WHEEL/RAIL DYNAMIC FORCES AS THE GENERATOR OF TRACK DETERIORATION AND THE FOCAL POINT FOR ITS MAINTENANCE

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Abstract: *Despite the fact that Maintenance & Renewal (M&R) of infrastructure represents the largest constitutive part of infrastructure life cycle costs, most governments and railways in the West Balkans (WB) region, already for decades, most attention directs towards infrastructure (re)construction, while M&R is largely neglected. One of the key reasons is the fact that infrastructure maintenance represents a very long process, lasting many decades, which is too long (and thus also uninteresting) from the viewpoint of the key stakeholders, be they (at) relevant banks which finance infrastructure activities, or railways which conduct them, or politicians that decide upon them. For that reason, these stakeholders find (re)construction projects much more attractive, as they are shorter (in time), yet financially intensive, which makes them possible to be "wrapped up" within their "terms", i.e. the time-frame corresponding to the stakeholders' holding of respective functions/positions. However, all these activities, including M&R, are eventually paid by all the citizens, who also utilize that infrastructure, and who thus should find it in their best interest that this infrastructure is kept in the optimal condition, i.e. that it is properly managed, or in other words – maintained. On the other hand, to manage M&R in an optimal manner, key and keen attention must be addressed to the dynamic forces acting at the vehicle/track (V/T), i.e. wheel/rail (W/R) interface, as they represent the key trigger and generator of the entire deterioration process of all Track Components (TC). For that reason, in the sense of appropriate assessment of TC condition and definition of the optimal regime of consequential M&R activities, it is of crucial importance to be able to measure (directly, or at least indirectly) the V/T dynamic forces, which are, on the other hand, a direct consequence of the track and rail geometry, but at the same time, their core generator. In that sense, Vehicle/Track Interaction Monitor (V/TIM) represents one of the latest-generation systems aimed at the measurement of TC quality, which, by the use of accelerometers, measures the dynamic vehicle/track interaction. This article explains the importance of M&R activities, influence of dynamic forces onto TC deterioration, as well as a possibility of their measurements and use of the measured data for the M&R optimization.*

Keywords: *Document, symposium, paper*

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1. INTRODUCTION

Railway lines have very long service lives (the oldest railway lines in the world are approaching the age of 200 years), during which the Maintenance and Renewal (M&R) costs of Track Components (TC) represent the largest part of their Life Cycle Costs (LCC), significantly larger than the initial investments, which may especially be true if all the phases of construction, Figure 8 (left), from planning, via design, to construction and subsequent M&R are performed inadequately.

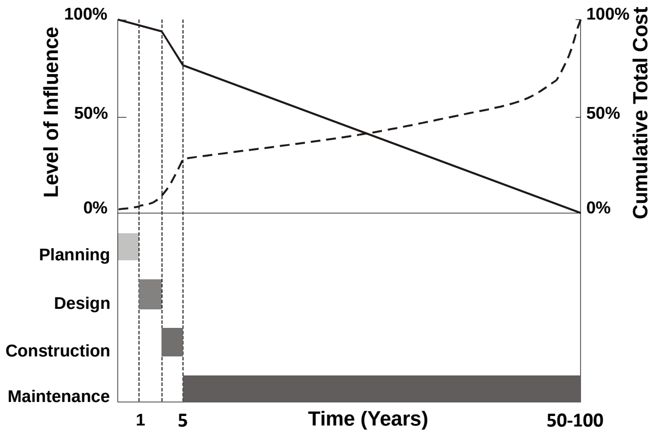


Figure 8: Importance of maintenance as a phase in an infrastructure life cycle [1]

What Figure 8 basically depicts is the increase of LCC over the (very lengthy) infrastructure life-time (right-side ***Y***-axis), and the decrease of the **influence** onto these LCC various phases in the railway infrastructure life-time have (left-side ***Y***-axis). Thus, ***planning***, as the starting phase, does not last very long, costs very little in comparison to the total LCC, but has the largest influence on these costs, also including the "trivial option" of "doing nothing", where, at least theoretically, the entire investment might be "saved" by deciding not to do it, and thus be used for other, possibly more profitable or useful things.

Once the decision to build has been made, the next phase, ***design***, also costs quite little and normally does not last too long, but already carries smaller influence onto the entire LCC than the planning phase, where the most important aspect is that mistakes made during the design phase, mostly related to "engineering compromises" made in order to save construction costs, boomerang later back as problems during infrastructure exploitation, sometimes increasing considerably the maintenance costs, which can accumulate considerably over the lengthy infrastructure life-span. These mistakes typically include wrong choice of a layout, insufficient geological investigations allowing layout to pass over inadequate soils, wrong choice of design elements (e.g. too sharp curves, too steep gradients), wrong selection of inferior materials for the substructure, which are very difficult and thus costly to repair during exploitation phase and cause frequent traffic disruptions, and finally wrong choice of inferior superstructure components, unfit for the traffic, causing too frequent maintenance, again resulting in consequential traffic disruptions and costs.

Similarly to design, also ***construction*** phase has lower impact onto the LCC than its immediately preceding phase – design, but carries substantial part of LCC, while lasting relatively short, which is exactly what makes it attractive to all the key stakeholders. Still, it can quite significantly influence the LCC, where again especially important are possible construction errors, such as inappropriate treatment and construction of substructure materials, their insufficient compaction, or incorrect or imprecise implementation of superstructure elements. Here, very important to mention, as a possible error, is the lack of appropriate work acceptance procedures, where the quality of construction works is effectively never properly checked (this topic is additionally addressed in the next chapter).

Finally, the last phase in the infrastructure life-span, ***maintenance***, has the lowest absolute impact onto the LCC, but spans over the most of the infrastructure life-span, reaching often more than 90% of it, which certainly allows for its costs to accumulate to represent the largest absolute part of the entire LCC. However, maintenance also has a certain impact onto these LCC, which is smaller than all previous phases, but still far from negligible. Namely, also the frequency and quality of maintenance can significantly decrease, or increase the deterioration of all TC, and thus impact the overall LCC. In that sense come the following chapters of this paper, explaining the main drivers of TC deterioration and how they can be monitored (measured) with a purpose of controlling them by planning optimal M&R.

However, despite the fact that M&R of infrastructure represents the largest constitutive part of infrastructure LCC, most governments and railways in the West Balkans (WB) region, already for decades, direct most attention towards infrastructure (re)construction, while M&R is largely neglected. One of the key reasons is the fact that infrastructure maintenance represents a very long process, lasting many decades, which is too long (and thus also uninteresting) from the viewpoint of key stakeholders, be they (at) relevant banks which finance infrastructure activities, or railways which conduct them, or politicians that decide upon them. For that reason, these stakeholders find (re)construction projects much more attractive, as they last shorter, yet are financially intensive, which makes them possible to be "wrapped up" within their "term", i.e. the time-frame corresponding to the stakeholders' holding of their respective functions/positions. However, all these activities, including M&R, are eventually paid by all the citizens, who also utilize that infrastructure, and who thus should find it in their best interest that this infrastructure is kept in the optimal condition, i.e. that it is properly managed, or in other words – maintained. This is in fact the key aim of this article, and that is to explain, primarily to the Serbian audience, that even though the railway part of civil engineering might not be the most popular and most significant over the past several decades, it should still be of interest not only for the entire civil engineering profession and professionals, but also to all of us as Serbian tax paying citizens, or possibly even parents or grandparents of future Serbian tax paying citizens, who will be repaying the loans we take today. As for the foreign part of the audience, it could also be interesting at least as a peculiarity of Serbian civil/railway engineering domain, if not for the similarity with their own railways.

In that sense, it is important to stress that the above-mentioned banks, over past several decades, probably in order to ameliorate the depicted situation, have developed a series of procedures, including various types of studies, required to prove not only the feasibility, but before all the sensibility of the investments, including also infrastructure-

related ones. In that sense, however, it is interesting to notice that the key railway infrastructure investments in Serbia over the past years, involving the so-called "Russian loan" (of about 900 million USD) aimed at the renewal of the existing lines and the (re)construction of the High-Speed Line (HSL) Belgrade-Subotica-Hungary (of about 3 billion EUR, according to the scarce public information about it), have both been financed not from the typical international investment banks, such as EBRD, EIB and WB, but from the bilateral loans, from Russia and China, respectively. Moreover, not only were the loans made on bilateral basis from the two mentioned countries, but the respective works are to be performed by the companies of the two mentioned countries.
However, the aim of this paper is not to discuss the logic and concept of these two key railway infrastructure endeavors in Serbia (they have been already discussed in detail by the first author of this paper in [2] (only in Serbian), in full accordance with the methodology of the *International Union of Railways* – UIC explained in [3]). The aim of this paper is merely to point out the extensive scale of these investments, which are, possibly with the exception of the much-talked-about "*Belgrade Waterfront*" project [4], unparalleled in the modern Serbian history (and most probably would not find a parallel in the number of coming years), and which should all make these projects relevant and of concern at least for the Serbian audience, if not also for the foreign one, if nothing else, then for the curiosity purposes.

2. MAINTENANCE, AS THE KEY PHASE IN THE INFRASTRUCTURE LIFE-SPAN

The railway infrastructure is by far the most expensive item in the railway industry, generating maintenance and renewal (M&R) expenditures of monstrous proportions every year. For example, average annual M&R expenditures per 1 km of only tracks and their components (TC) (excluding the rest of infrastructure elements) for West-European networks revolve around €50.000 [5], of which about 70% falls on renewals, 20% on manual maintenance and about 10% on mechanized maintenance (e.g. tamping & grinding), Figure 9. For that reason, any reduction of these expenditures would significantly influence the overall efficiency in the management of all TC.

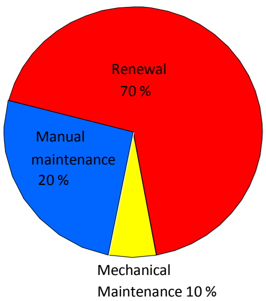


Figure 9: Share of track M&R costs on the Dutch Railway Network (ProRail) [5]

Having in mind what was stated about the "lion share" of M&R within the railway infrastructure LCC and the above items, it is clear that M&R should be paid acute attention by both railways and respective governments, as significant expenditures are at stake, which can both be saved if the infrastructure is maintained properly, or lost, if otherwise. On the other hand, to manage M&R in an optimal manner, key and keen attention must be addressed to the dynamic forces acting at the vehicle/track (V/T), i.e. wheel/rail (W/R) interface, as they represent the key trigger and generator of the entire deterioration process of all Track Components (TC).

In that sense, it should be mentioned that at minimum, the standard practice at main railways world-wide is to perform Track Geometry (TG) measurements during the track/work-acceptance procedure, but not only once, but several times over the period of the first couple of years (also typically corresponding to the warranty period for the performed works), when the initial settlements are the largest, to make sure their negative effects on the rise of very detrimental dynamic forces is avoided.

The last part here is often neglected, especially in the WB region, mostly due to the lack of suitable Track Recording Vehicles (TRV), which is very problematic, even alarming, as the largest absolute damage to all the TC can happen when the track is new, if the TG is allowed to deteriorate (without controlling it with TRV), thus causing increase in V/T dynamic forces, which, as will be discussed in detail further in the text, can quickly and significantly degrade all TC. This is also a common mistake among the railways in the WB region, and that is that they think that a new(ly) (re)constructed track does not require maintenance. In fact, due to the above reason, new tracks require even more attention, and in some cases (especially if construction has not been performed properly) require more maintenance than the old tracks, in order not to allow for these large absolute damages to occur. Namely, in case of old tracks, which are already quite deteriorated, any further deterioration does not cause significant absolute loss, as the residual value of such track is already low. However, in case of new tracks, whose residual value is large – i.e. in fact, theoretically 100%, any, even the slightest relative damage, represents a large absolute loss.

The importance of the detrimental effects of the dynamic forces onto the deterioration of all TC and its two-way link with TG has been long recognized and best described via the formula of Prof. Eisenmann depicted in Figure 10 and originating from 1970-ties in Germany, or the UIC/ERRI (*European Rail Research Institute* – earlier ORE – *Office of Research & Experiments*) D161 (as well as prior D117 [7] and D141 [8]) research [6] from 1980-ties, yielding the graph on the Figure 11 and the formula (2-1). The D161 research, as well as the two of its predecessors, originated from the fact that European railways desired to increase the nominal axle-loads from 20t to 22.5t and were concerned with the effects of this increase onto the TC deterioration as well as its link and mutual repercussions onto the TG.

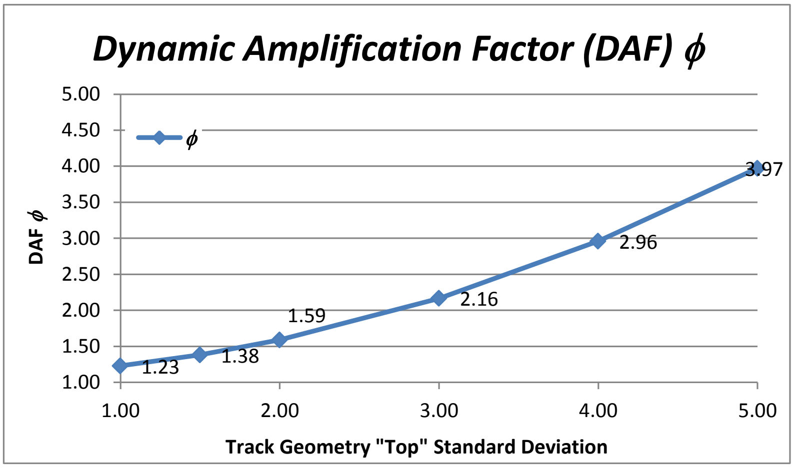


Figure 10: Relative increase of dynamic forces (i.e. the Dynamic Amplification Factor - DAF) with respect to TG "Top/LL" given in [mm SD]

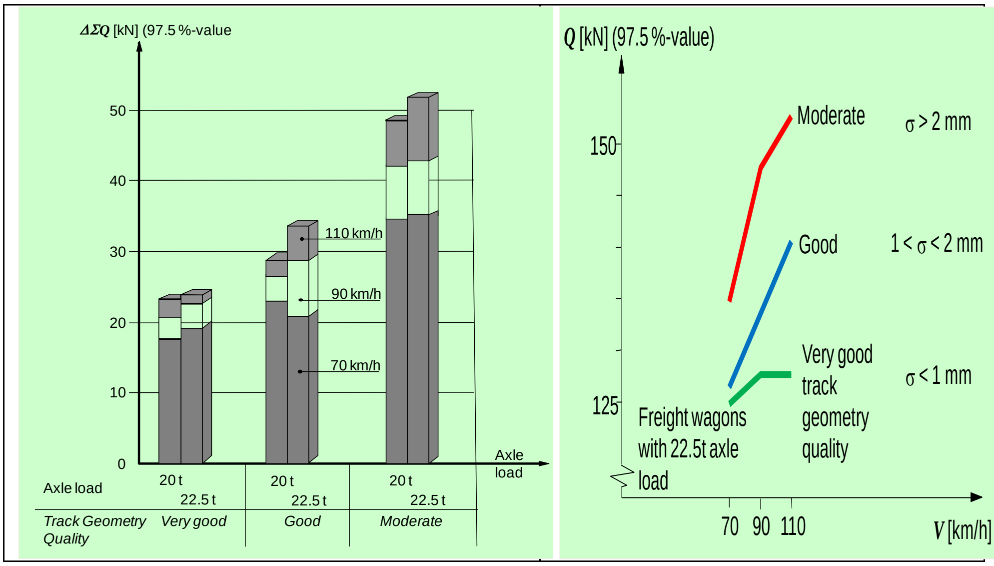


Figure 11: Dynamic component of wheel load versus axle load, speed and track quality [6]

$$E = k * T^{\alpha} * P^{\beta} * V^{\gamma} \tag{2-1}$$

where:

- ***E*** – Deterioration
- ***k*** – Coefficient adherent to particular circumstances at a certain railway
- ***T*** – Accumulated Traffic Load
- ***P*** – Representative Dynamic Axle Load
- ***V*** – Train speeds

while the exponents α, β, and γ represent empirically established constants, pertaining to different aspects of track deterioration (such as: rail fatigue, rail surface defects, fatigue of other components, track geometry deterioration) and carry different corresponding values, accordingly.

However, much to the D161 researchers' initial relief, as well as surprise, this (very extensive) research yielded one the key conclusions that *for most of the parameters examined, the increase remained less than the increase of 12.5% in nominal axle load, i.e. (22.5-20)/20*. However, much to their dismay, it also revealed that next to the vehicle speed (which was expected), ***the TG quality was by far the most important parameter***. As can be deduced from the Figure 11 (left), the dynamic component of the ***Q***-force (i.e. the "dynamic increment" Δ***Q***, representing the difference between the measured and the static force) for an axle-load of 20t on a "poor-quality" track is considerably greater than that for an axle-load of 22.5t on a "good-quality" track supplemented by the static increase of 12.5 kN. This also very much confirmed the conclusions of Prof. Eisenmann, depicted on the Figure 10.

Thus, it is clear that TG quality has a significant influence on the level of V/T dynamic forces, and thus consequently on the deterioration of both track, and rolling stock. Because of this, for decades the rail systems (railways, tramways, metros, etc.) around the world pay a significant attention to TG and its change over time and exploitation (e.g. MGT carried). In fact, the problem of TG and its correlation with the 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 (which may be caused by both the dynamic forces at the W/R (wheel/rail) contact point, and external influences, e.g. differential settlements due to problems in the subgrade or due to inadequate drainage, bad weld/joints geometry, etc.), they start increasing the dynamic forces, which again in turn exacerbate the TG, thus initiating a "vicious circle", where *TG and dynamic forces have mutually accelerating detrimental effects*. Due to this mechanism, sometimes seemingly small TG irregularities can rapidly develop into a problem of serious proportions, whose correction is then very expensive and time-consuming. Knowledge of locations with impaired (both track and rail) geometry is essential at any rail system, in order to be able to take appropriate actions before these irregularities grow and cause large and expensive damages to the track, and vehicles.

In that sense, what should be stressed here are the "standard" threshold values utilized in Europe [9]. Table 2 defines the limit values of TG longitudinal level for each Track Quality Class (TQC) and for each speed range in Europe. Typically speed ranges span from 80 to 300 km/h. Clearly, in Serbian case, before the new HSL is constructed, only the first two classes would be utilized (i.e. 0-80 and 80-120km/h), as maximum current speed on Serbian rail network is 120km/h.

Table 2: Longitudinal level ("Top") Standard deviation – D1 domain (3-25m waveband)

Speed [km/h]	**Limit value of Standard Deviation [mm]**				
	Track Quality Classes				
	A	**B**	**C**	**D**	**E**
V ≤ 80	< 1.25	1.75	2.75	**3.75**	> 3.75
80 < V ≤ 120	< 0.75	1.10	1.80	**2.50**	> 2.50
120 < V ≤ 160	< 0.65	0.85	1.40	1.85	> 1.85

This table is based on the currently known track characteristics of the European Railway Networks that participated some years ago in the Pan-European Track Quality Survey. The values in the table are obtained from the Track Quality Survey according to the method that is based on the cumulative frequency distribution of the reference Track Quality Index (TQI_{ref}), based on TG standard deviation, as shown in Figure 12. The graph on Figure 12 shows the percentage of track length undershooting a given TQI_{ref} value on the considered track section. For example, in this figure, ***X2*** % of the concerned track section has a TQI_{ref} value that is less than ***Y2***.

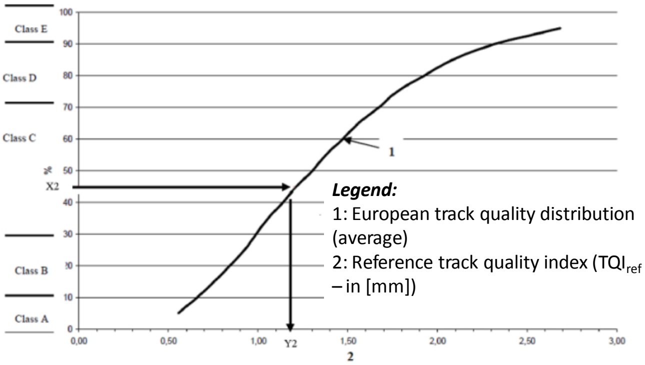


Figure 12: Determination of the classes of track quality according to European Norms [9]

The performed survey yielded the following Track Quality Classes (TQCs):

- Class A – best 10 % of the distribution
- Class B – between 10 % and 30 % of the distribution
- Class C – between 30 % and 70 % of the distribution
- ***Class D – between 70 % and 90 % of the distribution (this Class typically represents the class within which the candidate sections to receive maintenance/tamping should be sought)***
- Class E – above 90 % of the distribution, which represents the *worst 10 % of the distribution*, and where some other reasons are most probably contributing to such extremely bad TG, e.g. ballast contamination and substructure condition

The above-discussed two-way link between TG and dynamic forces was also found to be of large importance during the “ConnecTA” Project, i.e. the “*Technical Assistance to Connectivity in the Western Balkans EuropeAid/137850/IH/SER/MULTI*” [10], the motivation for which was the observation of the EU (stated in the respective ToR as well as in the preceding researches [11][12]) that the EU has been financing over the last couple of decades numerous infrastructure (re)construction projects in the WB region, after which, however, the respective countries and infrastructure authorities, failed to maintain regularly and properly the (re)constructed infrastructure, which hence deteriorated quite rapidly, causing at the end, arguably more damage than benefits.

For the purposes of this project, a similar reference survey was performed in this exercise for the Serbian rail network and benchmarked with the European standards. Here, also the actual limit values (10%, 30%, 70%, 90%) were determined, by taking the 5-years of TG measurements (roughly twice a year – i.e. 9 measurements in total, as during one of the 10 measurements, the existing TRV in Serbia seemed to have been out of calibration) and creating cumulative curves for the two key parameters: (1) Longitudinal Level (LL) ("Top")(Figure 13-Figure 14) and (2) Alignment (AL)(not discussed here), both in the "D1" wave-band, as it concerns speeds up to 160km/h, which is the case on the entire WB network, including that of Serbia.

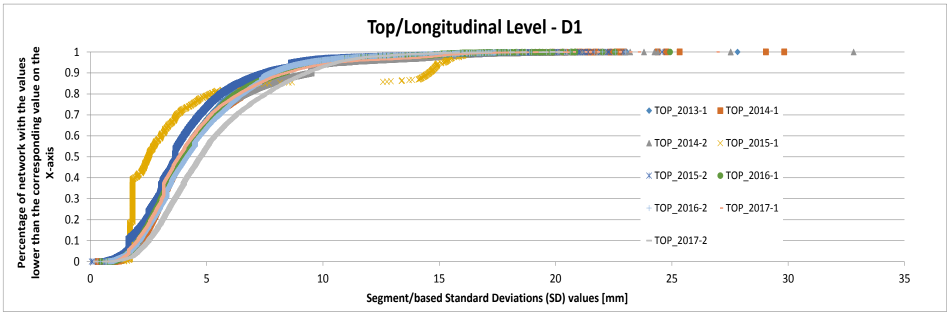


Figure 13: Segment-based Longitudinal Level (LL or "TOP") D1 Standard Deviation values in [mm] for the entire SRB network for 9 measuring campaigns on the SRB rail network in the period 2013-2017

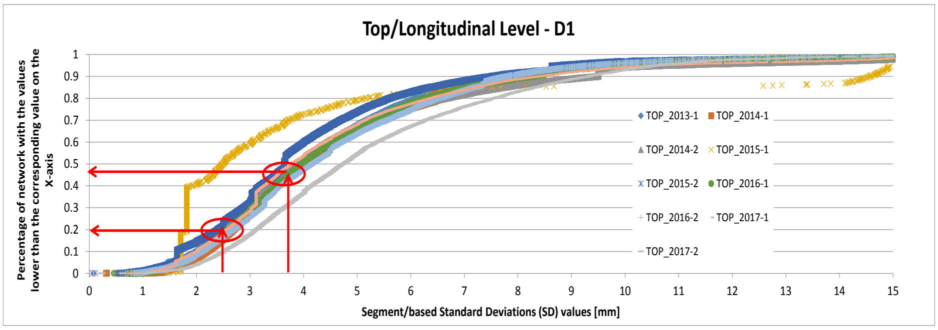


Figure 14: Segment-based Longitudinal Level (LL or "TOP") D1 Standard Deviation values in [mm] for the entire SRB network for 9 measuring campaigns on the SRB rail network in the period 2013-2017 (zoomed into the most important area)

In the light of the above, what Figure 14 shows is that if standard European thresholds for Top/LL are to be applied (Table 2 & Figure 12), which describe the "best", "good", "moderate", "poor" and very "poor condition" (also used in the Eisenmann formula), and even if for the lines with speeds above 80km/h the "more relaxed" limits pertaining to the speeds up to 80km/h are to be applied (i.e. 3.75mmSD, Table 2) to find the parts on the Serbian network with the higher SD value and label them as "requiring Tamping" (i.e. TG correction), it would correspond to the percentile value of about 47%, ***which means that 100-47=53% of the entire Serbian network would require Tamping***, which is quite a lot, i.e. ***poor !*** However, as some of the Serbian network sections have a design speed above 80km/h, to them a different threshold would apply, i.e. 2.5mmSD, Table 2. This value corresponds to the percentile of 20%, i.e. ***requiring 80% of the network to be***

Tamped (though, of course, not the entire network has the design speed above 80 km/h, so this is only for indicative/speculative reasons).

Previously mentioned UIC/ORE/ERRI research D161 and its conclusions and formulas, such as (2-1), as well as the above short elaboration on the two-way link between TG and dynamic forces, clearly underscore the importance of both of them. It is, however, worth mentioning that in addition to TG, also other rail and track irregularities decisively influence the rise of dynamic forces (and consequential deterioration of all TC), such as rail joints, bad-quality rail welds, rail corrugation, wheel-burns, squats, and many other rail surface irregularities (

Figure *15*-Figure 19), but also wheel surface irregularities, such as wheel-flats, Figure 20.

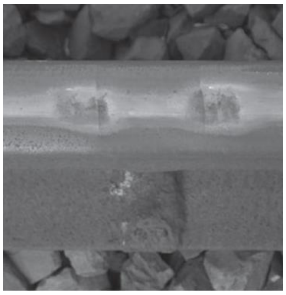
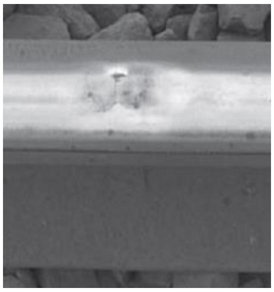




Figure 15: Left - mechanical rail joint; middle & right – bad quality (battered) rail weld

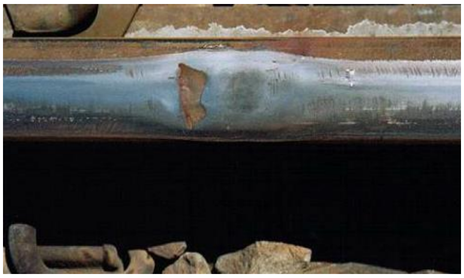



Figure 16: Left – starting/lighter form of a squat defect; right – more severe form of a squat defect

Figure 17: Wheel-burns, small (left), medium (middle) and severe (right)

Figure 18: Rail corrugation

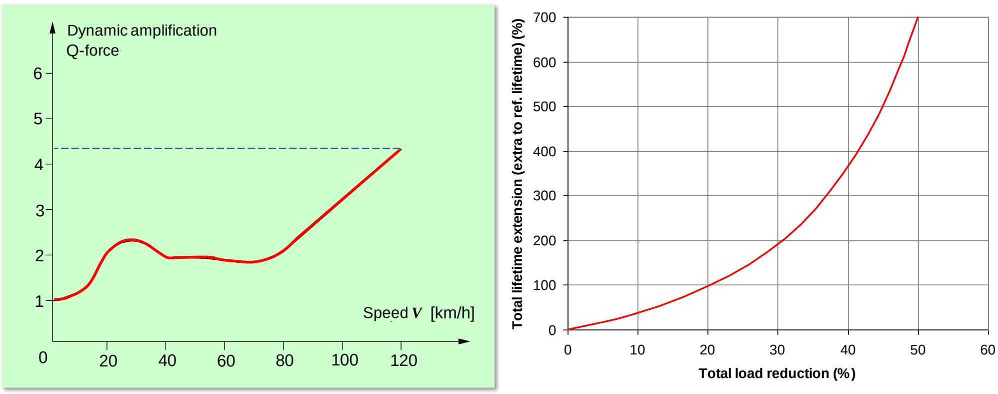


Figure 19: Left - dynamic amplification of the vertical wheel/rail force during the passage over a bad-geometry weld; right - relationship between the percentage of W/R load reduction (due to improved welds' geometry) and the welds' service lives

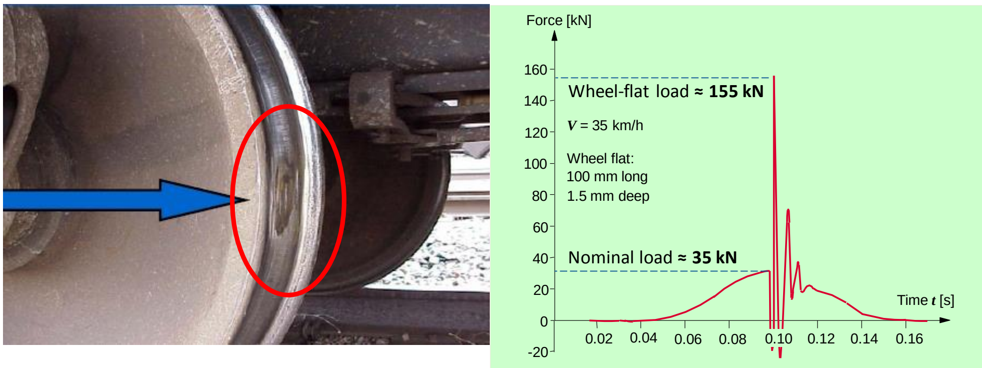


Figure 20: Left – a wheel-flat; right – Impact of wheel flat on the force between rail and sleeper

In terms of the importance of weld-geometry-quality, in terms of the level of dynamic forces it creates, it will be mentioned here only that there is a strongly non-linear relationship between the percentage of wheel/rail load reduction (due to improved weld geometry) and the lifetime of welds, going to the power of 3. This effectively means that by improving weld geometry by 50%, life of a weld can be extended by 700%, i.e. 8 times, Figure 19, i.e.:

$$\frac{LifeTime_{New}}{LifeTime_{Reference}} = \left(\frac{F_{Reference}}{F_{New}}\right)^3 \tag{2-2}$$

where:

$$F_{wheel} = F_{wheel,static} + F_{wheel,dynamic} \tag{2-3}$$

3. MEASURING OF VEHICLE/TRACK DYNAMIC FORCES, TRACK GEOMETRY AND M&R PLANNING

From all the elaborations provided in the previous chapter, it is clear that in order to manage M&R in an optimal manner, key and keen attention must be addressed to the dynamic forces acting at the vehicle/track (V/T), i.e. wheel/rail (W/R) interface, as they represent the key trigger and generator of the entire deterioration process of all Track Components (TC). For that reason, in the sense of appropriate assessment of TC condition and definition of the optimal regime of consequential M&R activities, it is of crucial importance to be able to measure (directly, or at least indirectly) the V/T dynamic forces, which are, on the other hand, a direct consequence of the track and rail geometry, but also the core generator of their deterioration. In that sense, ***Vehicle/Track Interaction Monitor*** (V/TIM) represents one of the latest systems aimed at the measurement of TC quality, which, by the use of accelerometers, measures the dynamic vehicle/track interaction. This part of the paper explains a possibility of measuring dynamic forces and using them for the M&R optimization.

Unlike traditional measurement systems, which are primarily based on TG measurements, V/TIM is based on an entirely different concept. The tendency of increasing trains speeds and axle loads has contributed to the fact that the accelerations, which occur as a result of V/T interaction, are gaining in importance. Therefore, the focus is primarily placed on local defects (shelling, rail corrugation, battered joints, bad-quality welds, loose/missing bolts, switches and crossing (S&C) defects), i.e. exactly those mentioned at the end of the previous chapter. These defects, which are often overlooked by railroad personnel, in combination with the ever-present desire of increasing speeds and loads, could produce extremely high impact forces, whose appearance during the passage of a large number of vehicles, could lead to accelerated deterioration of all TC, with unforeseeable consequences,

Figure *21*, [13].

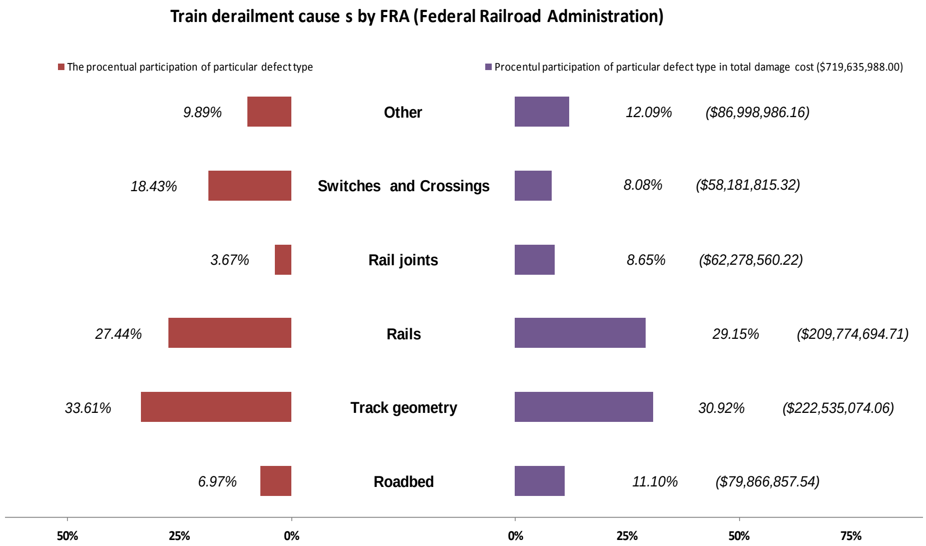


Figure 21: Relative contribution of particular defect types in the total number of railroad accidents in the USA (period 01.01.2010. - 12.31.2015) [13]

As it is often and explicitly stated, impact forces that occur as a result of local irregularities in the wheel/rail contact are often the main cause of track deterioration [14]. On the other hand, these defects precisely indicate the "target group", or more specifically the “origin” of the motivation for the creation and utilization of the V/TIM system, the analysis of whose data will be described in the remaining part of this paper, aiming at pointing out a convenient and cost-effective manner of permanently monitoring and thus controlling V/T dynamic forces, thus both preventing significant damages to all TC and enabling optimal M&R planning.

For decades TG is regularly measured by the specific track recording vehicles (TRV). However, their high costs (millions of €) have always prevented the railways from

having a numerous fleet of them. For this reason, it is a common practice that the fleet is dimensioned to measure the railway network’s condition at least twice a year, usually in spring and autumn, while for the high-speed lines (HSL) and heavy-haul (HH) lines measurements are normally taken more frequently (e.g. usually once a week in Europe for HSL). In recent years, again due to the increasing speeds and axle-loads, a large number of railways came to the conclusion that this measurement frequency is insufficient, because the time between measurements is too long and because of the mutually accelerating negative effects of geometric imperfections and dynamic forces, allowing rapid increase of geometrical irregularities with potentially unforeseeable consequences, and which could thus remain undetected in the meantime between consecutive TRV measurements. Therefore, they sought solutions that would provide more frequent measurements, but without extreme investments and timetable interruptions. Even with the acquisition of expensive TRVs and increasing frequency of their use, the problem with compromising timetable would still remain. The solution was found in the use of so-called "unattended" measuring systems that can be installed on all (revenue) vehicles (locomotives, passenger and freight wagons), and not only on the recording vehicles, and which could thus constantly measure track condition and send collected data automatically to the central database over a wireless connection, wherever the vehicle was travelling. Also, cheaper versions of measurement systems are selected for this purpose, like V/TIM, that only measure vertical and lateral accelerations, which due to the lower price, can be installed on a larger number of vehicles and thereby increase the measurement frequency and network coverage. For example, in North America only, there are currently 370+ of these systems, measuring 70,000+ km daily and sending collected data to the central database.
The primary objective for the use of this relatively simple and inexpensive system is to measure the abovementioned values and simply identify the locations on the network where there are elevated levels of acceleration, which produce increased values of dynamic forces, and which with its rapid growth over time can lead to serious and costly damage of infrastructure and rolling stock. Unlike traditional TG measurements, in this case it is not intended to collect absolutely precise TG values, but to survey the entire rail network, which usually extends over a large number of kilometers, in an objective, simple and inexpensive way, in order to come up with the 10% or 20% of the most critical locations which deserve the highest priority. It is important to understand, that ultimately, there is no significant difference between applying V/TIM system and traditional TG monitoring system in that sense, because using the latter would indeed lead to a bit more accurate measurements, with possibly more accurately defined relative positions for each of them on priority-list, but in the end, in both cases the railway would apply appropriate M&R measures on a certain percentage of those most critical locations, i.e. 10% or 20%, as the capacities of the machinery and man-power responsible for track M&R on most railways are usually exactly tailored so that their annual "output" matches the 10, or a maximum of 20%, of the worst locations on the network (see also Figure 12), and which would, in both cases, ultimately be practically the same. Therefore, the obtained results would be the same – i.e. the same 10% (or 20%) of the most critical locations on network, with far fewer resources and more importantly far greater measurement frequency and consequential network coverage, which further gives a significantly lower risk of problematic spots remaining unidentified.

In addition to this, secondary goal of V/TIM system application, besides identifying problematic locations, is to define appropriate track M&R activities based on the analyses conducted on measurement data, which will adequately improve track condition and prevent its further deterioration, as well as its further detrimental impacts on rolling stock degradation.
For this reason, expected results of the V/TIM application and analysis of obtained measurement data simply include:

- Obtaining the list and exact locations of places on the railway network with track/rail geometry problems and increased levels of dynamical forces at the wheel/rail contact
- Defining the urgency levels of the identified problematic locations
- Proposing 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.

The above goals have prompted a very interesting research that was performed by the second author of this paper within his Master thesis [19] at the Department of Civil Engineering of the Faculty of Technical Sciences, University of Novi Sad. However, before explaining the key results of this research, brief description of the V/TIM system will be provided, to further facilitate its better understanding and its utilization for M&R planning purposes.

3.1 VEHICLE/TRACK INTERACTION MONITOR SYSTEM

Vehicle/Track Interaction Monitors (V/TIM) 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 in the late 1990s. These systems use an array of sensors to accurately measure the dynamic response of a rail vehicle to the track. The standard V/TIM onboard monitoring units for both passenger and locomotive equipment consist of a main enclosure which houses all of the electronics, five (5) accelerometers and an externally mounted dual-purpose antenna for GPS and cellular communications [15]-[17].

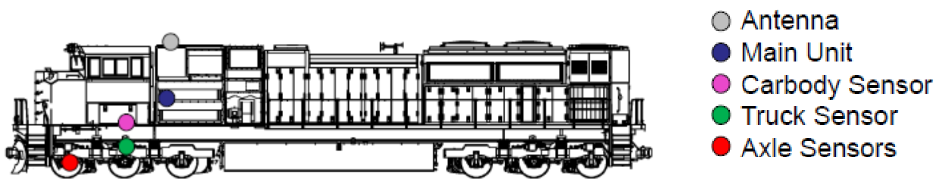


Figure 22: V/TI Monitor Component Layout [15]

Each accelerometer measures continuously and when a value exceeds a predetermined threshold, defined by a responsible authority, an exception is created which 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 is evaluated for severity based on its value. There are three severity levels:

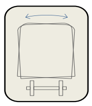
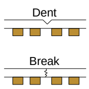
- "*Urgent*"– which are typically inspected within 24 hours.
- "*Near Urgent*"– which are inspected within 7 days
- "*Priority*"– which are typically inspected within 30 days or are used in long-term M&R planning

One channel of V/TIM system and one field in a database is reserved for each accelerometer, where everyone measures a specific exception type:

1. *CarBody Vertical* **– CBV acceleration**
2. ***CarBody Lateral*** – CBL acceleration
3. ***Truck Lateral*** – TRL acceleration
4. ***Axle vertical impact load*** – AXV1, AXV2 (axle acceleration individually measured for left and right side of axle box, which based on a specific real-time data processing algorithm and knowable axle loads and unspung masses, calculates the dynamic forces at wheel/rail contact)
5. ***Mid–chord Offset*** – MCO1, MCO2 track vertical geometry for both the left and right rail

A summary of the V/TIM exception types and their potential causes can be found in [16],[18], Table 3.

Table 3: V/TI Monitor Exception Types Summary [16]

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 and AXV2 Axle Vertical Impact		• Look for broken rail, broken joint, broken frog, battered joint, engine burn, crushed rail head, loose/missing bolts.	
MCO1 and MCO2 10-Foot Mid-Chord Offset Vertical Profile		• Look for mud and pumping conditions. • Look for pumping joints	

The key information is that a carbody sensor measures vertical and lateral acceleration 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” accelerations within one second. These exception types are typically associated with track profile and alignment conditions respectively.
A truck (bogie) sensor measures lateral acceleration of the truck frame. The Truck Lateral (TRL) exceptions are the root-mean squared (RMS) accelerations. 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 acceleration, static wheel load, and unsprung mass value.

3.2 VEHICLE TRACK INTERACTION - TRACK QUALITY INDEX ("VTI-TQI") SOFTWARE

In North America, for example, a large number of V/TIM systems produce a huge amount of data (especially if observed over a long period of time), which may be challenging to process without appropriate software. This kind of software becomes especially necessary in case the knowledge of the long-term behavior of the measured parameters was required, e.g. in terms of defining trends, which is a basic prerequisite for condition-based management of M&R works. Since over 3 million V/TIM defects recorded over a period of more than 3 years have been processed within the Master thesis research described in this paper, for the purpose of conducting these analyses over such a large amount of data, the second author of this paper developed a special software tool called “*Vehicle Track Interaction-Track Quality Index*” (VTI-TQI) [19][17]. The database of the VTI-TQI software hosted the earlier-mentioned cca. 3 million records that are related to the total of 25 considered subdivisions (network regions) of an Australian railway, spreading over 1,700 miles (cca. 3,000km).
Within the VTI-TQI software, also deterioration model(s) were developed, allowing automatic calculation of trends and setting of thresholds for certain urgent levels defined by the relevant railway staff, Figure 23 upper right, and Figure 24. Following the basic principles of trend-type selection, the change of values of each of the parameters in function of time has been monitored. In so doing, it was noted that linear trend in most cases approximated parameters behavior very well, also Figure 23 upper right, i.e. their growth over time.

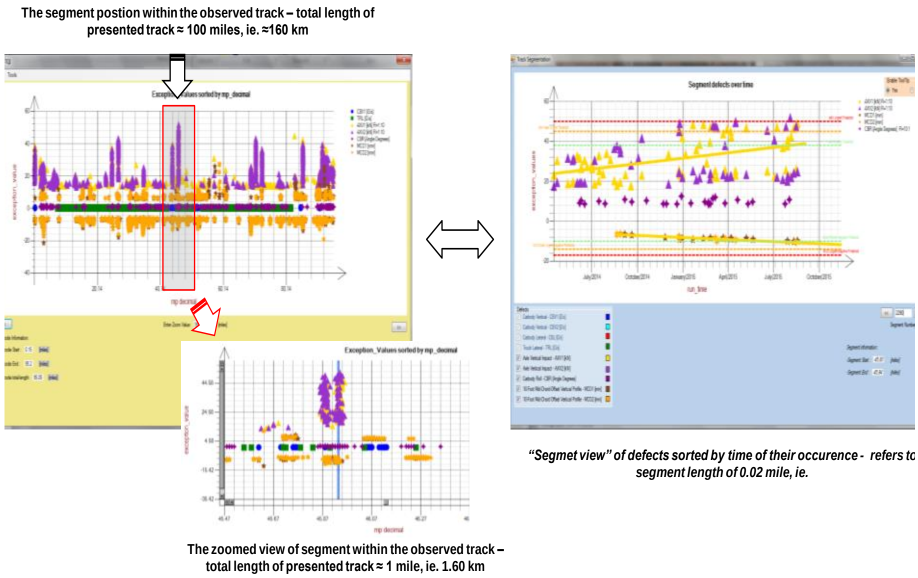


Figure 23: Visualization of data within VTI-TQI software [19]

Although this approach in most situations managed to establish connection between the given data in a correct way, it is important to state that certain deviations that imply much faster changes in defect values between consecutive measurements were also observed. This certainly implies a form of a non-linear trend, and demands extra attention and caution, Figure 24.

Situation shown in Figure 24, where a rapid increase of AXV and MCO defects can be observed, precisely represents the advantages of the V/TI Monitor system and the wealth of measurement data it produces. As it can be seen from Figure 24, impact forces have in a really short period of time (July- November 2013) grown from the value that was below the level of priority maintenance to the value that exceeded the limit of emergency maintenance. Although not a large number of segments with similar behavior could be observed during the performed analyses, it is necessary to keep in mind that such situations are clearly possible, which certainly require special treatment by a competent staff in charge of railway infrastructure M&R.

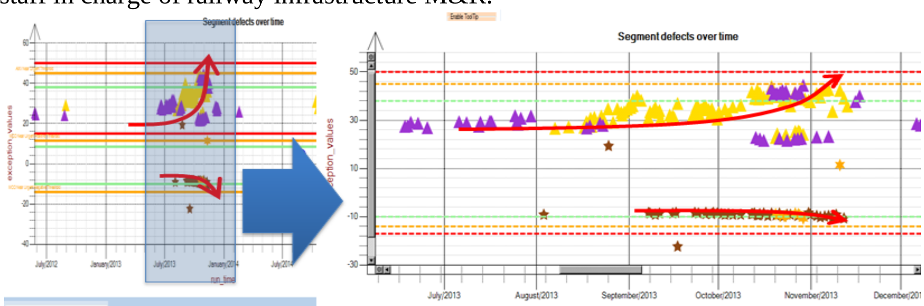


Figure 24: Extremely high growth of impact forces in a very short period of time of about 4 months [19]

The automatic analysis algorithm is conceptually identical to the previously described manual analysis, where based on discovered defects on a given railway segment, a linear trend is generated, during observed period of time, based on which the moment when this trend will reach the appropriate threshold value (defined by the railway on which network the V/TI Monitor measurements took place) is calculated.

The analysis revealed a number of situations that demanded further and more detailed considerations. For the purposes of this article, only those deemed most representative will be discussed, focusing primarily on those defects which are of greatest interest for railways – i.e. the dynamic impact forces. These forces, marked as AXV defects (vertical axle accelerations and associated dynamic forces at the vehicle/track contact), within V/TI Monitor system, and consequently implemented MCO defects (vertical track geometry, with the chord length of 3m), represent 'absolute measurements', which are independent of the characteristic of the vehicle itself, e.g. its primary and secondary suspension. For that reason, the most attention was aimed at this relationship. Specifically, AXV defects relate primarily to unsprung masses, and therefore indicate local, isolated locations and short-wave rail 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, in fact, AXV accelerations defects, AXV W/R dynamic forces defects and the MCO defects all originate from the same original AXV signal, only AXV defects are identified by processing AXV signal as peak-to-peak, MCO as double-integrated AXV signal, whereas for the calculation of AXV dynamic forces defects maximum downward zero-to-peak values were used.

For that reason, for example, parts of track which are characterized by small subgrade irregularities, can cause the occurrence of MCO defects, but the AXV defects (i.e. the AXV accelerations that exceed the threshold values) might not necessarily be generated. As opposed to that, vehicle's 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 effectively small deviations in the vertical track geometry (TG), Table 3. However, if such an AXV defect would remain long enough in a track, then, due to the rapid accumulation of (steadily increasing) dynamic forces, at a later stage it might be realistic to expected that this problem would spread and get worse, so that it would eventually manifest itself also through vertical TG irregularities, i.e. MCO defects, which will occur as a direct result. The situation displayed in
Figure *25* directly demonstrates this mechanism.

The deterioration of the segment shown in
Figure *25* can be divided into three periods. First, marked with the green line, clearly indicates the increasing trend of AXV defects (purple triangles). After a while (about 6 months after the start of the analyzed period), they reach the limit of the priority maintenance (upper horizontal dashed line) (this moment is marked with the vertical red line). Very interestingly this also exactly coincided with the moment when the given segment for the first time registered vertical TG irregularities, i.e. MCO defects (orange stars in the lower part of the chart, with yellow trend)(*here it is perhaps also necessary to clarify that of primarily importance for the V/TIM defects are the maximum values in*

absolute terms, so the sign has no importance here; that is why all AXV values are shown with the positive sign, while the MCO values are shown with the negative sign – merely for the representation clarity reasons). This is effectively also the moment when the new (second) period starts, that is evidently characterized by the increase in both AXV and MCO defects.

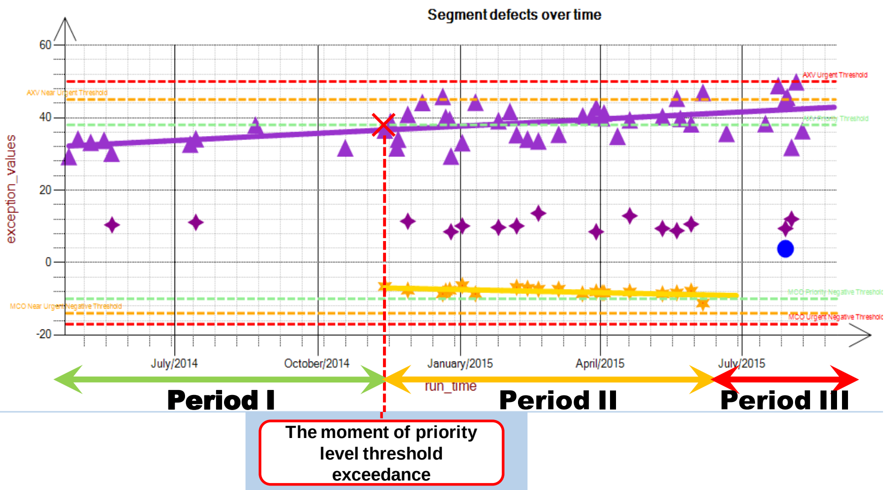


Figure 25: The influence of dynamic forces on track vertical geometry deterioration [19]

However, in this period, also the CBR defects (dark purple diamonds) indicating lateral tilting of the vehicle body start emerging. Analyzing the segments similar to the one displayed in
Figure *25*, identical mechanism of CBR defect appearance could also be recognized. It can therefore be concluded that it in situations with synchronized appearance of AXV and MCO defects on one side of the track, there is a large chance that the CBR defects would also consequently occur. This is actually a very logical sequence of events, which occurs as a result of different W/R contact heights (of a sufficiently large scale) between left and right side of the track, i.e. left and right rail.
A significant number of interesting situations identified during the analysis, referred to the Switches & Crossings units (S&C), which with their own characteristics (structural & geometrical) often initiate the occurrence of various V/TIM defects. At the same time, S&C exactly represent the TC 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 development of the AXV defects, where their values often produced the exceedance of "urgent level" thresholds. One of such regions, where the importance of these locations was clearly noticeable, is presented on Figure 26.
At the beginning of consideration of this region, it is important to emphasize that Figure 26 refers to the defects sorted by stationage of their occurrence, which in fact represents the abovementioned "manual analysis" that could be perform very quickly and easily using the "Track View" of the VTI-TQI software.

From Figure 26 it is easy to notice that in the whole section, spreading over 100 miles (~ 160km), only a few groups of defects are clearly highlighted, i.e. a few distinct locations with a large defect grouping. With further analysis of this section, based on abovementioned "Track View", the need for closer checking of these locations via Google Earth appeared. Namely, besides the stationage, all recorded V/TIM defects possess geographical coordinates as well, obtained by the GPS device, which is an integral part of the V/TIM system. By checking those locations on the map, it became clear that they were associated with S&C, Figure 27-Figure 28. Generally, such "peaks" within the "Track View", are typical for S&C locations, road crossings, bridges etc., which have, as it is already stated, the strongest influence on the M&R costs.

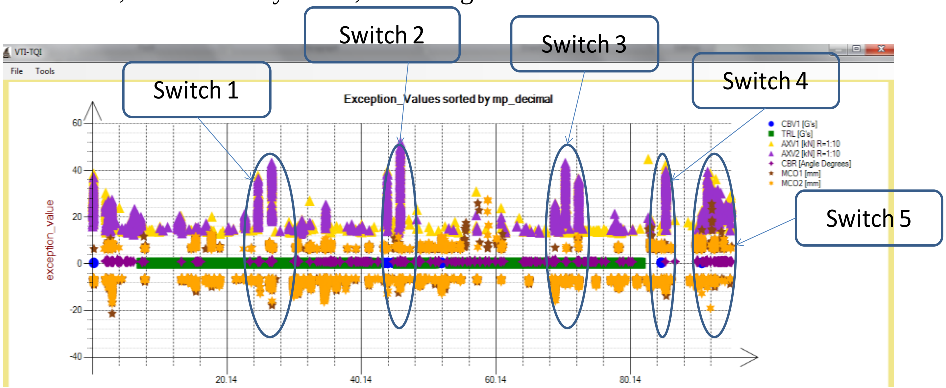


Figure 26: A characteristic situation from one of the investigated network regions [19]

Exactly because of that, the capabilities of V/TIM system are of great importance and benefit, as they enable railway infrastructure managers to identify and quantify the relative deterioration of rail and track geometry on such locations and consequential increase of the dynamic forces, which could directly relate to the respective M&R costs and finally enable their significant reduction. In the following figures (Figure 27-Figure 28), 2 out of 5 marked S&C from the Figure 11 will be presented individually, with a short description of respective locations, and unlike 100 miles of track length shown in Figure 26, segments with a specific length of 0.02 miles, i.e. ~32m, will be presented, which accurately correspond to each S&C position.

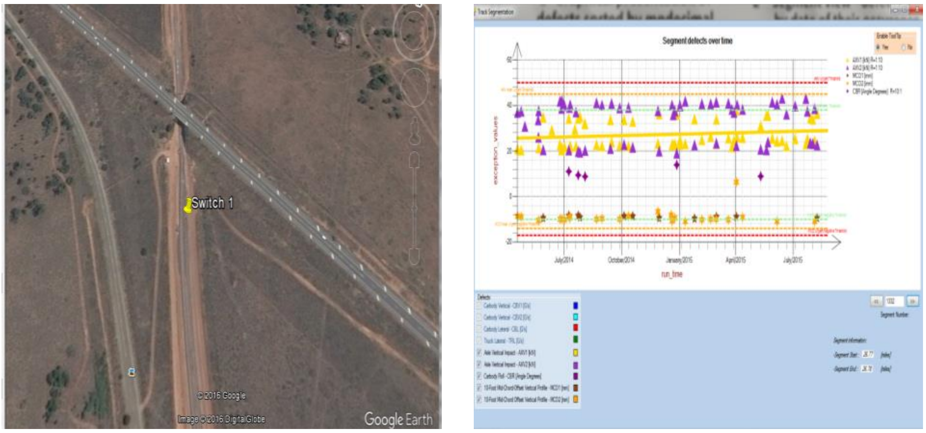


Figure 27: Switch 1 - Segment view [19]

As can be seen on the Figure 27, the 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 27. Because of their synchronized appearance since the measurements began, here we cannot talk about MCO defects development mechanism caused by AXV forces, but it is obvious that, unlike the MCO defects, the AXV defects are characterized by a much steeper (faster growing) trend.

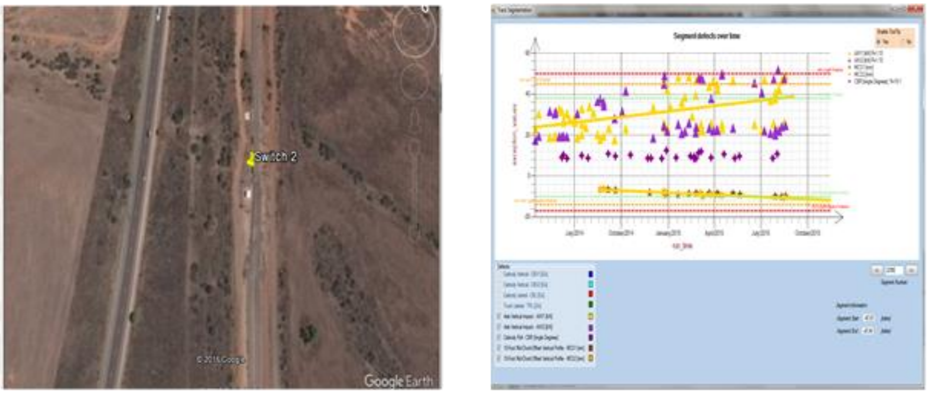


Figure 28: Switch 2 - segment view [19]

Unlike the segment shown in Figure 27, the S&C unit shown in Figure 28 has a considerably faster growth of both AXV and MCO defects. It is obvious, however, that vertical TG irregularities are certainly developed by the influence of AXV dynamic forces, which is conceptually identical to the situation shown in
Figure *25* from the beginning of this chapter.
Situations regarding the S&C units No. 3 & 4 are similar to the one shown in Figure 28, except that AXV defects trend line has a much slower change rate, for which reason they are omitted here.

As can be seen in Figure 27-Figure 28, these S&C units are in most cases characterized by quite a similar degradation mechanism. Impact forces generated in the W/R contact and irregularities within the vertical TG are dominant as in previously shown situations. The situation shown in Figure 29 is characterized by two consecutive crossings.

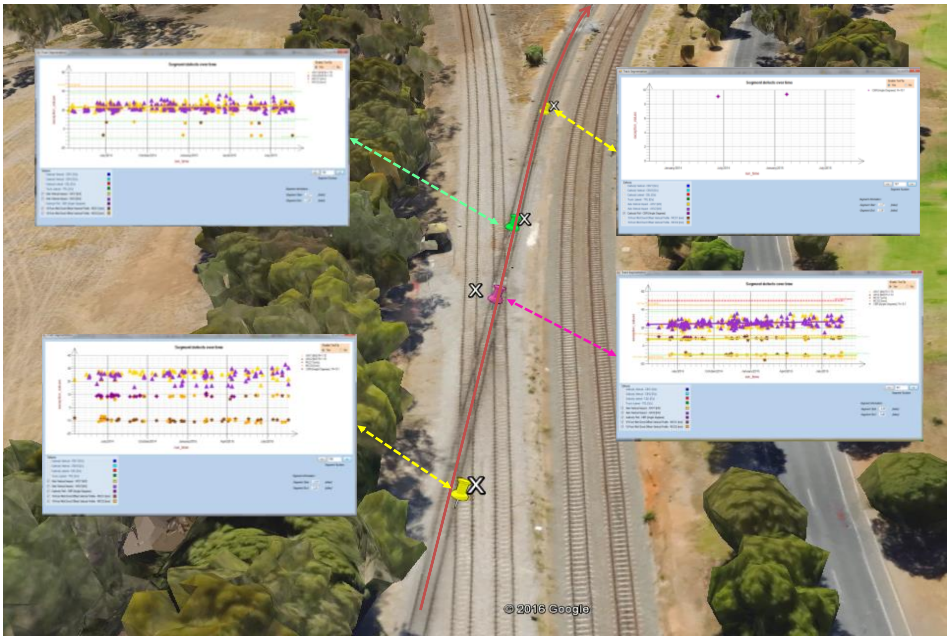


Figure 29: Defects generated at two consecutive crossings [19]

Related to the previously discussed situations, which were primarily related to S&C units, it is free to say that this situation is also quite similar. It is obvious that AXV forces have continued with their dominance. After a vehicle has passed over this (for it very unpleasant location), the situation completely changed, which is proven by the number of registered defects on the first segment to follow, i.e. the segment shown in the top-right corner of the Figure 29 (almost "empty" segment, i.e. segment with no V/TIM defects), and which was preceded by a series of segments related to the presented crossings.

Thus, in the case of the previously described S&C, it is possible to discuss a stable mechanism of defects appearance. Such places, due to their geometric and structural characteristics, obviously represent the origin of impact forces development. It is therefore of significant importance to be able to predict and quantify the severity of those irregularities, which is enabled by the use of the V/TIM system and VTI-TQI software. Also, during the analysis it could be noticed that “urgent level” exceedance usually occurs on these locations. In terms of that, the intention is to devote a special attention to these locations in the further research work.

4. CONCLUSIONS

Railways and countries in the WB region have over the past decades largely and unjustifiably focused primarily on (re)construction of railway infrastructure, while neglecting its Maintenance & Renewal (M&R) considerably, which has also been recognized by the EU which is mostly participating in these investments. For that reason, both the non-reconstructed infrastructure, as well as the newly-(re)constructed one, have deteriorated considerably. Considering that M&R represents the majority of the infrastructure Life Cycle Costs (LCC), this has caused significant losses to all the stakeholders in the region.

On the other hand, should M&R of the railway infrastructure be performed in the proper manner, acute attention must be given to the dynamic forces at the Wheel/Rail, i.e. Vehicle/Track contact, as well as track and rail geometric irregularities (which have mutually accelerating influence with the dynamic forces), as dynamic forces are long recognized as the main cause of the deterioration of all track components. For that reason, of key importance is the ability to regularly measure these dynamic forces (directly or at least indirectly, i.e. via accelerations), and thus monitor and keep them under control, and consequently the track deterioration, and use them to optimize M&R activities.

Respecting this imperative, an important research was performed at the Department of Civil Engineering of the Faculty of Technical Sciences at the University in Novi Sad within a Master thesis, where over 3 million vehicle/track interaction measurements recorded at a railway in Australia by the latest-technology Vehicle/Track Interaction Monitor (V/TIM) system over the period of more than 3 years have been analyzed and a dedicated software tool “VTI-TQI” developed, which revealed numerous important and interesting cases of deterioration.

Huge amounts of data collected daily by the V/TIM systems, provide unequivocally a whole new dimension to the problem with which the competent engineers in charge of railway infrastructure maintenance have to deal. If a software tool such as the VTI-TQI would also be applied alongside with the necessary knowledge experts must own in order to interpret, show and understand the data obtained with this system properly, it would be possible to achieve the situation where it could be said with certainty that we are “*one step ahead of the track deterioration process*”, as it would be possible to predict the time of reaching and exceeding certain maintenance levels for all V/TIM parameters or for any combination of them.

For modern railways, which 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 predicted M&R work becomes very important, and can save significant costs. This is exactly what V/TIM with the support of a tool like VTI-TQI can secure. 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. Regarding that, the process of deciding when and where the needed corrections will be executed is under the supervision of the staff in charge of managing the given railway infrastructure. V/TIM and software tools like VTI-TQI only aim to offer significant support and help in this sense.

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DINAMIČKE SILE NA KONTAKTU TOČKA I ŠINE KAO GENERATOR PROPADANJA KOLOSEKA I FOKALNA TAČKA ODRŽAVANJA

Apstrakt: *Iako u toku životnog veka infrastrukturnih objekata na održavanje i remont (Maintenance & Renewal – M&R) otpada najveći deo troškova, većina zemalja i železnica u regionu Zapadnog Balkana (West Balkans - WB), već godinama većinu pažnje posvećuje izgradnji, ili eventualno rekonstrukciji infrastrukture, dok se M&R u značajnoj meri zanemaruje. Jedan od ključnih razloga za to je činjenica da je održavanje dugotrajan proces, koji kod infrastrukturnih objekata traje više decenija, što je predugo (a samim tim i neinteresantno) s aspekta radnog veka većine glavnih aktera, bilo sa strane banaka koje finansiraju ove aktivnosti, bilo s aspekta institucija, kao što su železnice koje ih izvode, ili bar njima upravljaju, bilo, na kraju, s aspekta političara koji o njima odlučuju. Iz tog razloga, pomenutim akterima su daleko atraktivniji projekti izgradnje, ili eventualno rekonstrukcije, koji traju daleko kraće, a finansijski su intenzivni, što sa aspekta pomenutih aktera znači da se mogu zaokružiti u vremenskom roku koji odgovara njihovom bivanju na respektivnim funkcijama. Međutim, sve ove aktivnosti, faktički plaćaju građani, a takođe i koriste infrastrukturu, te bi stoga bilo u njihovom interesu da infrastruktura bude u optimalnom stanju, tj. da se njom pravilno upravlja, što drugim rečima znači da se održava. S druge strane, ako se želi upravljati M&R na pravilan način, ključna pažnja se mora posvetiti dinamičkim silama na kontaktu točka i šine, jer one predstavljaju osnovni generator čitavog prosa propadanja svih elemenata koloseka (Track Components - TC). Iz tog razloga, u smislu pravilne ocene stanja TC i definisanja optimalnog režima M&R aktivnosti, od suštinskog je značaja mogućnost merenja dinamičkih sila (direktno, ili bar indirektno), a koje su direktna posledica kvaliteta geometrije koloseka i šine, ali istovremeno, i osnovni generator njihovog propadanja. U tom smislu, Vehicle/Track Interaction Monitor (V/TIM) predstavlja jedan od najnovijih sistema za merenje kvaliteta TC, koji uz pomoć akcelerometara meri i opisuje dinamičko ponašanje vozila u interakciji sa kolosekom. Ovaj članak objašnjava značaj M&R aktivnosti, uticaj dinamičkih sila na propadanje TC, i mogućnost njihovog merenja i upotrebu mernih podataka za optimizaciju M&R.*

Ključne reči: *železnička infrastruktura; merenje i analiza stanja; geometrija koloseka; ubrzanja osovinskog sloga, osovinskog postolja i sanduka kola; dinamičke sile na kontaktu točka i šine; modeliranje propadanja stanja; planiranje radova na održavanju i remontu*