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Track Gauge Degradation Modelling on Small Urban Rail Networks: Zagreb Tram System Case Study

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Abstract

Track gauge is the most significant tram track geometry parameter. Its degradation, which manifests as gradual increase of gauge deviation from prescribed values during track exploitation, causes poor ride quality, reduces safety and triggers most of the maintenance activities. To optimize tram track maintenance procedures, it is necessary to increase the proportion of preventive maintenance at the expense of corrective maintenance. This requires creation of physical model of track degradation. Conducted survey of conventional track degradation models showed that, in order to quantify the influence of track design, construction and exploitation characteristics on gauge degradation, it is most favourable to adopt the mechanistic-empirical modelling approach. Zagreb high-capacity tram network presents an optimal testing ground for exploration of the possibilities for tram track gauge degradation model development. Analysis of modelling results gave new, practical insights about the effects of tram track design and construction elements and exploitation characteristics on gauge degradation. These models represent the first step towards predictive maintenance system establishment on Zagreb tram tracks.

Keywords: tram track, gauge degradation, influential factors, mechanistic-empirical model, segmented database, regression analysis

1. Introduction

In the past few decades, a growing number of cities are turning again to the tram as an efficient, adaptable and environmentally friendly mean of urban public transport. Numerous planned projects for renovation of existing, revitalization of historical and construction of new tram lines prompted the International Association of Public Transport (UITP) to, referring to the experience

of the rail intercity systems, warn about the following fact. The introduction of modern tram systems design solutions based on new technologies and construction materials in the long run will not yield the desired effect of establishing a sustainable urban transport system. This can only be achieved by the simultaneous development of modern tram infrastructure management system based on networking and mutual complementarity of design and maintenance activities in integrated tram track maintenance planning model [1].

Rail system management is a complex interdisciplinary process that includes managing, operation and maintenance of rail infrastructure and rolling stock, and organization of rail transportation. The emphasis that is nowadays placed on the necessity of reducing the total costs of rail systems requires optimizing each management step, including the track maintenance. Since the high implementation costs initiate significant investments in systems maintenance, primary objective for rail infrastructure management is to ensure a safe and comfortable ride with as long as possible system exploitation without any maintenance.

As rail vehicles of different weights run on tracks with various speeds, a wide range of stresses occur in the elements of track superstructure. They are a consequence of vehicle loading and the dynamic forces such as centrifugal, braking, acceleration, hunting oscillation, vertical inertia and vibration forces caused by irregularities in the rail and wheel contact surface. The consequences of these, usually very large, forces on track elements are numerous. Formation of rolling contact fatigue cracks, plastic flow deformations, shelling and uneven wear of rails, failure of rail fastening elements and changes in track geometry are the main adverse phenomena during track exploitation. They need to be adequately recognized and addressed by carrying out appropriate maintenance work.

The overall process of railway track maintenance includes the two basic types of activities—inspection and intervention.

Inspections are performed in order to acquire information needed for defining the maintenance schedule. These information can be gathered manually (with the use of analog and digital measuring instruments, usually when small sections of track are to be inspected) and automatically (with the use of inspection car) [2].

Interventions comprise of corrective and preventive track maintenance. *Corrective maintenance* is carried out in the case of detecting defects on the track [3]. *Deferred corrective maintenance* is applied to small defects that do not require immediate action, but they are rather grouped and treated subsequently. *Immediate corrective maintenance* is applied in case of major track defects that require immediate intervention to ensure traffic safety [4, 5]. *Preventive maintenance* activities are performed to maintain correct and reliable operation of the system. Their goal is to prevent and eliminate the cause of the defect. They can be *planned* under constant sustainability (predefined date) or *predictive* according to the system condition. They include monitoring of the tracks parameters and elements condition and behaviour, and development of methods, techniques, and equipment for the systematic system monitoring. [3].

To optimize track maintenance procedures, it is necessary to increase the proportion of preventive maintenance at the expense of corrective maintenance. This can be achieved by creation of a rail track *maintenance planning models*.

Section 2 gives an overview of general structure, classification and examples of several models developed for the conventional track systems. Section 3 gives an overview of the physical tram track gauge degradation model creation—from the influential factors and modelling approach identification to the assessment of the model representativeness. Section 4 presents results of model analysis in the form of the observed tram track gauge degradation influential factors ranking by the level of their impact on the degradation rate. Section 5 gives concluding remarks and recommendations for future work.

2. Track system maintenance planning models

Maintenance planning model is a decision-making support tool for systems maintenance management. It is used to assess the impact of the maintenance work implementation on the system service life. A comprehensive maintenance planning model consists of one or more *physical models*, integrated into *economic model* for planned maintenance activities costs estimation. Physical models can be used to describe exploitation behaviour of systems individual components or system as a whole. Activities justified by maintenance planning model need to be consolidated into the strategic maintenance plan taking into account time constraints and available resources for their implementation.

Creating a physical model to determine the exploitation life of the system's individual element, or the system as a whole, is the first step of establishing a modern approach to maintenance planning. This model can be established as a *failure* or *degradation model*, depending on which element and the type of maintenance work it describes.

Failure is defined as the point in time after which it is necessary to replace the observed element. It can be interpreted as actual physical failure or as economic failure that is a point in time after which is economically viable to replace the element. To establish a failure model, it is necessary to have information on the exploitation conditions in which the final element failure will occur. This information can be collected by long-term field observations or laboratory tests, by subjecting the elements to accelerated loads that may arise during the system operation.

Degradation is defined as gradual reduction of the observed elements quality, until it loses the properties required for whole systems quality. Since service life of rail systems is measured in decades, developed physical models of their exploitation behaviour rely on degradation monitoring approach. Mathematical models of track degradation estimate loss of tracks or its individual elements quality. If it is too low to ensure prescribed traffic safety and comfort, model suggests implementation of certain maintenance activities.

2.1. Rail track degradation models classification

Systematic research of rail track degradation began during the 1980s and 1990s of the past century, when the availability of data on tracks exploitation behaviour, especially in a digital format suitable for detailed analysis, was very modest. For this reason, researches mostly resulted in simple physical models of superstructure elements (rails, fastenings, sleepers and ballast) degradation [6].

A literature review showed that more recent studies, although numerous, are exclusively limited to standard 1435 mm gauge ballasted tracks, used for intercity traffic. To narrow gauge tram tracks, as a special group of slab track structures, is generally devoted less attention than to conventional ballasted railway tracks. Also, the existing railway regulations (International Union of Railways (UIC), Verband Deutscher Verkehrsunternehmen Oberbau-Richtlinien, European Committee for Standardization (CEN)) in general do not consider tram tracks [7]. Because of that, the following overview of degradation models and their classification is based exclusively on data for conventional ballasted intercity rail track systems.

Physical models of track degradation can be classified given the object of modelling, level of detail of the model and the methods of track data collection and processing during the model development.

Given the *object of modelling*, there are models of track geometry degradation and models of permanent way elements degradation (rails, sleepers, fastenings and ballast) [8].

Modelling the *track geometry* degradation refers almost exclusively to the modelling of track vertical geometry degradation, which occurs during exploitation due to settling of ballast material below the sleepers. There are two reasons for this. Geometry degradation rate is larger in the vertical than in the horizontal track plane [9]. Therefore, the vertical geometry is more relevant for the maintenance periodicity determination. The second reason is that modelling of the horizontal track geometry is substantially more complex task because it can degrade in either or both directions [10].

Most *permanent way elements* degradation models deal with the problem of rail wear. They usually state that rail wear at a given point of the track is proportional to the energy loss due to rail-wheel friction, and this energy loss is proportional to the hauled tonnage [11].

Given the *level of detail* and application of results, the analyses carried out during track degradation models creation can be divided into two basic groups.

Micro-analyses result in detailed *microscopic* track degradation models. These models are dealing with the forces on the individual permanent way elements and are usually based on engineering judgment or empirical evidence. Micro-analysis is performed through the analysis of the geometric parameters graphical representations and is used for occasional interventions with the purpose of eliminating defects on tracks.

Macro-analyses involve track data statistical analysis in order to determine the patterns in track behaviour during exploitation. They result in *macroscopic* track degradation models. These models, by inferential or descriptive statistical analysis of the measured track data, establish a correlation between the track degradation rate, exploitation conditions (exploitation intensity, speed and vehicle type) and used track superstructure elements. They are commonly used for cost-benefit analysis of rail infrastructure management strategies and contribute to defining the general policy of funds allocation and implementation of track maintenance [12].

2.2. Review of track degradation models

It is in the nature of the railway industry to hinder publicly publishing a detailed description of the track exploitation behaviour modelling procedures. Therefore, this review shows only a number of model examples (**Figure 1**) listed in the publicly available literature. Reviewed researches on conventional track structures degradation were carried out by the individual national railway administrations as well as universities and other research institutions. The leading institutions in this research area are Transportation Technology Center of Association of American Railroads (TTCI, Colorado), European Rail Research Institute (ERRI, the Netherlands), Queensland Rail (QR, Australia), Railway Technical Research Institute (RTRI, Japan) and Lueå Railway Research Centre (JVTC, Sweden).

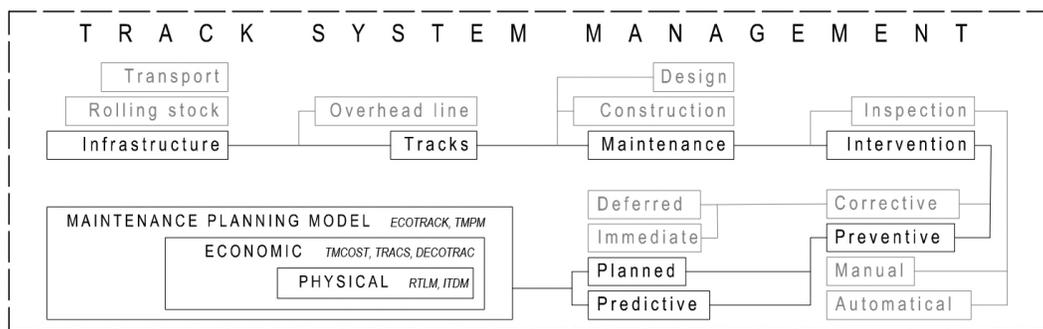


Figure 1. Maintenance models within rail infrastructure management process.

TMCOST—Track Maintenance Cost Model is a result of cooperation between TTCI and Massachusetts Institute of Technology (MIT). It consists of a series of separate submodels for rail, sleeper and ballast degradation assessment as a function of traffic load. It calculates maintenance costs by assessing the lifetime of individual track component and maintenance costs needed for achieving initial track quality [13].

RTLTM—Railroad Track Life Cycle Model is developed by the TTCI. It consists of a series of separate submodels for track vertical geometry degradation based on type, thickness and condition of ballast material, sleeper type and spacing, rail type, subgrade bearing capacity, designed vertical geometry, axle load and traffic volume [10].

TRACS—Total Right-of-Way Analysis and Costing System is a result of cooperation between TTCI and MIT. It was created as a TMCOST model upgrade. It estimates track maintenance and renewal costs as a function of the track route design geometry, track components, and traffic volume and type [14].

ITDM—Integrated Track Degradation Model is a result of cooperation between QR and Queensland University of Technology (QUT). It estimates track degradation as a function of axle load and rolling stock speed. It consists of four submodels for rail, sleeper, ballast and subgrade degradation. It predicts both individual subsystem degradation and whole track system degradation [15].

ECOTRACK—ECONomical TRACK is a result of cooperation between ERRI and International Union of Railways (UIC). This is a simple model that estimates tracks exploitation costs without detailed modelling of transport and track construction characteristics. It uses the measured track geometry values integrated in historical database. It predicts the geometry degradation rate by linear regression [5, 6, 10].

TMPM—Track Maintenance Planning Model is developed by QUT by integrating ITDM model into predictive maintenance interval and cost model [16].

DECOTRACK—Degradation Cost Of Track is a result of cooperation between Swedish Rail Administration (Banverket) and JVTC. It predicts rail degradation during exploitation in the form of fatigue and wear. Its input parameters are axle load, annual transport capacity in tonnes, speed, type and state of vehicle maintenance. The model results in anticipated rails lifetime and maintenance costs [11].

2.3. The possibility of developed models application on tram systems

The knowledge on degradation analysis and modelling of tram tracks is still rudimentary [17, 18]. The adoption of best practices in the establishment of a modern tram track maintenance system is certainly preferable than starting the process from scratch. However, the knowledge gained about conventional ballasted intercity rail system degradation cannot be directly applied to the narrow gauge tracks in urban areas. This is due to significant differences in the design requirements and exploitation conditions that are defined as key factors of any rail system degradation. These differences are related to the tram tracks location, design geometry, construction, vehicles and traffic organization [2].

The proximity between the tram tracks and the surrounding facilities and requirements for the rational use of city traffic areas during the tram route design demands narrower track gauges and tighter horizontal curves. For this reason, the tram vehicles are of smaller dimensions and weight. Axle loads on conventional railways are ranging from 16 to 25 tons per axle, whereas the axle load on urban tram tracks are generally lower than 13 tons per axle [19]. Also, the construction of trams undercarriage is different from conventional trains, and this difference is particularly pronounced in the case of modern low-floor trams. The differences are also reflected in the tram traffic flow characteristics given the movement priority and speed of the rolling stock. Due to a lack of space in densely built urban centres, trams often have to share the lanes with road vehicles and therefore adjust (primarily reduce) their speed. For the same reason, tram tracks superstructure is usually built on continuously reinforced concrete slabs, with grooved rails enclosed in pavement construction. The use of such rails also means that tram wheels flange is narrower than one on train wheel.

The review of the current practice has shown us that conclusions about the behaviour of conventional rail tracks during exploitation can only be used as a basis for further research of tram tracks degradation. In addition, significant differences between numerous tram systems construction, traffic conditions and monitoring procedures [2, 20, 21] complicate determining universal rules of narrow gauge tram track degradation. This indicates the need for research activities that would result in creation of a new approach to monitoring narrow gauge tram

tracks behaviour during exploitation and the development of a mathematical model of tracks degradation, taking into account joint effect of track design and exploitation conditions.

3. Creation of physical tram track gauge degradation model

A key element of the coordinated maintenance planning based on the track degradation modelling is up to date, digital, concise and widely available historical database on the tracks. It contains comprehensive information on tracks design and construction elements, exploitation conditions and monitoring and maintenance history (conducted inspections, activities and maintenance costs).

Although tracks monitoring and modelling are recognized as very important activities, many tram networks managements face similar problems when attempting to create such database. This is because most European cities have retained the traditional tram systems that date back to before the First World War. Nowadays, they face the problem of documenting their infrastructure in digital databases. In addition, the actual knowledge on the tracks condition is limited to a small number of managements' employees. Also, most of these employees do not have any tools for collecting, systematizing and integrating data in the historical database on which to conduct the assessment of the maintenance needs. Fortunately, cities that have recently upgraded their tram systems into modern networks based on the technologies and practices of urban light rail now have a large amount of precise digital documentation necessary for creation of historical databases [22, 23]. One such system is the tram system in the city of Zagreb, with about 80 km of tram tracks that were built and reconstructed during the past two decades.

Today, regular tram traffic in Zagreb is organized in 15 lines served daily by 178 tram vehicles operating on 116.3 km of 1000 mm gauge tracks. About half of the operational length of the tracks is placed in a separate tram corridor, whereas the rest share their corridor with road traffic (**Figure 2**) [24]. Two types of steel grades for grooved Ri-60 rails are used on Zagreb tram tracks: steel grade R200 rails at tangential and curved tracks with radius $R \geq 200$ m and wear-resistant steel grade R260 rails at curved tracks with radius $R < 200$ m. Rails are discreetly laid on the levelling layers, made out of micro synthetic concrete, which are built on reinforced concrete slab. The distance between levelling layers is one meter, and rails are fixed to them by elastic fastening systems.

Exploitation conditions on Zagreb tram tracks are very harsh: individual sections have a traffic volume of up to 15 million gross tonnes (MGT) per year, with vehicle passing frequency of < 90 s, and loads of more than 3.5 tonnes per wheel [25]. This high-capacity network presents an optimal testing ground for exploration of the possibilities to introduce the predictive maintenance system on narrow gauge tram tracks through the development of a track degradation model, based on the principles established on conventional rail track structures.

One of the main factors ensuring the tram traffic safety and ride comfort is maintaining high-quality track geometry. The required tram traffic safety refers to prevention of tram derailment. The required ride comfort refers to limiting the amount of lateral movement of trams in motion.

According to Ref. [26], tram track geometry is defined by track gauge (G) and cross level (h). *Track gauge* is defined as the spacing of the rails measured between their inner faces, 9 mm below the rail head. On newly built, reconstructed and repaired tangential tram tracks, gauge must be 1000 (+3, -2) mm. Maximum permissible deviation from this basic gauge in exploitation (ΔG) ranges from -2 to +25 mm. *Cross level* is defined as the difference in elevation (height) between the inner and outer rail in horizontal curve. Its value is determined by designer, depending on the curve radius and the design speed. It should be noted that the cross level is predicted only for tram tracks in separate corridors. If the trams and road vehicles share the same traffic area, cross level will not be implemented as it is incompatible with the pavement surface. For this reason, in the study of tram tracks geometry degradation, we will concentrate only on gauge degradation modelling.

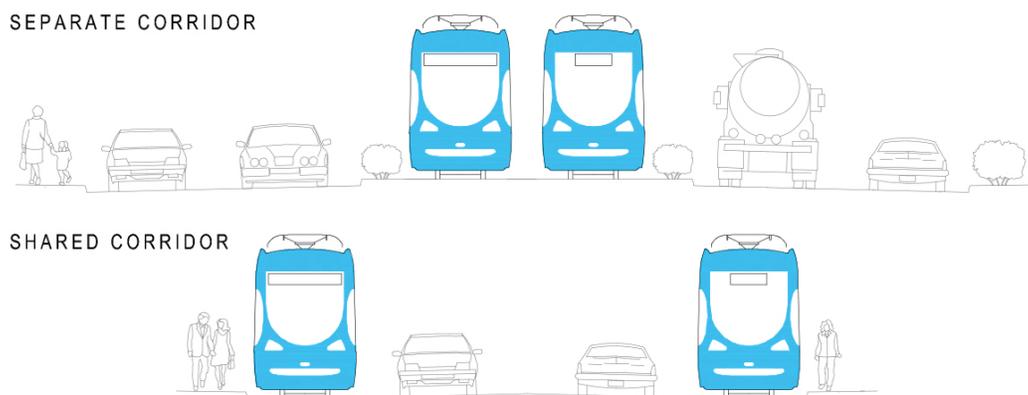


Figure 2. Types of Zagreb tram corridors—separate and shared.

When viewed in the ground plan, the trajectory of the moving rail vehicles centre of gravity has the shape of a sinusoid [27]. This hunting motion is a consequence of differences in the spacing between wheel flanges and the track gauge. This kind of motion gets more pronounced as the difference, that is, track gauge increases, primarily due to rail wear. Rail wear is a consequence of wheel rolling and sliding contact abrasion, and it is manifested as loss or movement of material in the contact area of rail head (**Figure 3**).

Besides compromising requested ride quality and smoothness, rail wear, that is track gauge increase, causes additional dynamic loads on track, its faster degradation and higher maintenance costs. Therefore, it is not surprising that measuring and modelling of gauge degradation are the most common forms of monitoring rail infrastructure within the planned maintenance system.

3.1. Choosing the modelling approach

Considering the *modelling approach*, applied type of statistical data processing (inferential or descriptive) and therefore needed input data and analysis complexity, mathematical models of track geometry degradation can be divided into probabilistic, mechanistic, empirical and mechanistic-empirical models (**Figure 4**) [5, 6].

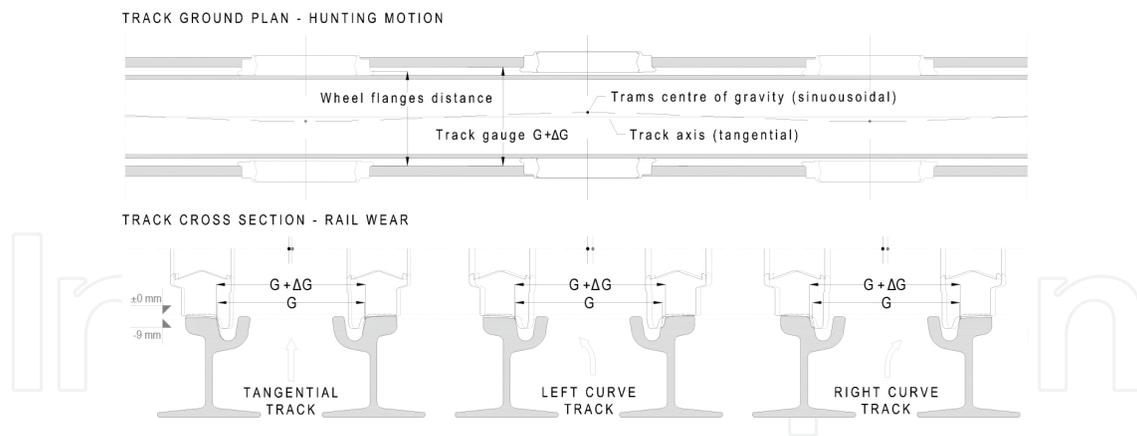


Figure 3. Hunting motion and tram track gauge increase due to rail head wear.

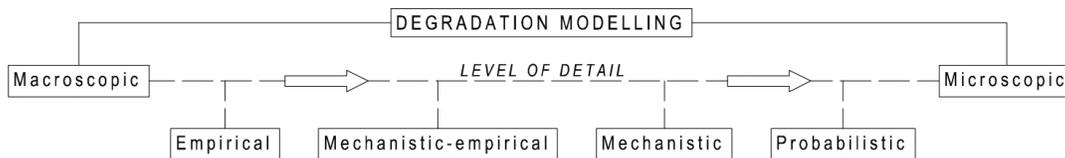


Figure 4. Input data and analysis complexity—degradation models hierarchy.

Probabilistic model uses the inferential statistics techniques to define probability that the quality of particular track section in one time period will be the same in the next period [5, 28–34]. The application of such degradation models showed that exclusive use of statistically determined probability of track degradation, instead of using actual measured data, does not provide a complete and accurate assessment of the track quality [23].

Mechanistic model simulates track degradation using well-established theoretical principles of track components behaviour during exploitation [35]. This so-called engineering approach uses the inferential statistics techniques to predict the degradation rate of the track, of certain initial quality, on the basis of known exploitation conditions. These models can be very sophisticated and often require the use of complex computer algorithms and long-term calculations. However, they can simulate the tracks behaviour in different conditions, even before its exploitation, and help to define tracks most important properties needed for improving its exploitation behaviour [36–39].

Empirical models are based on track quality data obtained experimentally or by field observations. They define degradation rate of individual track sections (so-called track degradation evolution [12, 36]) using descriptive statistics methods. They put into correlation the data on systematic track monitoring and exploitation period defined through track exploitation time or intensity in million gross tonnes [4, 40, 41]. Model results may significantly vary depending on the data used for their development and therefore should not be used to predict the track degradation [36]. They are mostly used for a better understanding of the observed degradation processes, as a first step of creating or for validating other types of models [42, 43].

Mechanistic-empirical model is based on a combination of mechanistic and empirical modelling procedures. This is considered the most effective track degradation modelling approach [44]. Creating such model requires track segmentation, that is separation of linear rail infrastructure on segments with homogeneous characteristics of degradation influential factors, monitoring and maintenance history. By summarizing the information obtained through track monitoring on each observed segment, it is possible to predict the need for maintenance of the whole network for a certain exploitation period [4–6]. This model determines the track degradation rate by statistical regression analysis using least square method [6, 45]. It is usually carried out over the average values of the track quality parameters, calculated from the values measured in individual points (chainages) of track section [46]. Regression model defines the degradation rate of the dependent variable—the observed track quality parameter, as a function of independent variable—the exploitation period expressed as time or exploitation intensity [4]. This allows defining critical maintenance limits for the observed geometry parameter or track element in the investigated sections [47]. In addition, there is a recent trend of track degradation modelling using artificial neural networks. Its aim is to achieve a rational insight into the track exploitation behaviour without its monitoring [48].

Through review of the development, preparation and characteristics of railway tracks geometry degradation models, two main objections of their end users were identified. Models are either too general and do not take into account the specific rail traffic and track characteristics, or too specific, that is they require a large amount of input data and interpretation of their results requires a high level of insight into the degradation problem. That is why today most researchers aim to develop as simple as possible degradation models that are convenient for the implementation and interpretation.

After modelling approaches, characteristics and procedures analysis, it was concluded that modelling of tram track gauge degradation during exploitation, due to the availability and format of the data on the Zagreb tram tracks, should be carried out using mechanistic-empirical approach.

3.2. Gauge degradation influential factors identification

Track geometry degradation in the form of gauge increase caused by rail wear is the subject of numerous research studies conducted to accurately determine the mechanisms of its development. Studies have shown that this process is very complex and depends on a number of influential factors. They can be divided into three basic groups: *traffic*, *construction* and *design geometry* influential factors.

Gauge degradation is primarily a result of the dynamic loading from vehicles running on tracks. These forces occur because of the irregularities in wheel-rail contact surface and track geometry. The rate of degradation is proportional to the exploitation intensity and vehicles speed. With regard to construction factors, studies have shown that the increase in rail steel hardness slows down the process of gauge degradation. Horizontal track geometry design elements also have a major effect on the degradation process, in particular the track curvature. Gauge degrades faster in horizontal curves than in tangential track sections, and the degradation rate is proportional to tracks curvature [21, 44, 49–52].

For the purpose of tram track gauge degradation modelling, beside exploitation intensity, the following six design, construction and traffic characteristics were defined as influential: track curvature, rail quality, that is steel hardness, rail fastening system stiffness, paving system type, estimated tram operation speed due to the corridor type and due to arrangement of stops and crossings. The aim of the model creation is to determine the individual contribution of influential factor on tram track gauge degradation rate.

3.3. Segmented database creation

For the purpose of this investigation, a review of the available construction and supervision documentation made for the (re)construction of tram tracks in Zagreb in the period 1997–2004 was performed. It resulted in identification of 11 sections of the network (more than 26 km of tram tracks) suitable for model creation.

Reviewed documentation included the results of control track gauge measurements conducted just before the commissioning of the (re)constructed track. Gauge measurements were carried out in the tram travelling direction, above every discrete rail levelling layer, that is at 1-m interval. Measured gauge values were denoted with corresponding track chainage values (geographic locations of gauge measurement cross sections along the track) defined in digital georeferenced track design blueprints. During gauge measurements, characteristic track superstructure element sections chainages were observed and recorded. Also, locations of specific track cross sections (locations of rail welds, station platforms and road crossings) were marked.

In order to determine gauge degradation due to track exploitation, continuous gauge measurements in the same track cross sections were repeated during spring months of 2011 and 2013.

For these tram tracks, described by more than 26×10^3 georeferenced cross sections, a comprehensive historical database of geographically synchronized modelling input data was made. In addition to the gauge values, to each section, an observed traffic, construction and design geometry characteristics and the value of exploitation intensity were assigned.

Calculation of exploitation intensity was conducted by integrating data from the available Zagreb Municipality Transit System – ZET Ltd. internal documents. These documents include information about an hourly frequency of vehicles on a single tram line, the daily number of vehicles of a certain type on each tram line, tram lines network maps and approximations of vehicles capacity utilization. Cumulative exploitation intensity was defined as the product of total number of exploitation days (defined by track gauge measurements dates on observed track segments) and daily gross mass of trams with passengers (in MGT).

Created database, which contains more than 34×10^4 quantitative and qualitative data on tram tracks, was then divided into 425 segments, that is linear track gauge data sets with homogeneous characteristics of gauge degradation influential factors. A small portion of segmented database is shown in **Figure 5**.

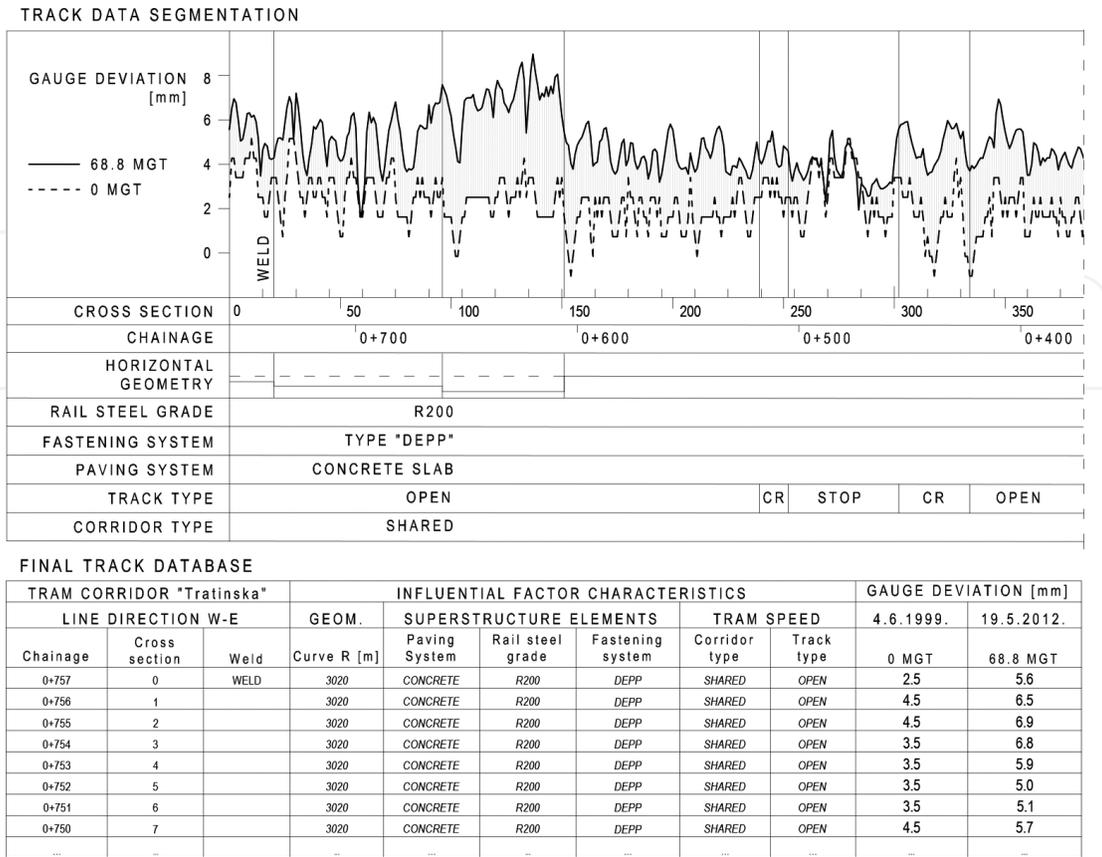


Figure 5. Portion of segmented track database.

3.4. Gauge data filtering and compression

On the basis of the gauge values measured after different exploitation periods, deviation values from the prescribed gauge of 1000 mm were calculated in each measurement cross section. In order to minimize possible measurement and/or geographical data synchronization errors, the following steps of track gauge deviation data filtering were carried out.

Mean gauge deviations differences and standard deviations were calculated on each of the identified 425 segments, in the corresponding exploitation period. Outliers were identified along each segment as individual gauge deviation differences which deviate from the mean of the segment for more than triple of the standard deviation value. These outliers were substituted with the first larger or smaller non-outlier gauge deviation difference value within the same segment. Segments that showed high data variability were excluded from further analysis. In general, excluded segments were ones in crossings, in tram stops where there was an occurrence of rail plastic flow and less than 30 m in length.

After this initial filtration, data compression and filtration were continued along each segment, track and then section. In this way, 35 representative and, according to observed gauge degradation influential factors (all but exploitation intensity—it will be used as independent variable in regression analysis), characteristic types of tram tracks were identified.

3.5. Regression analysis

It is a well-known fact that track gauge degradation process is more pronounced in a short period immediately after track construction or renewal, that is new rail installation or old rail reprofiling. This period of initial severe rail abrasion, during which the rail profile adapts to the shape of wheels flange, is followed by a period of more gradual rail degradation. In this gradual increase, which directly affects the track gauge, *linear trend* was observed [9]. This means that gauge degradation can be quantified in a linear mathematical equation, which describes the relationship between gauge deviation and track exploitation period, taking into account degradation influential factors.

By regression analysis of the relationship between compressed gauge deviation difference values and the track section exploitation intensity, linear function was defined for each of the observed 35 types of tracks. Model slopes, that is regression coefficients, define the modelled rate of gauge degradation during exploitation for each characteristic type of track. Example of linear gauge degradation models for four types of tram tracks is shown in **Figure 6**.

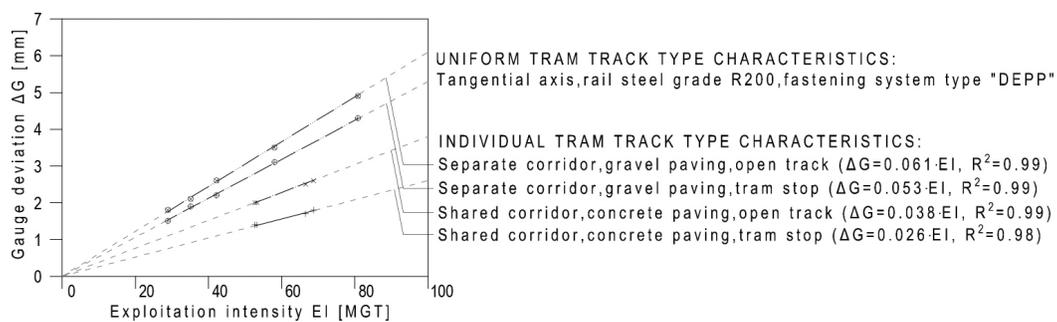


Figure 6. Example of linear gauge degradation models for four types of tram tracks.

Analysis of the models representativeness showed that there is a strong link between the observed variables in all 35 cases ($0.74 < R^2 < 0.99$) and that average model residuals (± 0.3 mm) in regard to the achievable accuracy of measurement (± 0.3 mm), as well as their variability ($< 20\%$), are satisfactory.

4. Tram track gauge degradation modelling results

Comparison of models regression coefficients showed that track gauge degradation rate is as follows:

- smallest at tangential sections of tram tracks on stops in shared road corridor, built with head hardened, elastically fastened rails enclosed with concrete paving slabs and
- largest at separated open track sections, in horizontal curves with radii less than 300 m, built with wear-resistant rails enclosed with gravel.

Further analysis of modelled regression coefficients relationships showed that the observed track gauge degradation influential factors, by the amount of their average impact, may be ranked as follows:

- Tram speed dependent on the tram corridor type has the greatest impact on the gauge degradation rate. In the case of the Zagreb tram network, the ability to develop higher travelling speeds is achievable exclusively in separate tram corridors that extend through avenues and major streets central belts. The tram speed on shared road corridors is limited by the behaviour of other road users, and typically shorter distances between tram stops and signalized intersections. In general, higher tram speed causes larger dynamic forces on the track, that is more prominent rail damage and track geometry degradation during exploitation.
- The second largest influence on the gauge degradation rate has track horizontal curvature. The results of this research showed that, of course, higher curvature increases gauge degradation rate, but also that the influence of track curvature on outer grooved rail wear is neglectable in curves with radius larger than 1200 m. Additionally, it was observed that the distribution of gauge deviation values along the horizontal curve depends on curve radius and length. In curves with radius less than 300 m and longer than 50 m, maximum rail wear occurs at the end of the curve (given the tram travelling direction). Otherwise, gauge degradation is more prominent in the vertex zone of the curve.
- The third gauge degradation influential factor is track superstructure elasticity. In average, gauge degradation rate is higher when tram tracks are built using stiffer rail fastening system. More detailed elaboration of this tram track gauge degradation influential factor is given in Ref. [53].
- The track quality defined by its rail tensile strength is the next tram tracks gauge degradation influential factor in order of relevancy. As expected, the use of higher grade steel rails can slow down the rate of rail head wear during exploitation. However, the results of this research showed that, in order to reduce rail wear in curves, head hardened wear-resistant rails should be used.
- Fifth in-line gauge degradation influential factor is corridor type according to the arrangement of tram stops. Research has shown that the positive effect of dynamic forces reduction by reducing the tram speed to zero along the tram stops is annulated by the occurrence of additional dynamic effects caused by trams decelerating and accelerating.
- Influence of paving system used for enclosing the tram tracks (by either gravel or concrete slabs) on gauge degradation rate is little to none, if we exclude the effect of differences between achievable tram speed on different track corridor types (shared or separate).

5. Concluding remarks and recommendations for future work

Developed gauge degradation models represent the first small step towards establishing a preventive maintenance system on Zagreb tram network. For now, they can provide only an

insight in (by design, constructive and traffic characteristics specific) track sections degradation behaviour. Although the models are of satisfactory representativeness, the overall process of model creation pointed out the following challenges.

The research was limited by the availability and form of the input data about tram tracks required for the creation of database over which the modelling would be carried out. These data were collected and stored over the years by various stakeholders for numerous reasons, other than modelling gauge degradation. It is our recommendation, prior to any future extensive trams network (re)constructions, to establish procedures for detailed recording of these characteristics and their integration into a single database. Also, keeping track of exploitation parameters of network's individual track sections, compared to the current practice of keeping records of exploitation parameters of tram lines, would significantly simplify and therefore accelerate the process of exploitation intensity calculation.

After final step of gauge deviation data compression and filtering, tram track segments along the road crossings were excluded from further analysis. Large variability of empirical data along these segments suggests that road vehicles at crossings definitely affect the gauge degradation. However, the comparison of the calculated average values of gauge deviations along these segments showed no regularity. It was concluded that for the establishment of track gauge degradation model on these segments, it is necessary to include data on the intensity of road traffic which they are exposed to.

To conclude, for small urban rail networks such as tram network in Zagreb, the use of deterministic mechanistic-empirical approach and statistical (regression) analysis in track degradation modelling has provided specific and useful new insights into the tracks behaviour during operation. Such modelling approach was adopted rather than probabilistic, multi-parameter one. It is our belief that creation of simple and easy to use model, rather than comprehensive simulation tool, would initiate sooner modernization of tram track maintenance procedures and regulations. However, for gradual increase in portions of network that could serve as a platform for further research and creation of predictive tram tracks degradation models, a closer cooperation between tram network managements design, construction, maintenance and transport organization divisions is needed.

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