregularities of rails, so that the carbody "feels" only "rough" irregularities (of longer

wavelengths). For this reason, CBL defects do not necessarily need to directly coincide with lateral accelerations of the axle, i.e. with TRL defects. Of course, there is a certain relationship between them, and it is realistic to expect the occurrence of CBL defects at high-levels of lateral axle accelerations but, as can be seen in Figure 13, they might not be as large and prominent as TRL defects.

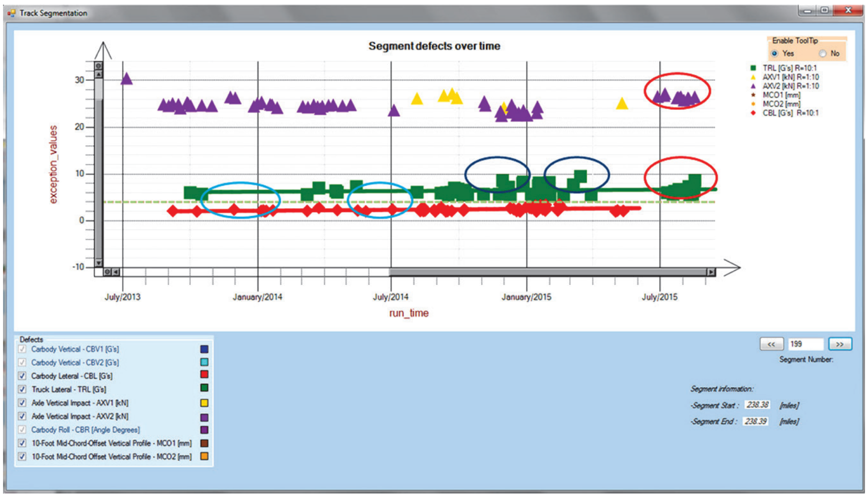


Figure 13 Connection between CBL and TRL defects [1]

As can be seen in Figure 13, TRL defects are in this case constantly above the "urgent maintenance limit" (green horizontal line - the "urgent maintenance limit" for TRL defects is defined with the same value as the "priority maintenance limit" for CBL defects). A certain TRL defect trend obviously exists and, as can be seen in Figure 13, its slope is almost identical to the slope of the trend defined by CBL defect values. These defects were registered while measuring vehicles were travelling at the speed of 70 km/h (± 5 km/h).

The concept of measuring vertical acceleration of the carbody (CBV1 & CBV2) is similar to that relating to lateral acceleration of the carbody (CBL), the only difference being that the CBV is oriented in the vertical plane. If in case of the CBL the connection with bogie (truck) lateral acceleration (TRL) is analysed, then in case of CBV defects the attention must primarily be paid to their relationship with vertical TG irregularities (MCO) and vertical axle-box accelerations AXV, as well as with the related W/R impact forces. It is important to note that, after their first appearance, the CBV defects remain within the originally recorded ranges for quite a long time.

3.3. Switches & crossings problems discovered with V/TI Monitor and VTI-TQI software

A significant number of interesting situations identified during the analysis concern the switches & crossings (S&C) units which, due to their own characteristics (structural & geometrical), often initiate occurrence of various *V/TI Monitor* defects. At the same time, S&Cs exactly represent the RIE whose M&R expenditures occupy the largest part of M&R budgets. During the analyses of different network regions, it could be noticed that S&C locations dominantly lead to the development of AXV defects, and that their values often exceed *urgent level* thresholds. One of such regions, where the importance of these locations was clearly noticeable, is presented in Figure 14.

At the beginning of discussion about this region, it is important to emphasize that Figure 14 refers to the defects sorted by chainage, which in fact represents the abovementioned "manual analysis" that could be performed very quickly and easily using the "Track View" of the *VTI-TQI* software.

Figure 14 clearly shows that only several groups of defects, i.e. several distinct locations with a considerable grouping of defects, can be identified on the entire 100 mile (~160 km) section. With further analysis of this section based on the abovementioned "Track View", it became evident that these locations should be checked more closely via *Google Earth*. Namely, in addition to chainage information, all recorded *V/TI Monitor* defects possess geographical coordinates obtained by the GPS device, which is an integral part of the *V/TI Monitor* system. By checking those locations on the map, it became clear that they are associated with S&C units (Figure 15 - Figure 19). Generally, such "peaks" shown in "Track View"

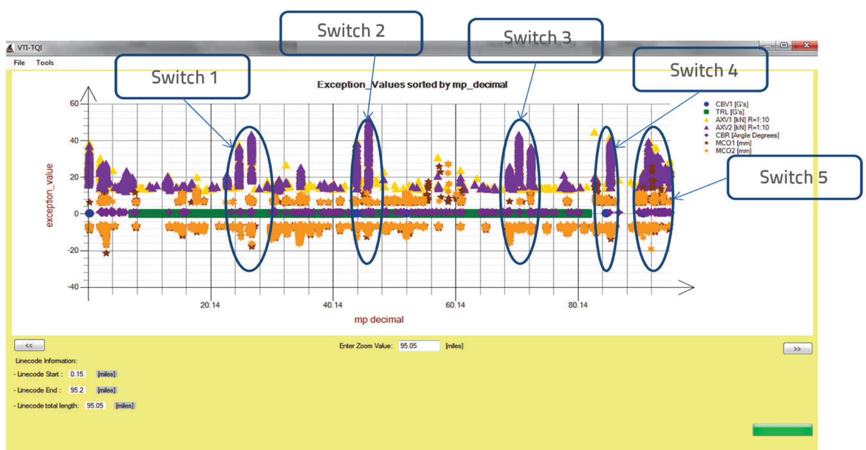


Figure 14. Characteristic situation from one of the investigated network regions [1]

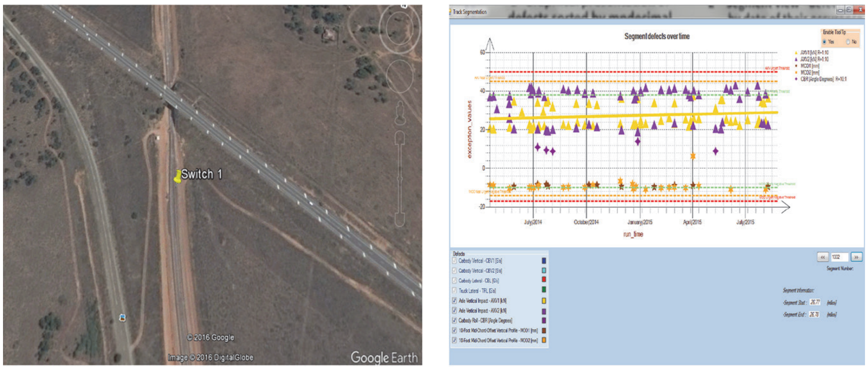


Figure 15. Switch 1 - Segment view [1]

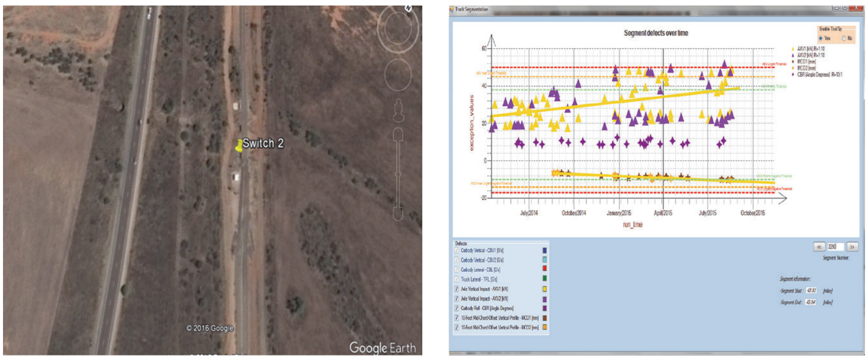


Figure 16. Switch 2 - Segment view [1]

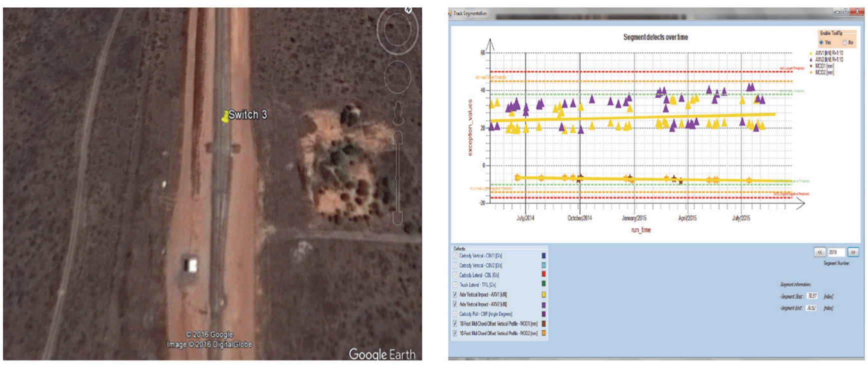


Figure 17. Switch 3 - Segment view [1]

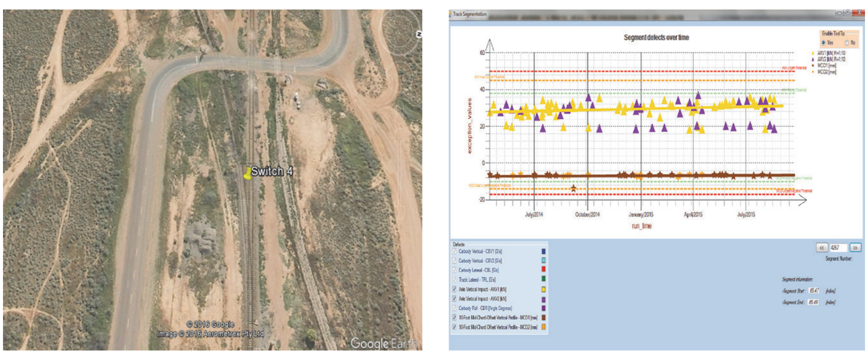


Figure 18. Switch 4 - Segment view [1]

are typical for S&C locations, road crossings, bridges etc., which have, as already stated, the strongest influence on the M&R costs. This is precisely why the *V/TI Monitor* system capabilities are of great importance and benefit: they enable railway infrastructure managers to identify and quantify relative deterioration of rail and track geometry on such locations and consequential increase in dynamic forces, which could directly be related to the respective M&R costs and finally enable their significant reduction. In the following figures (Figure 15 - Figure 19), every marked S&C from Figure 14 is presented individually, with a short description of respective locations and, unlike 100 miles (~160 km) of track length shown in Figure 14, segments with the specific length of 0.02 miles (~32 m), accurately corresponding to each S&C position, will be presented.

As can be seen, development of AXV and MCO defects during the observed period of time (the beginning of 2014 - end of 2015) is characteristic for the switch presented in Figure 15. This is one of the locations where we cannot talk about MCO defects development mechanism caused by AXV forces, considering their synchronised occurrence ever since the first measurement. It is however obvious that, unlike the MCO defects, the AXV defects are characterized by a much steeper (faster growing) trend.

Unlike the segment shown in Figure 15, the switch shown in Figure 16 exhibits a considerably faster growth of both AXV and MCO defects. It is obvious, however, that vertical TG irregularities are caused by AXV dynamic forces, which is conceptually identical to the situation shown in *Figure 11*.

Situations in Figure 17 and Figure 18 are similar to the one shown in Figure 16, the only difference being that the AXV defects trend line has a much slower change rate (slope).

As can be seen in figures 15 to 18, these S&C units are in most cases characterized by a rather similar degradation mechanism. Impact forces generated in the W/R contact and

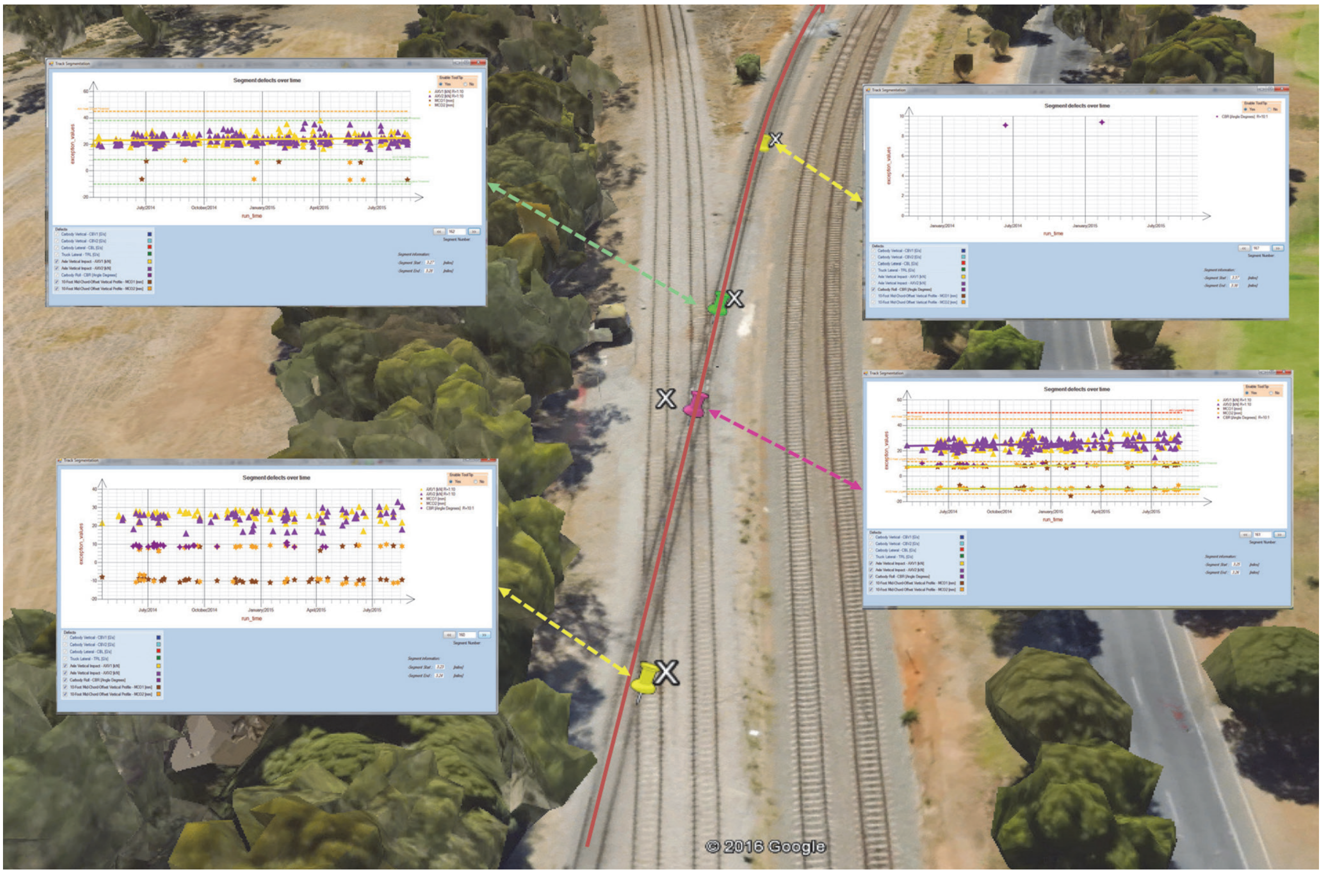


Figure 19. Defects generated at two consecutive crossings

irregularities within the vertical TG are dominant, just like in previously shown situations.

The situation shown in Figure 19 is characterized by two consecutive crossings. Related to previously discussed situations primarily focusing on switches, it can be stated that this situation is also quite similar. It is obvious that AXV forces still remain dominant. After a vehicle has passed over this location (quite unpleasant for the vehicle), the situation changed completely. This is evidenced by the number of irregularities registered on the segment presented in the top right corner (Figure 19) (where almost no defect has been registered), and which follows after a series of segments relating to crossings.

Thus, a stable defect occurrence mechanism can be noted in case of the previously described S&C. Due to their geometric and structural characteristics, such places obviously represent the origin of impact forces development. It is therefore very significant to predict and quantify the level of severity of these irregularities, which is enabled by the use of the *V/TI Monitor* system and *VTI-TQI* software. Also, it was observed during analysis that "urgent levels" were usually exceeded on these specific locations. Consequently, as already mentioned, it is of highest significance to devote special attention to such locations, i.e. to define their specific deterioration models, in the oncoming research work.

4. Conclusions

Unlike traditional systems that primarily focus on the measurement of track geometry, the *V/TI Monitor* is characterized by a completely different concept, based on the measurement of vehicle accelerations (axle-box, bogie (truck) and carbody) in interaction with the rail/track. In addition to easy and cost-effective identification of low percentage (usually 10-20) of the most urgent locations on the network, which make up the top-priority maintenance list, the primary focus of this system is on detecting irregularities of local character, as they constitute the main causes of rail/track deterioration according to relevant research published so far. Furthermore, the key potential of *V/TI Monitor* lies in its autonomy and characteristics that allow this system to perform daily measurements, without causing any traffic disturbance, which is of great importance for both the passenger and freight customers, as well as for the railway system itself.

Huge amounts of data collected daily by the *V/TI Monitor* systems undoubtedly offer a whole new dimension to the problem with which competent engineers in charge of railway infrastructure maintenance have to deal. If a software tool such as the VTI-TQI is applied alongside with the knowledge of rail infrastructure experts in order to properly interpret, show and understand the data obtained with this system, it would be possible to reach the situation in which it could be stated with certainty that we are "one step ahead of the track deterioration process", as it would be possible to predict the time when a specific parameter, or a combination of several parameters, will exceed a relevant maintenance level.

For modern railways that spend significant financial resources on M&R every year, and are characterized by large traffic volumes, as well as high speeds and/or axle-loads, any M&R work that can be predicted in advance is highly significant, and can greatly reduce the costs. This is exactly what the V/TI Monitor with the support of a tool like VTI-TQI can provide. Of course, although it is theoretically possible, it is not realistic to expect that all situations characterized as critical will be resolved at the same time. In this respect, the process of deciding when and where required corrections should be made, will be supervised by the staff in charge of railway infrastructure management. V/TI Monitor and software tools like VTI-TQI only aim at offering significant support and help in this respect.

REFERENCES

[1] Tešić, P.: Analiza mernih podataka Vehicle Track Interaction (V/TI) sistema (The analyses of Vehicle Track Interaction (V/TI) measurement data), Diplomski rad, Univerzitet u Novom Sadu, Fakultet Tehničkih Nauka, Novi Sad, Srbija, 2016.

[2] Jovanović, S., Guler, H., Čoko, B.: Track degradation analysis in the scope of railway infrastructure maintenance management systems, Gradjevinar, 67 (2015) 3, pp. 247-258.

[3] Jovanović, S., Božović, D., Tomičić-Torlaković, M.: Railway infrastructure condition-monitoring and analysis as a basis for maintenance management, Gradjevinar, 66 (2014) 4, pp. 347-358.

[4] Guler, H., Jovanovic, S., Evren, G.: Modelling railway track geometry deterioration, Proceedings of the ICE – Transport, 164 (2011) 2, pp. 65 –75, https://doi.org/10.1680/tran.2011.164.2.65

[5] Federal Railroad Administration - Office of Safety Analysis, http://safetydata.fra.dot.gov/

[6] Tzanakakis, K.: The Railway Track and Its Long Term Behaviour, Springer, 2013, https://doi.org/10.1007/978-3-642-36051-0

[7] Haladin, I., Lakušić, S., Košćak, J.: Measuring vibration damping level on conventional rail track structures, GRADEVINAR, 68 (2016) 6, pp. 461-476, doi: https://doi.org/10.14256/JCE.1532.2015

[8] Maldonado, R., Dick, M.: Expanded Use and Evaluation of Autonomus Vehicle/Track Interaction Equipment, IHHA – International Heavy Haul Association Conference 2015, Perth (Australia), 2015.

[9] Clark, D., Toth, T., Dick, M., Maldonado, R.: V/TI Monitor Cluster Analysis and Implementation, AREMA 2015 annual conference & exposition, Minneapolis (USA), 2015.

[10] Clark, D., Toth, T.: Vehicle Track Interaction, Proceedings of the 2006 AREMA Annual Conference, Louisville (USA), 2006.

[11] Jovanović S., Matić B., Marinković M., Railway track superstructure and maintenance (Gornji stroj i održavanje železničkih pruga), Lecture notes, University of Novi Sad, Faculty of Technical Sciences, Department of Civil Engineering and Geodesy, 2017, ISBN 978-86-7892-984-7

[12] Pace, P., Jovanovic, S.: Using measurement data for decision support, International Railway Journal, 51 (2011) 7, pp. 37-39.