ERRAC-EURNEX-Europe's Rail student competition 2024

Master and PhD (graduated 2022 and 2023)

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Master-abstracts

An Analysis of Freight Wagon Brake System Failures

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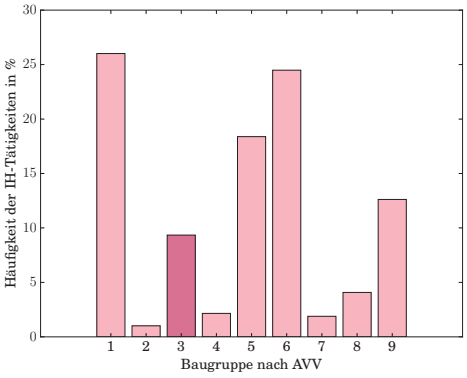
Keywords

Freight Wagon, Brake System, Maintenance, Sensor-Based Monitoring

Abstract

The master's thesis analyses a dataset of 1,471,007 records of freight wagon maintenance activities in Germany from 2022 to investigate brake system failures. Contrary to results from previous research [1], corrective maintenance measures on the brake are only in fifth place in the comparison of assemblies, with a frequency of 9.3 % (see fig. 1). One explanation for this is the different timing of the data documentation. In contrast, the brake is frequently represented among the ten most frequent maintenance tasks, which also applies to unscheduled activities. The composite brake sole and the brake rigging are particularly frequent individual components. Overall, activities on the mechanical part, the brake pads and the pneumatic part of the brake occur often; this also applies to the unscheduled tasks. Taking into account the fault severity, unscheduled occurrences on the brake rigging in particular prove to be a relevant source of faults. For faults of classes 4 and 5 according to GCU (major and critical failures) [2], the proportion of these is 19.3 %. Possibilities for sensor-supported on-board monitoring include the installation of sensors on the brake rigging and the brake pads. The pressure in the brake pipe can be monitored by pressure sensors [3]. Wayside monitoring can use cameras and image recognition software to detect the condition of brake pads and brake rigging [4, 3].



Number	Assembly
1	Running gear
2	Suspension
3	Brake
4	Wagon underframe and bogie frame
5	Buffing and draw gear
6	Wagon body
7	Loads and load units (ILU)
8	Particular incidents
9	Operational/other

Figure 1: Distribution of the assemblies for unplannend maintenance activities

Future work and perspectives

The analysis leaves some important questions unanswered, which are a good starting point for further research. The frequency of activity around the running gear should be investigated, as the divergence from damage reported in a previous study [1] is significant. One possible cause is the switch to composite brake pads and the associated increased wheel wear. In addition, the causes of the increased frequency of damage to the brake rigging should be technically analysed in order to prevent future failures. The cost/benefit ratio of monitoring solutions must also be carefully considered. Specific analyses of the individual cost aspects of sensor-based monitoring can be carried out for this purpose.

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Nichtlineare Einflussanalyse der selbsterregten Drehgestell- und Kastenschwingungen

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Key words: vehicle dynamics, equivalent conicity, car body hunting, nonlinear system analysis

The occurrence of strong lateral oscillations of the car body at low equivalent conicity is known from the daily work of railway vehicle engineers. When the frequency of the lateral bogie oscillation is low, coupling occurs with the movement of the car body. This results in strong lateral movements of the car body. The phenomenon is known, but has not yet been systematically investigated. In general this coupled movement effects only the ride comfort, not the safety. As in the homologation process the compliance with safety limits is examined, it can happen a railway vehicle adheres to the safety limits, but strong lateral oscillations of the car body may occur. This phenomenon is described by Polach [4, pp. 24–26] and in the Handbook of Railway Vehicle Dynamics [2, pp. 685, 701]. The only investigations that have been carried out are based on linear models. Examples are Stichels investigations [5] or Wickens publication [6, chap. 6]. However it has been shown that these can only reproduce the behavior of a rail vehicle to a limited extent. By using a non-linear model, the previous results of other authors shall be confirmed and the conditions which lead to self-excited oscillations of the car body shall be investigated.

The investigations are performed using the software SIMPACK for multibody simulations. As the rail-wheel-contact has a significant influence on the system behavior 12 different profile combinations are examined. Additionally the friction coefficient, the Kalker-Faktor, the stiffness of the primary suspension, lateral stiffness and damping in the secondary suspension are varied. The thesis starts with a theoretical introduction to various aspects of rail vehicle dynamics. This is followed by the introduction of the vehicle model used, which is then examined in terms of plausibility. The model used represents a generic passenger coach with four wheelsets and two bogies. Subsequently the proper research is done. Here, the analysis of so-called bifurcation diagrams is carried out, which are used in rail vehicle dynamics to analyze the stability of railway vehicles. In a first step simulations are made with profiles that have a equivalent conicity bigger than or equal 0,1. Only one profile combination showed strong lateral oscillations. This profile combination shows a very small equivalent conicity at small amplitudes of the lateral wheelset movement. In a second step profile combinations with equivalent conicity smaller than 0,1 are considered. Also here profile-combinations with low equivalent conicity lead to the occurrence of strong lateral oscillations of the car body. It can be shown the equivalent conicity at small amplitudes of the lateral wheelset movement has the biggest influence. A stiff primary suspension increases the lateral oscillations of the car body. Also a stiff lateral stiffness of the secondary suspension, a low friction coefficient and Kalker-Faktor enhance this effect. Increasing the lateral damping

in the secondary suspension can stabilize the system, but too high damping can lead to an opposite effect.

The results suggest that the occurrence of strong lateral oscillations of the car body at low equivalent conicity are the result of the coupling between the eigenmodes of the car body and the hunting motion of the whole bogie or single wheelsets. To have a better understanding of the effects the relationship between the motion of the wheelsets, the bogie and the car body is examined. Therefore the frequency of the lateral movement of the car body is drawn over the vehicle speed and compared with the eigenmodes frequency of the car body, the frequency of the wheelset hunting according Klingel [3] and the frequency of the lateral movement of the bogie according Boedecker [1]. It could be shown that in the case of self-excited oscillations of the car body, the natural frequency of the car body's eigenmodes and that of the bogie's lateral motion have approximately the same values. This occurs mainly in vehicles with high eigenfrequencies of the car body eigenmodes caused by the vehicle design and when profile combinations with low equivalent conicity are used.

Despite the detailed investigation, some questions remain unanswered. For example, it was not possible to clarify what causes the system to switch from a hunting motion of the wheelsets to a hunting motion of the bogie. Also, the influence of a yaw damper could not be investigated. It would also be of interest to couple the non-linear investigation with a linear one.

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RAIL WEAR AND RAIL STEEL GRADE

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Key words: rail wear; rail steel grade; curve radius

A comprehensive analysis of rail wear is crucial for ensuring the efficiency and safety of rail networks. This research focuses on investigating the precise factors that influence rail wear, especially the combination of curve radius and rail steel grades.

The investigations indicate that rails in curves experience significant wear, specifically the outer rails, which suffer from lateral and comparative wear (combined vertical and lateral wear). The correct rail steel grade selection is essential in reducing rail wear. According to the manufacturer, using head-hardened rails of grade R350HT can reduce wear by a factor of 3 compared to standard steel grade R260, while R400HT rails can provide even better results [1]. These positive effects are due to the increased hardness and wear resistance of the steel by heat treatment.

Rail wear is measured by the track recording car based on rail profile measurements. Digital stereoscopic imaging and the use of a laser slit precisely illuminate the rail head. This method allows for an accurate comparison between the target and actual measurements, enabling the calculation of the wear rate in the rail profile [1] [2].

The investigation of 470 curves on two mountainous Austrian lines with tight curves based on measured rail wear over a 12-year period shows that rail wear decreases as curve radius increases, based on different curve radii with the same steel grade. The difference between the radius classes $R < 250m$ and $250m < R < 400m$ is particularly significant, highlighting the importance of curve radius as a factor influencing rail wear. These results apply to lateral and comparative wear.

After conducting a detailed analysis of how various rail steel grades impact rail wear at the same curve radius, the following findings were obtained: In general, it can be concluded that rail steel grade R350HT exhibits less wear in tight curves compared to rail grade R260. This outcome is evident not only in each curve class examined but also in the different types of wear that are influenced. However, this effect is slightly more pronounced for lateral wear than for comparative wear. In summary, the results indicate that the selection of rail steel grade significantly impacts rail wear.

Compared to the improvement announced by the rail manufacturers, improvement factors are lower in the field application due to various boundary conditions. The lateral wear improved by a factor of 2.17 in the curve class $250m < R < 400m$, and the combined wear improved by a factor of 1.65. Similarly, in the curve class $400m < R < 600m$, improvements were observed, with the lateral wear improving by a factor of 3.09 and the combined wear improving by a factor of 1.95. The empirical study's results indicate a two-fold improvement. However, it is possible that this improvement is due to changing boundary conditions, specifically traffic growth and changing vehicle fleets.

In addition, the wear rate was specifically analysed for the curve class R < 250m on one line with very sharp curves. This analysis considers significant influences such as changes in main traffic direction. To eliminate this effect, the data was only analysed up to 2019. The results clearly show that the use of high-strength rails has a greater impact on comparative wear than other factors. The data suggests that the use of R400HT rails in narrow curves is a useful approach to reducing wear. The transition from R260 rails to R350HT rails was a significant improvement, but R400HT gives even better results, resulting in less rail wear.

The results of the analysis clearly show that both curve radius and the choice of rail steel grade has a significant influence on rail wear. This has far-reaching implications for the maintenance and repair of rail networks. It also provides a valuable guide for stakeholders to make optimised decisions on the selection and correct rail steel grades for a given curve. This can not only reduce wear, but also increase efficiency and availability.

The combination of data-based analysis with practical approaches provides a holistic view of the complex issue of rail wear. This work not only contributes to scientific understanding, but also provides concrete solutions that can be directly incorporated into the operation of rail networks. However, further research is required to address some aspects.

Specifically, the influence of factors such as speed, track load, vehicle collectives, and maintenance methods on rail wear should be studied in more detail. Additionally, changes in the main direction of traffic, continuously welding of rails replacing the former jointed track, and structural changes in the superstructure, such as variations in sleeper types and rail profiles, may also play an important role on the investigated line. Future studies will provide additional insight into how different conditions affect rail wear by investigating aspects such as rail lubrication [3] or wheel wear. Furthermore, a more detailed analysis of possible causes of irregularities or deviations in the measured data could lead to more accurate predictions of rail wear.

To conclude, the size of the curve radius and rail strength have a significant impact on rail wear. The wear of outer rails in tight curves decreases with a larger curve radius and higher rail strength. While this work has provided valuable insights, there are still unanswered questions and opportunities for further research. A systematic investigation of these aspects could refine and expand the results of this study, leading to a deeper understanding of the complex relationships in the field of rail wear.

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Effects of stabilisation tamping on track quality behaviour

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Key words: stabilisation tamping, deterioration rate, track quality

Due to its highly positive effect on track quality behaviour, the stabilisation tamping – a tamping action following the track renewal – must be examined apart from standard maintenance tamping of track. For some years now, the stabilisation tamping has been done in Austria, but there has hardly been any further investigation. While Hummitzsch [1] saw a decrease in deterioration rate in the first year after construction for a limited dataset, it is also known from Lichtberger [2] that good behaving track should not be tamped early, while poor-behaving track should.

For now, the stabilisation tamping is known to increase track quality, as well as decrease deterioration rate, but only in approximately three out of four cases. Most of the time the stabilisation tamping will be executed in the first two years after the construction of the track. The main objective was to examine, when to do the stabilisation tamping and which boundary conditions can influence the decision for or against the stabilisation tamping.

Various boundary conditions show only small influence on the room of improvement due to the stabilisation tamping. Meanwhile, the point in time of the stabilisation tamping indicates the highest room for improvement for the deterioration rate in the first six months after (re-)laying of track. A measuring data-based decision for a stabilisation tamping in this timeframe is quite complicated, if not impossible, if three or even four measurement points are required and track is measured only four times per year in maximum.

We can show, that the decision for a stabilisation tamping can be based on only two measurement points. The distribution of decrease in deterioration rate, as well as the distribution in deterioration rate show the same median and spread for the calculation with three and four measurement points. For two and three measurement points, the median is still the same, while the variation increases slightly. The overall trend over time also did not change by variation in the number of measurement points. Therefore “correct” implantation of the stabilisation tamping at an infrastructure manager would be the next step, with regular evaluation of the carried out stabilisation tamping actions.

Besides the timeframe, the deterioration rate before the stabilisation tamping is also important. It can be observed, that higher deterioration rates not only show higher degrees of absolute improvement in deterioration rate, but also result in a higher success rate as of reduction of deterioration rate. This is quite important since the critical part for stabilisation tamping is the reduction of deterioration rate as track quality improvements can be observed for most tamping work. Also, it must be emphasised, that not all tracks, especially good tracks, need stabilisation tamping.

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HUMAN FACTORS IN RAILWAY SAFETY MANAGEMENT

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Keywords: Rail Human Factors; Human and organizational factors; SPADs; Survey administration and analysis; Human Reliability Analysis

Obs.: The referred dissertation has a related published paper: 'Human reliability and Organizational factors—How do Human Factors contribute to Signals Passed At Danger?' (Neves et al. 2024).

ABSTRACT

Human Factors (HF) are key role in Railway Safety being crucial in the most demanding activities in the field. These factors are inherently and significantly linked to the frequency and severity of Signals Passed At Danger (SPADs). The main objectives of this dissertation, and related published paper, were to analyse both active and latent dimensions of HF in terms of SPAD occurrences, with the development of models that place Human and Organizational Factors (HOF) at the centre of the discussion.

On the organizational aspect of Rail HF, a translated and validated surveying tool was applied in the Portuguese Railway actors. The questionnaire was allowed by the Portuguese National Security Authority (NSA). The Safety Responsibles of all Train Operating Companies (TOCs) and the Infrastructure Manager (IM) were contacted to get valid answers from the all workers related with train driving.

Regarding the individual level of the human error in SPADs, Survival Analysis was applied in a train-drivers database in order to identify explanatory variables and factors that contribute to the occurrence of SPADs. The database was created with information provided by the Portuguese Railway NSA, the IM and multiple TOCs, from the start of 2016 to the end of 2021. It included each train-driver's age and certified rolling stocks and itineraries, and anonymized information from train-drivers associated with SPAD in the same time period. This compounds a total of 725 train drivers and 59 SPADs analysed.

The incorporation of both human and organizational factors is crucial for a comprehensive evaluation of the occurrence of SPADs. Furthermore, plans could be devised to implement a SPAD reduction strategy and human resources allocation improvement according to the results obtained in this study and evaluate the effectiveness of such tools afterwards.

From the Organisational Factors and Safety Perception analyses in the Portuguese case study, one of the largest indicators for job satisfaction is the number of hours worked, where a significant share of participants described their workload as unacceptable. Responses to various items point to time pressures and operation under pressure. Both workers and managers show great concern for safety, shown by items on the General and Safety Culture and the Job Characteristics constructs. Safety is of paramount importance for workers and managers alike, though workers do not feel heard. Most respondents state that they cannot get proper rest after a shift, and few participants have had two consecutive shifts separated by less than 12 h. Additionally, all respondents suffer from various levels of fatigue. Pressure from deadlines,

excessive workload and staff shortages are amongst the biggest causes for stress. ANOVA tests results point to the impact of Experience in Current Position in Job Satisfaction. General and Safety Culture showed different mean responses across Age Groups, Positions and Organizations.

Moreover, considering Human Reliability study, the Human behaviour in SPADs was best modelled by a Normal distribution, with a mean time to failure of around 1200 days. The Cox Proportional Hazards Model pointed that the risk of SPAD for train drivers with less than 25 years of experience is 7.9 times the risk of SPAD for train drivers with between 25 and 30 years. Train drivers with certified itineraries between 4 and 12 have 3.4 times the SPAD risk of train drivers who have, at most, 4 certified itineraries. Also, drivers younger than 40 have a SPAD risk 2.8 times the SPAD risk of train drivers aged between 40 and 50 years old. Train drivers with longer certified itineraries show higher SPAD risk. Adding to that, train drivers who experienced a SPAD during the study period were more than 24 times more likely to relapse and commit a second incident.

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Appendix

Table A1 - Average and variance organized by demographic variables for three factors: Job satisfaction, general and safety culture and occupation stress.

–	Construct		Job satisfaction		General and safety culture		Occupational stress	
Factor	Class/Value	N	Avg.	Var.	Avg.	Var.	Avg.	Var.
Age group	25–34	17	3.952	1.624	2.728	0.677	2.309	1.311
	35–44	20	4.534	1.296	3.660	0.640	2.050	0.972
	45–56	87	3.898	1.130	3.290	0.429	2.255	0.885
	Over 56	24	4.224	1.503	3.383	0.350	1.860	1.164
Position	Train driver	75	4.087	1.218	3.267	0.475	2.057	0.963
	Train manager	44	3.724	1.076	3.067	0.416	2.494	1.044
	Commercial service inspector	9	4.368	3.489	3.778	0.423	1.778	1.403
	Technical personnel	9	4.840	0.416	4.305	0.214	1.972	0.486
	Service inspector	5	4.663	0.501	3.560	0.155	1.890	1.157
	Other positions	7	3.857	1.364	2.778	0.289	2.307	0.372
Company	Entity 1	121	4.041	1.250	3.201	0.413	2.208	1.019
	Entity 2	13	3.505	1.871	2.973	0.635	2.192	0.864
	Entity 3	9	4.840	0.416	4.305	0.214	1.972	0.486
	Entity 4	6	4.250	1.141	4.211	0.164	1.658	1.454
Experience in current position	Less than 1 year	13	4.986	1.377	3.697	0.460	1.969	1.289
	1–5 years	24	4.240	1.176	3.354	0.816	2.335	0.701
	6–10 years	6	4.104	1.754	3.256	0.500	1.433	1.235
	11–19 years	19	3.816	1.301	3.095	0.627	2.618	0.668
	20 years or more	87	3.907	1.167	3.254	0.409	2.134	0.980
Location	Greater Lisbon	61	4.087	1.423	3.258	0.693	2.184	1.252
	Coimbra	39	4.050	1.139	3.455	0.380	2.024	0.766
	Faro	14	4.089	1.202	3.299	0.402	2.682	0.374
	Entroncamento	15	4.342	1.368	3.116	0.341	2.213	1.039
	Porto	10	3.894	0.503	3.246	0.174	1.840	1.278
	Other locations	10	3.500	2.063	3.111	0.760	2.005	0.980

Table A2- Descriptive statistics (mean, standard deviation, minimum and maximum) of numeric variables of the database.

Variable	Average value	Standard deviation	Minimum value	Maximum value
Time 1 [days]	204.77	563	1	2118
Time 2 [days]	2101.33	367	25	2192
Itineraries [-]	8.81	5.76	1	24
Rolling stock [-]	4.23	2.22	1	14
Kilometres [km]	857.67	618.43	25.45	2660.98
Age [years]	50.13	8.57	21	64
Experience [years]	19.67	6.20	0	34.19
KM/IT [km]	93.57	24.96	25.45	206.20

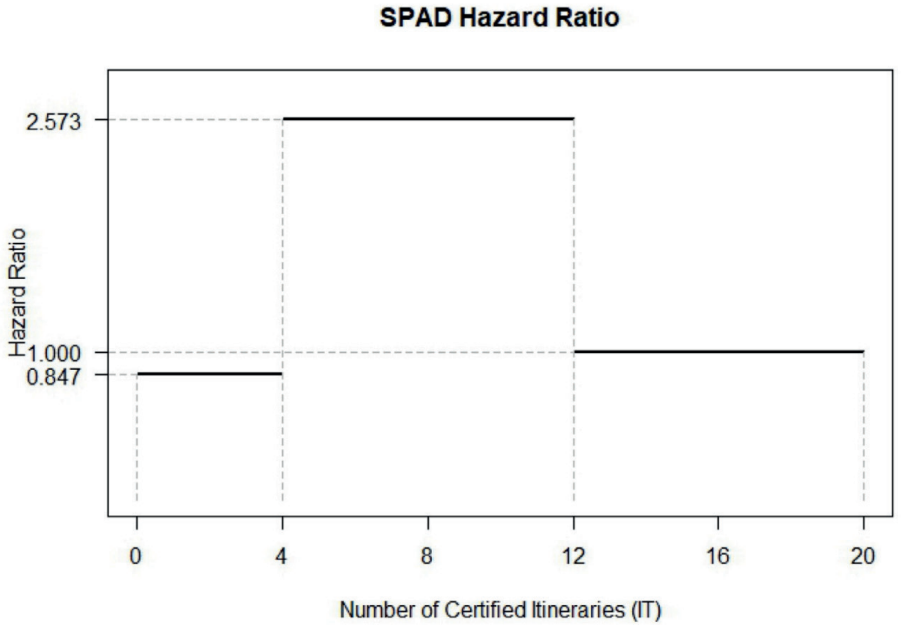

Figure A1 - Effect of certified itineraries (IT) in SPAD hazard.

Development of a Machine Concept for Vegetation Control in the Ballast Bed Using the Methods of Mowing and Vacuuming

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Key words: **Rail Lines Maintenance, Non-chemical Weed Management, Herbicide-free Methods, Mowing, Vacuuming**

Main Objectives of the Work

Vegetation control on railway tracks is an important part of regular maintenance work to ensure safe and reliable railway operations. The chemical vegetation control, using herbicides, is established and very common. This is due to its economic efficiency, effectiveness and comparatively high working speeds. With changing regulatory framework conditions and growing public concern about the use of herbicides, the development of herbicide-free methods of vegetation control is needed. [1-3]

This thesis focuses on weed management on the ballast bed by applying the method of mowing. This method is commonly applied on the side of the track and in some instances on the track area when vegetation is resistant to herbicides or where herbicides are not allowed. The method of mowing controls plants with height above the rails with low energy requirement. [1, 2]. The process is supplemented by the method of vacuuming in order to collect the clippings and not leave them behind.

To develop and design a concept machine which combines both methods, the guideline VDI 2221, as part of the product development process, has been applied. As a part of this, requirements and a number of possible solutions have been worked out.

Contributions

The developed machine is designed for operation on a road–rail carrier vehicle, a Unimog from Daimler Truck AG, Wörth, Germany, to allow easy and flexible use of the machine. In use, the carrier vehicle is equipped with two mounted attachments (see Fig. 1).

The front attachment consists of a folding frame that carries five height-adjustable mowing units. One mowing unit, in its position adjustable, is provided for each of the areas between the rails, between the flank and rail, and the area on one flank. The mowing units are each fitted with two vertically rotating flail mowers, which are driven by two bevel gearboxes and a hydraulic motor.

In addition to cutting, the mowing units also carry out a mulching process at the same time. All mowing units are connected to a hose that leads to the central vacuum unit on the central attachment. Through gravity and deflection separation, the clippings are removed from the air stream of the vacuum unit.

Future Works and Perspectives

The next step in a possible development process is to work out the overall design in a higher level of detail. Based on this, a prototype can be manufactured to prove the concept idea. When manufacturing a prototype, a machine of reduced size with a smaller working width, can be considered first.

An automatic adjustment of the mowing units during operation represents a possible next step in further development. This step will support the precision of the numerous adjustments at the correct time which must always be guaranteed. Camera- or sensor-based, supportive automation may be a possible option. Also, the collection of data on the infrastructure components installed along the tracks may be a beneficial database in the automation process.

Conclusion

In accordance with the guideline VDI 2221, possible versions of a concept machine have been considered. A concept machine, carried by a road–rail vehicle, suitable for the application on the ballast bed utilising methods for non-chemical weed management, has been designed. The design provides a basis for future experimental investigations.

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Appendix

The following rendering gives an overall impression of the complete concept machine with all its components on a track, mounted on a carrier vehicle. The outriggers and the mowing units are positioned in an exemplary working position.

Fig. 1: A Rendering of the Complete Concept Machine

Detection of short-section Ballast Breakdown in Track: A Fractal Analysis Approach with Reduced Window Length

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Key words: data analysis, targeted maintenance, track quality, fractal analysis, ballast condition

Continuous monitoring is essential to ensure the safety and proper condition of railway tracks. Vehicles (measuring cars) equipped with measuring tools routinely inspect the tracks, assessing critical factors such as alignment, cross level and gauge. One way of assessing the quality of the track is analysing the longitudinal level of track recorded by the track measuring car. The longitudinal level is used to calculate different quality indicators, most frequently the standard deviation of the longitudinal level [1–4]. Analysing the standard deviation over time, we can describe the deterioration of the track. This quality indicator is used to schedule track tamping [5, 6]. While track tamping restores track geometry, it might not be the most sustainable maintenance measure, especially when ballast condition is already weak [7]. In order to identify whether the ballast condition is causing the error, we need to analyse the longitudinal level differently based on the wavelengths within the signal. Power density spectra [8] or fractal analysis [9] are possible options. This work focuses on the technique of fractal analysis. Previous work estimates fractal dimensions of a local patch of signal data and repeats this computation in a sliding window manner. To capture the characteristics of both the ballast and the substructure simultaneously, the length of this window is typically chosen to be 150 meters [10]. The application of fractal analysis enables the characterization and analysis of irregularities occurring in the track geometry [9–11]. This makes it possible to assign recorded data to a specific damage pattern. Considering the temporal change of the estimated fractal dimensions, the root-cause of the failure can be narrowed down to different parts of the track structure [10].
Restoring track geometry by tamping forms the biggest cost-driver in track maintenance [4]: if settlements occur in track, the required track geometry can be restored by tamping. If the ballast has impurities, the required elasticity decreases, which in turn leads to higher stress and faster deterioration of track [12]. Settlements and changes in the stiffness of the ballast bed have a considerable influence on the service life of the track and must therefore be rectified as quickly as possible.

This work applies fractal analysis techniques to the investigation of ballast condition. By analysing 114 known isolated defects in the ballast bed, the research modifies the existing fractal analysis method by reducing the window size to improve the detection accuracy of isolated defects. This refined fractal analysis enables targeted, component-specific maintenance interventions, optimising both effectiveness and resource allocation. Using the fractal analysis approach developed by Landgraf and Hansmann [10], we empirically evaluate eight different window sizes to find the most effective one for describing ballast deterioration in fractal dimensions. Due to the reduction of the window

size, we adapt the fractal analysis algorithm by using the so-called RANSAC algorithm (**Ran**dom **Sa**mple **C**onsensus) [13]. In general, RANSAC is used to detect outliers. In our case, RANSAC is used to estimate the fractal dimension in a robust manner. The aim of this work is to determine which window size best captures isolated defects and to set an appropriate threshold for the fractal dimension. This threshold is set using the F1 value, a metric that combines precision and recall to assess the accuracy of the classification model. We also validate the effectiveness of the modified fractal analysis in assessing ballast bed conditions. This involved examining data from areas of poor ballast quality. This analysis helped to determine the ideal window size for detecting isolated defects and confirmed that a window size of 12.5 meters with a fractal dimension threshold of 25 was optimal for accurately identifying isolated defects in the ballast bed.

Until now, it has not been possible to describe the condition of the ballast bed in turnouts due to the large window size of 150 meters and the small length of the turnouts themselves. In addition, isolated defects in the subgrade, such as those caused by culverts crossing track, have not been detected by fractal analysis using a window size of 150 meters. This work shows that it is possible to describe and analyse a specific component of the track by applying fractal analysis using a reduced window size. Future studies will provide further insight into how the modified fractal analysis can be transformed to investigate other components in the track, such as turnouts or the condition of the subgrade.

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Wheel-rail interaction models for rail corrugation monitoring through axlebox acceleration measurements

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Keywords: Axle-Box Acceleration, Rail Roughness, Corrugation monitoring, Wheel-rail interaction.

Main objectives of the work

This work aims to develop an algorithm for the identification and monitoring of rail corrugation growth using axlebox acceleration measurements taken from an instrumented trainset running on the subway network of Milan. The irregularity estimation procedure begins by developing models for the analysis of wheel-rail interaction in the frequency domain, starting from the state of the art present in literature [1]. Further enhancements in the modeling of the components are then introduced, obtaining innovative models. These are then used to process acceleration data and reconstruct the rail roughness profiles. The results yielded by the algorithm are assessed in both their precision, robustness and reliability in predicting rail corrugation growth over time.

Contributions

The estimation algorithm developed in this thesis reconstructs the rail corrugation profiles by directly multiplying the measured acceleration spectra for the transfer function of the measurement system. Literature suggests that, for the frequency range of corrugation monitoring, it is sufficient to take into account the dynamic of the wheelset and the tracks, while neglecting the rest of the vehicle [2]. Several models of increasing complexity of the interaction between the wheelset and the track are developed and tested, starting from a state-of-the-art model of a flexible half-wheelset which neglects the dynamic coupling between the two wheels. The full dynamic of the whole wheelset is then added, creating a multi-input, multi-output system. Finally, the influence of the contact angles between wheels and rails is added. All models use the receptances of the components to compute the transfer function of the measurements system. The rail is modeled as an infinite Timoshenko beam lying on a double layer, continuous support, according to Faccini et al. in [3]. Wheelset receptances are computed using a modal model whose mode shapes have been obtained through a Finite Element simulation and whose eigenfrequencies are adjusted according to the results of an experimental modal identification campaign. The contact between wheelset and rail is accounted as a linear Hertzian spring.

The transfer functions obtained by the three aforementioned approaches are employed to reconstruct the moving average of peak-to-peak amplitudes of the irregularity profile of a right turn of a section of Milan underground network. The curve under analysis presents corrugation on its lower rail and it is covered by the instrumented trainset multiple times per day, allowing to average results

of several runs. The curve is also measured by a track recording car. This allows to compare the results of the algorithm against independent data.

Finally, a series of modified transfer functions are constructed, each obtained by randomly varying the modal frequencies and damping ratios of the nominal one. The modified transfer functions process an accelerometer signal which reproduces the effects on the measurement system of a rail profile having uniform irregularity at all wavelengths. The standard deviation of the reconstructed profile spectra at each frequency is then computed.

Future works and perspectives

Perspectives associated with this thesis work are a more in-depth analysis on the limits of the methodology, especially in the effective possibility of reconstructing track geometry on both rails by introducing the full effects of the wheelset lateral dynamics. A second field of investigation could be the development of a corrugation measurement algorithm that is independent of train speed.

Conclusions

The proposed methodology is shown capable of tracking the presence and development of corrugation on the lower rail of the curve under analysis. The averaging of different reconstructions performed on the same day can improve the results. However, the methodology shows greater uncertainty in the reconstruction of the higher rail, where corrugation is absent. Results of the robustness anaysis highlight significant dispersion in the results at frequencies corresponding to the natural frequencies of the wheel-rail dynamic. These results have significant impacts on the reliability of the reconstructed rail profiles, since small variations in the measurement conditions can significantly affect the measurement system output. This is worsened by corrugation spatial wavelengths being usually associated to the natural frequencies of the system.

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"RAILAND, a thesis of many dimensions: about the future of labour in rail transportation"

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KEY WORDS: ATO, Technological unemployment, autonomous trains, EU transport policies, train drivers

1. Main Objectives of the Works:

The primary objectives of the thesis presented are to examine the ethical implications of automation in the transportation sector, particularly focusing on the railway industry and the impact of ATO (autonomous train operations) on society, transport, and a particular **focus on train drivers** . The thesis aims to analyze the **potential social and economic impact of automation on various stakeholders**, including workers, passengers, and labor unions, and to evaluate the ethical dilemmas arising from the adoption of new technologies.
Data have been collected towards a series of interview of European train drivers, rail workers and passengers (around 300 people). These are the three research questions discussed:

R.Q 1) Are driverless trains going to be a reality in next future?
R.Q 2) How do people and railroad workers view automation—what are their attitudes?
R.Q 3) Is it possible to develop (or propose) EU policies to avoid train drivers' mass dismissals and guide them towards a just transition to a digitalized world?

2. Contributions:

The works make several significant contributions to the discourse on automation and its ethical considerations, especially in the realm of autonomous trains operations (ATO):

Ethical Scrutiny: They provide a comprehensive examination of the ethical concerns associated with the automation of transportation jobs, including the fairness of reducing high-intensity jobs, the necessity of re-skilling workers, and the role of labor unions in advocating for workers' rights.

Stakeholder Perspectives: The works consider the perspectives of various stakeholders, including workers, passengers, employers, and labor unions, in assessing the ethical implications of automation. By exploring these diverse viewpoints, they offer a more nuanced understanding of the complex ethical landscape surrounding automation in the transportation sector.

Policy Recommendations: They propose practical policy recommendations to address the ethical challenges posed by automation, such as promoting higher education and re-skilling initiatives for workers, imposing barriers to the market for newer technologies, and empowering labor unions to advocate for workers' rights in a digitalized world.

3. Future Works and Perspectives:

Looking ahead, there are several avenues for future research and exploration in this area:

Impact Assessment: Future studies could conduct rigorous impact assessments to evaluate the social, economic, and environmental consequences of automation in the transportation sector. This could involve examining the effects on employment patterns, income distribution, and overall well-being in society.

Ethical Framework Development:Researchers could further develop ethical frameworks specifically tailored to guide decision-making processes related to automation in transportation. This could involve incorporating principles of fairness, justice, and human dignity into policy-making and industry practices.

Technological Innovation: Continued technological innovation presents both opportunities and challenges for the transportation sector. Future works could explore emerging technologies, such as artificial intelligence and autonomous vehicles, and their implications for the future of transportation and labor.

4. Conclusions:

In conclusion, the thesis presented offer valuable insights into the ethical considerations surrounding automation in the transportation sector, with a particular focus on the railway industry. By examining the perspectives of various stakeholders and proposing practical policy recommendations, they contribute to a deeper understanding of the complex ethical challenges posed by technological innovation. Moving forward, further research and collaboration will be essential to address these challenges effectively and ensure a just transition to a digitalized future in transportation. Here there is the synthesis of the RQ answered with an empirical collection of data:

R.Q 1) Feasibility of Driverless Trains in the EU

- The research explores the potential for EU entities to introduce driverless trains within a 10-15 year timeframe.
- While the possibility is acknowledged, definitive conclusions remain elusive, necessitating further investigation.

R.Q 2) Acceptance of Driverless Transport

- Both passengers and employers in the railway sector demonstrate a willingness to embrace driverless transportation.
- Factors influencing acceptance include cost efficiency and reduced risk of human error accidents, suggesting a favorable outlook for implementation.

R.Q 3) Challenges and Strategies

- The feasibility of implementing an EU-wide minimum legal salary is questioned due to potential discord.
- Instead, strategies such as 'duty to re-skill' and imposing 'entrance barriers to the market' for newer automated technologies are proposed.
- Stakeholder cooperation, particularly in investing in worker education, is deemed crucial for navigating the transition effectively.

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GNSS Multipath Error Models for Safety Critical Navigation in Railway Environments

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Keywords: railway signaling, robust GNSS, multipath error modeling, digital track map

Main Objectives of the work

Safety critical applications in railway environment require accurate and reliable positioning information [1]. Sensor-based localization, in particular GNSS, is foreseen as a key-changer for railway signaling because it can be a cost-effective system. However, in railway scenarios, the performance of GNSS may be compromised due to the presence of various local error sources, like multipath, Non-Line of Sight or interference. These local error sources are difficult to model and predict, but since the trains can only move along the tracks, they have shown a certain level of location dependent consistency. Furthermore, its impact can be partially seen by some GNSS receiver measurements and observables.

In this master thesis work, first, multipath is modelled as a product of a nominal model, that characterizes the error behavior in a nominal open-sky scenario and which is parametrized with the elevation of the satellite, and a location track map specific inflation factor along the railway lines. The methodology to derive this statistical error model for multipath is as follows: The isolated code-multipath observations are projected into a discretized digital track map, similar to [2], normalized by the nominal reference model, and Gaussian over bounded, using the methodology of [3], for each specific map location, resulting in a discretized map of inflation factors. The methodology will be used to derive a map, which might be used as an a-priori multipath uncertainty model to be used by positioning algorithms. The model captures the local multipath risk within a discretized digital map, based on the post-processing of several real scenario datasets. The model can be integrated to the railway domain, as the concept of digital maps is already well established for applications like routing, map matching or fleet management [4].

Second, a model addresses the problem by means of a shallow neural network, which estimates the conditional distribution of the multipath error. In detail, the error distribution is modelled to be dependent on set of selected features, that have been shown to be able to describe the multipath error. The neural network now estimates a set of discrete quantiles that are used to characterize the full distribution using a modified quantile loss function. The procedure is as follows: Train the network with the features as input and the multipath samples as target values, predict the conditional quantiles and determine the corresponding Gaussian bound. The trained model might be used by GNSS receivers for any railway scenario to describe in real-time the multipath error for reliable and safe satellite-based localization.

Both approaches are evaluated with an adapted single frequency H-ARAIM algorithm [5], using precise GNSS products to investigate the quality of the multipath error models in detail. The evaluation is performed with a real railway scenario dataset collected by the German Aerospace Center (DLR) with the Advanced Train Lab of Deutsche Bahn in an urban environment in the Berlin area. The dataset includes various error sources, such as bridges or railway stations.

Contributions

In the context of the master's thesis the following research contributions were made:

- Proposal of a discrete map matching algorithm that projects observations collected within the tracks to discrete track points while accounting for uncertainties involved,
- Development of a map-based multipath error bound model based on empirical observations for rigorous error description within the tracks,
- Presentation of a novel AI-based methodology for safe error description based on a set of descriptive GNSS features without introducing any assumption on the underlying distribution,
- First design of H-ARAIM for railway applications with special focus on the railway environment.

In addition, the work presented is now a contribution to the EU Horizon 2020 project RAILGAP to support the characterization of GNSS technology and satellite-based positioning for unsafe and safe railway applications.

Future work and perspective

After the finalization of this master thesis, the following research has already been conducted: In [6], we replaced the nominal multipath error model for the normalization with respect to the elevation angle, which originates from civil aviation, with a model that represents the actual installation environment of the antenna on the roof of the train. In [7], we studied the application of fault detection and exclusion within the ARAIM system and the improvement of system availability while maintaining a safe error description. A final point is analysis of the generalization performance of a pretrained neural network by studying a different dataset to verify that one model can provide safe error description capabilities for an unseen scenario.

Conclusions

In this work two strategies to model the multipath error for railway scenarios have been presented in an attempt to overbound the error on code measurements. They can be considered for further applications in the railway domain, if a safe description of the error is needed. The presented neural network-based error model is not tailored to railway applications only and can therefore be used for any other dynamic scenario. Furthermore, the adaptations for H-ARAIM, originally designed for aviation, have opened up further fields of applications in train navigation. ARAIM service provider, such as the ESA, could extend their use cases for a railway signaling. The railway navigation community could make use of the proposed multipath error models for safety critical train localization.

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AUTOMATIC TRAIN PROTECTION SYSTEM IN RAILWAY SAFETY

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Keywords: Railway Safety Management, Automatic Train Protection, Signal Passed At Danger, Generalized Linear Model, Zero-Inflated Model.

ABSTRACT

One of the most common railway safety systems is the Automatic Train Protection (ATP) system. ATP system monitors train's instantaneous speed, preventing both overspeeding and Signals Passed At Dangerous (SPADs). The objective of this dissertation was to introduce different ATP errors and its influence in SPAD events and to address the reliability of the two subsystems of the Portuguese ATP: i) Infrastructure system, and ii) On-Board system.

The safety measures to be applied when an ATP error occurs depend on the type of error and the subsystem in which the error occurred. Different scenarios were drawn regarding the various errors. The reliability analyses performed using statistical models detected temporal and operational tendencies in the two errors studied. Two databases were created with historical information: one regarding Balise errors, and other with On-Board errors. Both databases considered a study period from the beginning of 2016 to the end of 2021. The errors were spatially discretized by station and explanatory variables defined in order to characterize the occurrences depending on the signaling density and train traffic, among others. By testing different statistical models, the impact of the excessive number of zeros and the over-dispersion on the analyses could be identified and avoided. By using multiple variables, it was possible to predict the errors occurrences for different railway lines and conditions.

These two complementary studies allowed a better understanding of the functioning and role of the ATP in the railways system. The results obtained from the statistical analyses can be used as a starting point for the implementation of mitigation measures to minimise the errors occurrences. Furthermore, the effectiveness of the applied measures must be evaluated, ideally by the implementation of the same analyses sequence and models.

In compliance with the safety legislation, the scenarios illustrate the influence of errors on the operation of the train. While errors related to the Infrastructure system affect the operation of the ATP for a short and limited distance, On-Board system errors may lead to the ATP being completely inoperable for significant time periods.

Regarding the results obtained from the statistical analyses of the two databases, it is possible to present a comparison between the two types of errors studied: Unlike the On-Board system errors analysis, the Balise Error analysis shown both considerable data over-dispersion and excess of zero values observations; There is a clear seasonality of the Balise Error occurrences, with a considerable increasing in the summer months; The stations with higher predicted On-Board Error occurrences were all identified as potentially Departure station, meaning that there is an significant probability of a train starting its service without an active ATP.

The explanatory variables defined to characterize operational conditions such as train flow and signaling density proved to be statistically significant, with both errors being more frequent in locations with high traffic and signaling density.

Lastly, by combining the results of the two errors analyses, it was possible to predict the railway lines and stations with higher occurrences where ATP system is not available as SPAD inhibitor.

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Appendix

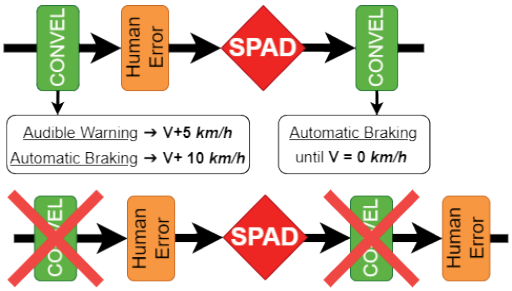

Figure A1 - SPAD sequence for ATP equipped railway tracks and train (top) and with absent ATP system (bottom)

Table B1 - List of variables for the Analysis of the On-Board System

Variables	Average	Std. Deviation	Minimum	Maximum
Y1	0.149	0.658	0	33
Start	0.083	0.277	0	1
nTrain/100	15.339	18.693	0	104.61
Balise/km	8.008	7.935	0	35.781

Table A2 - List of variables for the Analysis of the Infrastructure System

Variables	Average	Std. Deviation	Minimum	Maximum
Y2	6.333	25.076	0	606
Start	0.091	0.288	0	1
nTrain/100	18.253	19.957	0	104.61
Balise/km	12.615	9.615	1.703	39.162

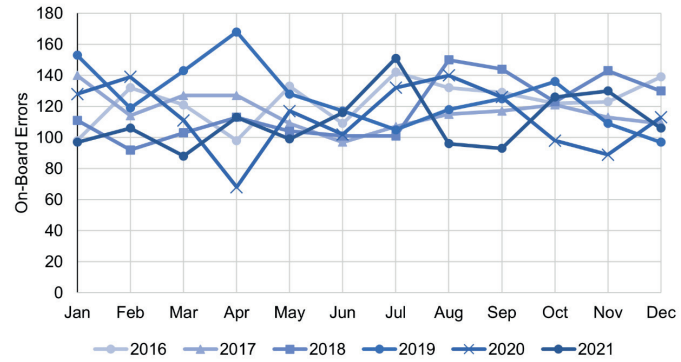

Figure A2 - Monthly reported On-Board System Errors (2016-2021) in the Portuguese Railways

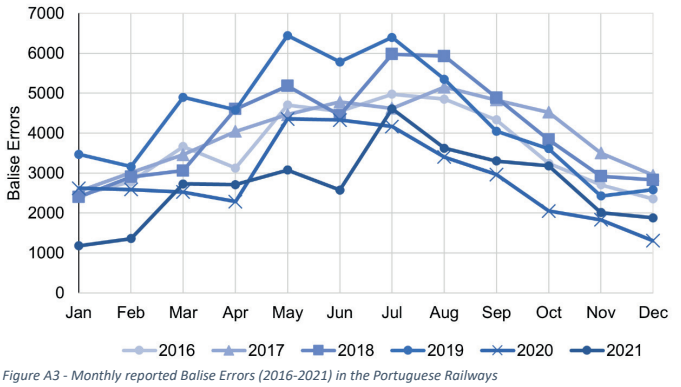

Figure A3 - Monthly reported Balise Errors (2016-2021) in the Portuguese Railways

General traffic simulator for railway

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Key words: Digital model, Traffic management, Prototyping, System engineering

Main objectives of the works

As part of my 2022 master 2 internship on railway testing at IKOS Consulting, I had been asked to provide for a tool that could be able to help prototyping and testing several signaling systems on every possible track and train configurations. In order to investigate on the ways of railway simulation, I spent the first two months at Alstom Valenciennes working on their "TrainLabs". TrainLabs are digital models of the railway stock, sometime combined with real hardware such as doors or passenger information systems that are used to spot design flows, make fast diagnosis, and make maintenance easier. They are exact replica of the on-board circuitry and thus are specific to one type of rolling stock only and do not allow for fast prototyping and testing of the entire railway system. Using this method to certify sub-system without the need of costly field tests has been a research topic during the Shift2Rail initiative [1].
SNCF's DGEX, willing to provide territorial agencies and consultants for an easy and highly compatible railway track prototyping tool is developing the OSRD software (Open Source Railway Designer). This ongoing project is a user-friendly software but does not allow for easy in-depth modifications. Other private projects have also flourished such as SIMONE, a testbed for ETCS and CBTC, but are not accessible to researchers.

Contributions

In order to provide for a tool able to help researchers prototyping and testing new railway signaling systems, I have decided to follow the engineering rules "modularity, simplicity and fidelity". Modularity is provided by the structure of the script. Every main sub-system has its own plug and play module with specific interfaces and can be easily replaced or customized.
To have a simple simulator, python scripts have been used, Python being one of the most used language by researchers and engineers. I have then defined a common system architecture that could be used for main lines but also for subways, tramways, light trains and new systems such as Hyperloop, Urbanloop or Spacetrain as schematized in figure 1.

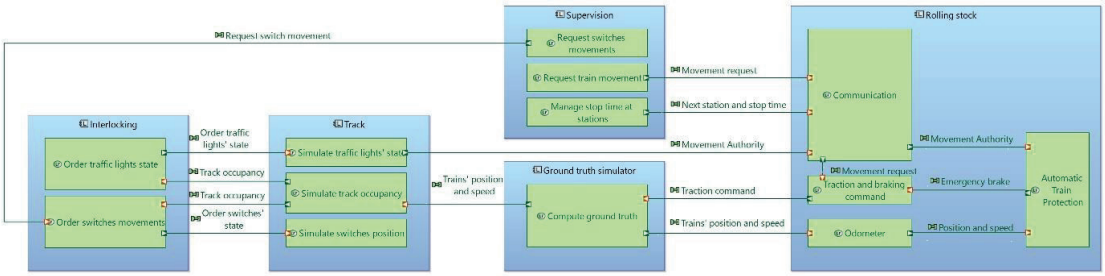

Figure 1 Main system architecture

In figure 1, the blue boxes represent plug and play modules and the green ones the main fully customizable functions.
In the "ground truth simulator" module, I have considered tensile force, running resistance force and adherence. "Rolling stock" emulates the traction commands allowing manual or automatic

driving and includes an Automatic Train Protection that I have adapted from the ERTMS standards in subset 76. "Track and interlocking", implemented with another intern, includes an easy-to-use track configurator based on Excel and interlocking and signaling rules based on [2]. Supervision provides for programmable train and track supervision.
Fidelity is being ensured by testing on real life applications. I have used the simulator on Paris' subway and on main lines using timetables, train configurations taken from Wikipedia and track configurations coming from Google Maps, Carto Graou and cartometro.com. Trials have shown promising accuracy on train positioning.

Future works and perspectives

In continuity of my work, a 2D simulation of trains' position is currently being implemented. Using SNCF's railway shapes available at ressources.data.sncf.com, this planar emulation will provide for WGS84 coordinates enabling the simulation of GNSS signals received by the trains. It will be used in a PhD on cooperative positioning for GNSS [3] to gather GNSS data received by a fleet of trains and test a software real time prototype.
In future projects aiming at creating the first test line for light trains, this railway simulator should become the basis of the test line's digital model. It could then provide manufacturers for an integration testbed for systems they would be testing on the real track.

Conclusions

This new traffic simulator, by following the rules modularity, simplicity and fidelity, is a tool specifically shaped for research and prototyping on railway signaling systems able to emulate an entire railway system with every possible track, train, signaling system and operation scenario. It has already found applications on training courses, industrial prototyping and research and will keep evolving to be even more flexible and accurate.

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Examining the Impact of Metro Expansion and Automation on Driver Resources: A Case Study of the West Midlands Metro Network

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KEYWORDS
metro automation; driver resources; metro expansion.

OBJECTIVES

The research objective is to thoroughly examine how the West Midlands metro system's expansion and automation will affect the need for drivers. This research is specifically designed to accomplish the following research goals:

- To assess the present West Midlands metro system in order to get a baseline knowledge.
- To analyse the possible expansion of the West Midlands metro network.
- To investigate the changing work profiles for drivers in light of the metro growth and automation.

Overall, this research offers useful information on how need for drivers is changing as well as the wider implications of the automation and expansion of the West Midlands metro network. The objective of this research is to enhance comprehension of worker dynamics within the rapidly growing transportation sector through the utilisation of publicly available data and simulation models. The focus of this study is to provide recommendations for the management of driver resources in the context of metro development and automation. These recommendations aim to support rational decision-making and efficient metro system management.

CONTRIBUTIONS

- Addresses the timely issue of metro expansion and automation's impact on driver resources amid a global trend.
- Offers unique insights into West Midlands Metro Network's experience through a case study, benefiting similar urban expansions.
- Fills a knowledge gap by providing insights crucial for informed decision-making in public transportation planning and policymaking.
- Suggests enhancements in resource allocation within metro networks, optimizing human resources and leveraging automation.
- Provides insights into potential employment consequences for drivers in an increasingly automated sector, enabling proactive preparation.
- Holds practical implications for various stakeholders in public transportation systems, fostering informed decision-making.
- Contributes to broader academic discussions on sustainable development, resource management, technology adoption, and workforce dynamics.

FUTURE WORKS AND PERSPECTIVES

The findings derived from the process of modelling and simulating the current operations of the West Midlands Metro provide valuable insights that may be used to enhance efficiency and customer satisfaction throughout the whole network. The identification of discrepancies in service delivery and variations in asset utilisation across different stations reveals opportunities for optimising resource allocation and optimising service level performance. The rectification of shortcomings may be accomplished by focusing on stations that exhibit inadequate services or are not fully utilising their potential, as shown in the study. It makes strategic sense to focus improvement efforts on these particular hotspots due to resource restrictions. This exemplifies the ability of operational analytics to provide actionable information for the progression of metropolitan operations. Furthermore, it is worth noting that the SIMUL8 platform has significant importance as it functions as a useful analytical instrument that goes beyond the confines of only assessing the present state of things. The method's ability to effectively describe complex and dynamic systems makes it well-suited for analysing hypothetical situations as well. The existing network model has the potential to be extended in order to assess

the impacts of various automation tactics on anticipated extension routes before they are put into practise. This would provide substantial understanding on the technological, operational, and workforce implications across several development paths.

When developing infrastructure, such as the proposed West Midlands Metro expansions, it is essential to meticulously evaluate the many aspects that impact the incorporation of automation. Both the literature review and case studies emphasise the significance of adopting a gradual and phased methodology for improving power, signalling, and rolling stock systems rather than following a strategy of large-scale and instantaneous deployment. The integration of modern technology necessitates continuous updates to new lines in order to ensure smooth compatibility over time. By using a progressive methodology, it becomes feasible to methodically address technological obstacles while concurrently guaranteeing the reliability of new infrastructure before progressing towards more advanced stages of automation. The evaluation of such initiatives has shed light on the need for detailed planning for expansions and the possibility of automation in such endeavours.

The anticipated schedule that predicts the gradual integration of automated grading systems provides significant information about the preparedness of the workforce. The initiation of partial automation inside the GoA2 system allows for the attainment of operational stability before the eventual shift to full driverless capabilities. The concept of incremental growth aims to achieve a harmonious equilibrium between rapid implementation and the demands associated with change management. The roadmap enforces stringent governance protocols to authorise the progression of each step only upon thorough verification of severe requirements. However, it focuses on ambitious timetables that align with benchmark metro systems. By using rigorous project management strategies and effectively mitigating risks, this roadmap has the potential to guide the growth of the West Midlands metro towards attaining exceptional levels of automation, passenger service, and operational excellence on a global scale. The use of a staged strategy mitigates the risks associated with this intricate shift while simultaneously prioritising safety.

The examination of trends suggests that the changing responsibilities of drivers require the implementation of proactive initiatives. The significance of reskilling and upskilling becomes apparent when contemplating the supervision of automated activities and the potential occurrence of obsolescence. The effective facilitation of the integration stage can also be achieved through the implementation of new supervisory and customer service positions. Additionally, it is crucial to provide programmes that support affected workers in order to effectively manage the disruptions that may arise. Most importantly, higher education in the rail industry can be updated to match the industry requirements. Engaging stakeholders is important as it fosters understanding of the anticipated effects of advanced metro automation.

In order to effectively navigate the challenges and opportunities presented by the expansion of metro networks and automation technologies, it is essential to adopt a well-rounded and equitable approach. This approach should aim to maximise the advantages brought about by these advancements, while also taking into account the potential negative effects on the workforce. To achieve this, it is important to implement timely reskilling or upskilling initiatives and comprehensive change management programmes. By doing so, we can ensure a smooth transition and create a sustainable and inclusive future for all.

CONCLUSIONS

The potential of transport innovation to augment the workforce is quite significant. The primary objective of this research was to examine the impact of two often-seen transit phenomena, namely network expansion and automation, on driver resources. The West Midlands area was chosen as a case study for the purpose of this research.

The use of a mixed-methods methodology, including the integration of case study analysis, forecasting, and literature review, resulted in the acquisition of diagnostic, predictive, and prescriptive insights about the efficient administration of change. The research revealed the need for progressively integrating automated integration throughout the process of growth. It was shown that the duties associated with driving will gradually decrease.

The primary implications of this research include the incorporation of analytics into the decision-making process, namely within the domain of planning, and the formulation of workforce policies that are congruent with projected shifts in job roles. Nevertheless, it is important to underscore that the workforce needs to retain its central position in the realm of innovation. The manifestation of development should be consistent with the group's common objectives.

In recent times, the railway sector has seen the initiation of several educational and workforce development initiatives through a range of European Union (EU) and international programmes. Within the

domain of European transport projects, it is crucial to recognise the presence of many notable undertakings. Among the several projects mentioned, namely "ASTONRail project (funded by ERASMUS+), STAFFER project (funded by ERASMUS+), EURNEX, SKILLRAIL, and SKILLFUL", it is noteworthy to highlight their significance as notable endeavours. These efforts are primarily focused on enhancing the worldwide capabilities needed to efficiently handle the many disruptions that have arisen as a result of advancements in the sector.

Transport authorities need to proactively foster widespread innovation that yields societal advantages at large. The enhancement of worker empowerment plays a pivotal role in exerting influence and fostering transformative processes within organisational contexts. In addition, it is crucial for communities to actively engage in the process of providing their own ideas and opinions. Urban regions have the capacity to successfully amalgamate technological breakthroughs with robust social awareness via the exhibition of confidence, attention, and a collective spirit.

This research signifies a noteworthy achievement in the ongoing effort to provide fair and ethically sound opportunities for mobility in the next few years. Continuous study is required to understand the complex dynamics of transportation. In this particular setting, there is a notable potential for the improvement of the labour force, under the condition that we demonstrate a collective commitment to its joint construction.

THERMAL STUDY OF BRAKING IN FREIGHT TRAINS

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Key words: tread braking, thermal model, finite difference, 1D and 2D model comparison.

Main objectives of the work

Train braking is a critical aspect for railway safety. This master thesis focuses on evaluating the thermal field evolution established in the contact between the railway wheel and the brake blocks. Commonly used in freight trains, this type of brake is favored for its reliability, cost-effectiveness, and design simplicity. However, it generates frictional heat, leading to thermal fatigue stress and subsequent wheel damage (e.g. wear), resulting in reduced wheel life. To enhance operational safety, optimize system design, and streamline maintenance management, predicting the evolution of the wheel temperature field during braking is of particular importance.

Historically, studying this phenomenon involved expensive and time-consuming dynamometric bench tests, especially when examining various system variations, such as wheel speed and braking power. Modern solutions leverage finite element (FE) models, categorized into 1D radial, 2D circumferential, 2D axisymmetric, and 3D, as presented in the literature.

In this thesis, the focus shifts to finite difference (FD) models for their computational efficiency. Specifically, circumferential 2D, see (1); axisymmetric 2D, see (2); and radial 1D (equation (3) refer just to wheel for brevity) FD models have been developed. While the results of the circumferential and axisymmetric FD models were benchmarked against existing literature FE findings, the equivalent parameters of the 1D FD model were determined through a comparative analysis with the developed axisymmetric 2D FD model.

$$\frac{\partial T}{\partial t} = \kappa\left(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2}\right) \tag{1}$$

$$\frac{\partial T}{\partial t} = \kappa\left(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{2}$$

$$\frac{\partial T_w}{\partial t} = \kappa_w \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_w}{\partial r}\right) + \frac{1}{\rho_w c_w (R_w - L_w)}\left(\lambda_w \frac{\partial T_w}{\partial z}\bigg|_R - \lambda_w \frac{\partial T_w}{\partial z}\bigg|_L\right) \tag{3}$$

Where the suffix "w" is used for wheel; T is the temperature; t is the time; κ, c and λ are respectively thermal diffusivity, specific heat, and conductivity; r, z and θ are respectively radial axial and circumferential coordinates; R and L are respectively the "right" and "left" axial border coordinates.

Reproducing FE results from Bosso et al. [1] for the circumferential model and Vernersson [2] for the axisymmetric model, Figure 1 visually depicts the comparisons between FE and FD models.

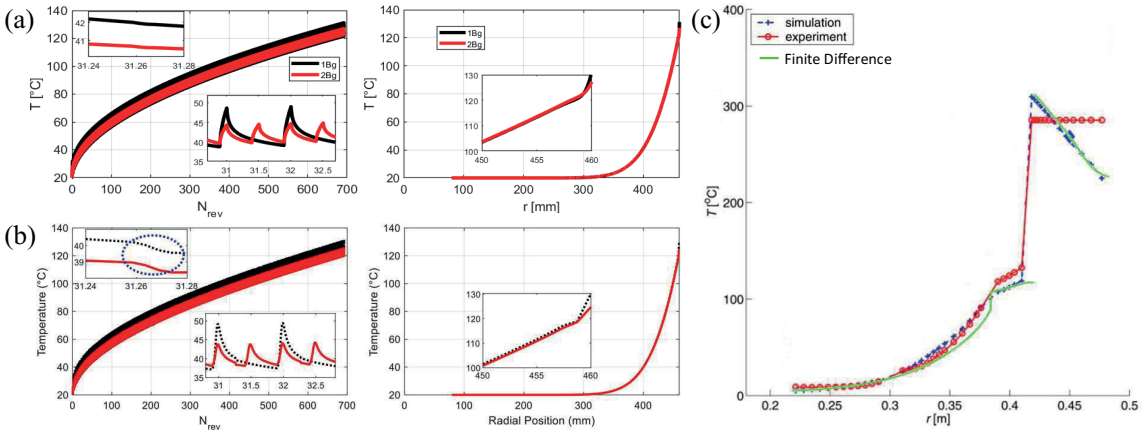

Figure 1. (a) Results of the 2D Circumferential FD model, (b) Results of Bosso et. al. [1], (c) Comparison of the results obtained from 2D Axisymmetric FD model (in green) with those of Vernersson [2].

As evident from the results, FD closely replicate the outcomes obtained through FE models, confirming the accuracy and effectiveness of the FD approach.

Figure 2 illustrates a minute-by-minute comparison between temperature of the developed axisymmetric 2D FD model averaged along the axial direction (T_{1D}^{ax}) with the temperature from the 1D FD model (T_{1D}) over a 5-minute braking period. As observed, the 1D FD model accurately reproduces the results of the

axisymmetric 2D FD model when averaged along the axial direction, demonstrating a computational advantage of more than two orders of magnitude over the latter.

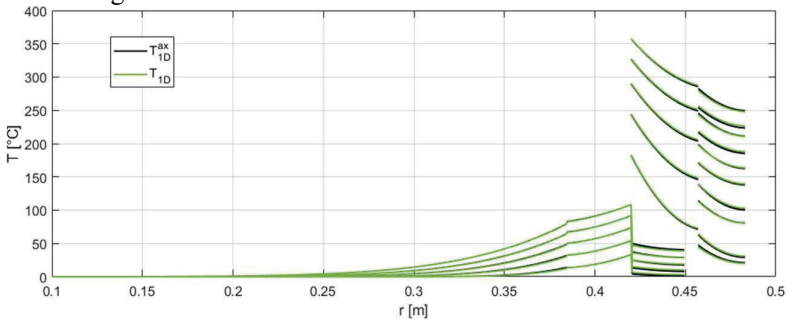

Figure 2. Comparison of the averaged axisymmetric 2D FD model temperature in axial direction with calibrated 1D FD model.

Contributions

The contributions of this thesis work include:

- Introducing the application of FD to investigate the thermal field in tread braking.
- Developing a calibrated and fast 1D FD model derived from an axisymmetric 2D FD model.

Future works and perspectives

The future developments of this study are outlined below:

- Integrate the fast 1D FD model into TrainDy to contribute to the study of longitudinal train dynamics (LTD). This model can account for the dependence of the wheel/rail friction coefficient, and consequently, the braking force of each wagon, on the temperature of the wheel and block. Additionally, the 1D FD model can facilitate the thermal calculation of the rail, considering that the wheels of the first wagons are in contact with a 'cold' rail, while those of the last wagons are in contact with a 'hot' rail.
- Utilize knowledge of the thermal field to enhance the precision in characterizing the wear of friction components during the specific braking history of the train.
- Extend the application of FD to encompass the thermal study of disc brakes as well.

Conclusions

Overheating of the wheel during braking by brake blocks is a significant issue due to its adverse effects on wheel life and the potential risk of train derailment in severe cases. Extensive international scientific literature has focused on developing models to predict the thermal field evolution of the wheel and block during braking. This master thesis has contributed by creating thermal models that analyze the temperature evolution in the contact between the wheel and blocks, utilizing the FD method. The developed models include a 2D circumferential model, a 2D axisymmetric model, and a 1D radial model.

The two 2D models differ in the degrees of freedom they consider and in the variability of the different thermal fields they provide. Specifically, the circumferential model allows the derivation of hot spot temperatures by neglecting axial effects, while the axisymmetric model provides average temperatures in the circumferential direction. Computationally, the circumferential model is found to be disadvantageous compared to the axisymmetric model, due to the large grid density it requires for convergence. This is because the axisymmetric model considers average heat fluxes over the entire outer part of the rim, while the circumferential model must sustain large thermal gradients over the entire block contact zone.

The creation of the 1D model, calibrated in the present work against the more widely used axisymmetric 2D model, has a computational advantage of more than two orders of magnitude over the latter.

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FLEXIBLE PROJECT MANAGEMENT IN HIGHLY REGULATED RAILWAY SIGNALLING PROJECTS

Link: Flexible project management in highly regulated railway signalling projects (diva-portal.org)

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Keywords: Signalling, Railway, System development, Lean Philosophy, Stage-Gate Process

Railway is a complex system, with many components that are linked with one another. If a failure occurs in a sub-system, it can affect the functionality and the safety of the whole. Signalling represents a crucial component of the railway system because it ensures safety, and it optimizes capacity on the lines. In Europe, private companies control the development and the implementation of new signalling equipment in the railway lines. However, railway signalling systems must satisfy the European standards, which evolve year by year and client requirements. These delimitations limit the possibility to change the generic system development process and it often leads to apply the same processes in each project, without adaptations according to each project needs, which would lead to a leaner and more optimized process in terms of time and resources employment.

Recently, Alstom Rail Sweden AB performed the implementation of a new signalling system in a depot, located in Älvsjö, in the south area of Stockholm. A depot can be considered a simplified environment because the speed of vehicles is restricted and consequently less safety measures are required in respect with the usual railway track, where trains can travel up to 200 km/h in Sweden. Therefore, considering the simplification, the system implementation has considered *only* the safety measures essential for the system.

In this Master Thesis, Älvsjö depot project has been compared with another depot project that was performed according to the procedure applied in all Alstom signalling projects. The comparison project project took place in another depot, located in the northern area of Stockholm, in Hagalund. In the comparison, the parameters taken into consideration are the resource allocation and the project days of delay. The results from the data have revealed that initial project delay can be caught up through process tailoring according to the features of a project. Furthermore, the comparison has proofed that general standardization, given by a Stage-Gate process, can be useful to provide a common structure to every project. On the other hand, to optimize the process, complex projects require flexibility and the elimination of superfluous steps, which summarize some of the Lean philosophy principles.

Railway industry is in constant innovation and evolution on the technical and legislation aspects; however, the system development processes often are overlooked. Employing redundant processes can have an impact on the outcome for example through project delays or mistakes and in a complex industry like the railway, several stakeholders could prevent the consequences of a redundant process with optimized system development processes.

Due also to the complexity of the systems implemented, this is a vast topic that could open the doors to further research through the analysis and comparison of different aspects regarding pilot projects, that have employed different system development processes in different European countries.

Untersuchung des entstehenden Radprofilverschleißes bei der Weichenfahrt

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Key words: vehicle dynamics, switches & crossings, multibody simulation, wheel wear

Wheel wear is a relevant topic in the maintenance of rail vehicles. The life expectancy of a railway wheel is about 300 000 to 2 500 000 km of track [4]. With a turnout density of about 1 turnout per line kilometre, wheel wear during turnout travel cannot be completely neglected. Special dynamic processes play a role in the turnout, which influence material removal and the development of rolling contact fatigue.

The investigation of wheel wear during turnout travel was carried out with the help of multi-body simulations using the software SIMPACK. The turnout models from the S&C benchmark [1] were used for the investigations, as well as the vehicle models of the FLIRT 3 and the Manchester benchmark vehicle for passenger traffic [5]. Different wear modelling methods were investigated and implemented for the evaluation. The distribution of material removal and rolling contact fatigue over the wheels of the vehicles and the contact points between wheels and rails were investigated. The influence of the coefficient of friction, the diverging track radius, the speed and the direction of travel was investigated. Subsequently, a simplified turnout model was presented for the simulation of the diverging track of the turnout.

The friction coefficient has major influence on the wheel wear prognosis. Higher speeds result in greater material removal and less predicted rolling contact fatigue. The direction of travel has little influence on the rolling contact fatigue and material removal distribution. In general there is more material removal and rolling contact fatigue predicted for the diverging track scenarios than for the through route scenarios. In the through route scenarios studied, the nose of the crossing and the switch rail are particularly relevant to the amount of wear and the prediction of rolling contact fatigue. In the diverging track scenarios, the wear is dominated by the wear in the curve, but the transition to the switch rail has also an influence. Here it was observed that the leading wheelsets in the bogies experienced increased material removal compared to the following wheelsets. The predicted amount of fatigue on the material surface is similar in a curve and in the diverging track of a turnout. Sub-surface

fatigue is less common than surface fatigue. For the prediction of material removal and rolling contact fatigue in the diverging track of a turnout, it has been shown that for most investigations it is sufficient to model the switch area without the crossing area. Simplified turnout modelling significantly reduces simulation times. The through route scenarios should continue to be analysed in the turnout model with the crossing. To determine material removal, the Krause and Poll [6] wear model is well-suited. Ekberg's model [3] is the most reliable for predicting rolling contact fatigue. If rolling contact fatigue and material removal are to be considered together, the Burstow model [2] can be used. The result of the master thesis is a comparatively low wheel wear in the turnout, related to one turnout run per line kilometre with line wear.

Future investigations of the topic should consider varying vehicle parameters such as damping stiffness, axle load, wheel diameters, and axle distance, as well as examining the influence of worn wheel profiles. Additionally, the simplified turnout model developed in this study should be further tested. If the different turnout scenarios experienced by a vehicle wheelset and their respective frequencies are known, they can be combined to form an average turnout scenario. The evaluation of the wheel wear in this scenario would support the more detailed determination of the influence of switches and crossings on overall wheel wear.

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PhD-abstracts

ADVANCING KNOWLEDGE MANAGEMENT FOR SYSTEM INTEGRATION

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Key words: knowledge sharing; lessons learned; railways; tacit knowledge; LEAF

- Main objectives of the works

Reliable public transport is crucial in contemporary society. The demand for greater safety, faster interconnectivity and environmentally friendly public transport solutions imposes great challenges on European railway organisations. Combined with these regulatory and public demands, recent technological advances in European traffic management systems and the digitisation of trains make it inevitable for policymakers and transport organisations to improve their knowledge management systems. Effectively managing lessons learned in the complex sociotechnical domain of today's European railway network is imperative to avoid repeating the same mistakes and to deliver promised system performance to the European public. This research explores current knowledge management practices for large-scale technology projects in the Dutch railway network with the aim of improving organisational learning and increasing system performance.

Conducted over a period of three years in the Dutch railway sector, the research focuses on developing an approach for effectively managing the lessons learned from large-scale technological projects, such as the introduction of new trains and the implementation of the European Railway Traffic Management System (ERTMS). It presents several practical and scientific cases in these areas and emphasises the need for managing both tacit and explicit knowledge to facilitate organisational learning, avoid project delays, and cost overruns.

Three main research objectives are outlined: explaining lessons learned and current problems in their management, providing insights into their improvement, and supporting transport organisations in embedding the identified insights into their processes. Eleven research questions guide a mixed-methods approach to explore these objectives.

- Contributions

To achieve the first objective, a conceptual framework called the LEAF (Learnability, Embraceability, Applicability, Findability) framework has been developed. To achieve the second objective, case studies were then conducted to test and extend the framework, revealing the importance of mutual trust and technological findability. The third objective was achieved by prescribing strategies, including fourteen principles for effective system management, a collaborative knowledge platform, a virtual reality-based learning system and a blockchain-based platform for knowledge sharing. These contributions were shared with the academic community through eight scientific peer-reviewed publications (Abbas, 2022).

- Future works and perspectives

Future work includes conducting explanatory research to outline the rationale behind the identified dependencies of LEAF characteristics and identify inter-correlations. Future research may also conduct targeted studies where the direct impact of promoting LEAF characteristics for knowledge management of lessons learned in a project team can be investigated based on individual project KPIs, such as project cost and system reliability.

- Conclusions

In conclusion, this research provides policymakers and railway organisations with the necessary tools to improve organisational learning and system performance by clarifying the main problems with the management of lessons learned, describing the necessary features to be improved and prescribing strategies for effective knowledge management of consolidated lessons learned.

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IMPACT ASSESSMENT OF TRAIN-CENTRIC RAIL SIGNALLING TECHNOLOGIES

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Key words: railway signalling, impact assessment, moving block, virtual coupling, roadmapping

Main objectives

Researchers and professionals in the field of railway transportation face the crucial need of determining the viability of implementing new signalling technologies across diverse rail market segments and assessing their advantages over conventional railway signalling while ensuring safety. Given that official approval from local authorities and governmental agencies is required for deploying new railway technologies, a well-defined strategy is essential to guide investment decisions and the overall system migration process. The focus is on ensuring that proposed railway technologies enhance operational efficiency and guarantee safety for both passenger and freight transport. While Moving Block (MB) relies on radio-based communication and continuous train position and integrity updates, Virtual Coupling (VC) introduces advanced concepts, significantly reducing train headways through synchronized platooning facilitated by Vehicle-to-Vehicle (V2V) communication and coordinated braking and driving. However, uncertainties persist regarding the safety validation and feasibility of VC, necessitating a comprehensive examination from technical, financial, and regulatory perspectives. Therefore, this research aims at assessing the performance, safety, and feasibility of VC with respect to MB by deriving and evaluating specific design configurations.

Contributions

This PhD thesis provides substantial contributions to both the scientific community and society. Scientifically, it explores the market potentials and operational scenarios of VC through a 'Strengths, Weaknesses, Opportunities and Threats' (SWOT) analysis, and conducts a hybrid Delphi-Analytic Hierarchy Process (Delphi-AHP) multi-criteria analysis to assess the impacts of rail signalling innovations, specifically MB and VC, across eight criteria. These criteria are infrastructure capacity, system stability, energy consumption, lifecycle costs, travel demand, safety, public acceptance, and regulatory approval. The definition of new Key Performance Indicators (KPIs) and a comprehensive framework integrating multiple cross-disciplinary methods for the evaluation of technical, technological, operational, and societal/regulatory criteria adds significant value to the railway literature. Moreover, this thesis develops a roadmapping framework and scenario-based roadmaps for VC deployment by performing a gap analysis and identifying step-changes between current and future states of the railway sector in terms of operational, technological and business perspectives. Additionally, it introduces a Fault Tree Analysis-Stochastic Activity Network (FTA-SAN) approach that aims at better understanding complex system behaviour and the impact of braking applications and failures of design variables on safety and performance.

Societally, the research offers valuable insights for the railway industry, aiding in strategic planning, decision-making, and the development of safer and more efficient rail systems to five market segments, namely high-speed, mainline, regional, urban and freight. The societal relevance of this thesis extends beyond the technical domain, as the proposed tools and methods in this thesis support the design and assessment of more capacity-effective railway systems, which can increase flexibility and satisfaction of customers' travel needs. Moreover, the research indicates that VC has the potential to enhance safety, comfort, and efficiency in railway services, making rail transport more attractive and

environmentally friendly. The exploration of VC's impact on different market segments, including its potential benefits for freight services and flexible train operations, reinforces its societal relevance and contribution to sustainable and advanced transportation solutions.

Future works and perspectives

Future research directions include investigating the impact of demand variation on rolling stock composition during peak and off-peak hours under VC, expanding the FTA-SAN approach to higher-level modelling artifacts and detailed use cases, addressing communication technology gaps, and developing standardized requirements for VC deployment. Specifically of interest are exploring the design of optimized compositions of VC convoys, and evaluating the flexibility offered by VC and the potential implementation of on-demand train services for both passenger and freight railways. Moreover, a deeper study on the information architecture and information flow of cooperative systems can lead to a higher performance of VC operation. These future research directions aim to deepen understanding, improve the safety-performance analysis, and enhance the applicability of VC in diverse scenarios. Further recommendations for practice include developing tailor-made scenario-based roadmaps that relate to the operational characteristics of each market segment, where for instance roadmaps would include the possibility of either segregating the platforms into sections delimited by boards (e.g., to regional and urban railways) and/or by physical barriers and platform doors (e.g., to high-speed and mainline railways). Moreover, in the case of a pessimistic scenario where longer durations are required to complete a certain step-change, a re-ordering or re-classification of the priorities of the defined actions could provide a more optimal path towards the deployment of the investigated technology. These recommendations can further support infrastructure managers, railway undertakings, and decision-makers in identifying critical scenarios and accelerating the implementation of action plans.

Conclusions

To conclude, this PhD thesis effectively addresses the main objective of evaluating train-centric rail signalling technologies for different market segments. It contributes to the railway field by developing methodological frameworks that support the analysis, assessment, and development of complex systems and next-generation rail technologies. The interdisciplinary approaches integrated into the proposed frameworks address complex decision-making processes, including market potential analysis, impact assessment, roadmapping, and safety and performance evaluation. The findings emphasize the crucial role of safety in VC deployment, and provide practical recommendations for stakeholders in the railway industry to foster technological developments and steer the necessary regulations to the migration towards effective train-centric operations.

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DEVELOPMENT OF CONDITION-BASED TAMPING PROCESS IN RAILWAY ENGINEERING

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Keywords: Condition-based Track Tamping, Operating Phases and Motion Behavior, Ballast Condition Determination, Ballast fluidization

Main objectives of the works

Maintenance of ballasted tracks becomes an increasingly demanding task with the continuous increase of railway traffic of both passengers and freight. Nowadays, most of track maintenance work is conducted using modern tamping machines. The process of lifting, leveling and non-synchronous, directional constant pressure tamping has been proven to provide optimal results regarding continuous ballast compaction and restoration of initial track geometry.

Most desirable method of track maintenance, from an economic point of view, is condition - based predictive maintenance. This method dictates that decisive parameters should be adjusted to the encountered track condition. State-of-the-art tamping machines, however, operate with previously defined tamping parameter combination, whereby only a minority of parameters are adapted to the ballast bed condition.

Research conducted in the scope of this thesis investigates fundamentals of the tamping process and the soil mechanical component of ballast compaction. For this purpose, comprehensive investigation of the track tamping process during regular track maintenance in different ballast conditions is conducted, primarily focusing on the interaction between the tamping tine and the ballast matrix during ballast compaction. For the very first time, these two components are observed on a vibration cycle scale, and a new method of measuring and interpretation of their force-deformation relationship in form of a load-displacement diagram is developed. This presentation made it possible to determine tamping characteristics, such as reaction force and compaction energy, that result from a given set of tamping parameters. Comparison of tamping characteristics between tamping machine employment at different locations made it possible to clearly identify the ballast bed condition based on its interaction with the tamping tine. This observation represents the base for future development of condition-based tamping process in which the tamping parameters would be adapted to the ballast condition measured by the machine during tamping.

Irrefutable evidence of a periodic loss of contact between tamping tine and ballast matrix is presented based on contact points obtained from load-displacement diagrams. Existence of this contactless phase in each vibration cycle reduces ballast wear and has a positive influence on the compaction process. Soil dynamic behavior of track ballast during compaction was investigated and in-situ tests were conducted to enable a qualitative description of track ballast dynamic fluidization, a phenomenon that plays a decisive role in clean ballast compaction by both tamping unit and dynamic track stabilizer.

A numerical simulation of the tamping tine - ballast matrix interaction during compaction was developed, providing the possibility to model continuous fouling of the track ballast by adjusting one single parameter - elastic stiffness of the ballast model. Model calibration was conducted using in-situ measurement results and it was utilized to carry out a comprehensive study of tamping parameters and their effect on the load-displacement curve and tamping characteristics.

Contributions

Measurement system and analysis algorithm presented in this thesis provide the possibility to transform and upgrade the tamping unit from track maintenance into a Smart tamping tool, resulting

in optimization of the tamping process and a prolongation of ballast life cycle, while increasing the quality of the whole track system.

Future Works and Perspectives:

Moving forward, several avenues for future research and practical applications emerge from the findings and innovations presented in this thesis:

Advanced Condition-Based Tamping Development:

The identified method for ballast bed condition identification lays the foundation for the development of more sophisticated and adaptive condition-based tamping processes. Future research should focus on refining and expanding these methods to enhance their efficacy in diverse railway environments.

Numerical Simulation Refinement:

The numerical (mechanical) simulation model introduced in this study provides a valuable tool for understanding the tamping process. To enhance its practical utility, future efforts should concentrate on refining the model by incorporating additional variables and real-world complexities, ensuring a more accurate representation of tamping dynamics.

Field Implementation and Product Development:

The Smart Tamping System that is being developed as a product based on the findings from this thesis, other research initiatives, transforms railway maintenance through adaptive tamping, dynamic fluidization control, and data-driven optimization. This innovation promises extended ballast life, enhanced track quality, and cost savings, marking a significant stride toward sustainable and efficient railway infrastructure management.

Exploration of Smart Maintenance Technologies:

The conceptualization of the Smart tamping tool opens the door to broader considerations of intelligent technologies in railway maintenance. Future research should explore the integration of smart technologies beyond tamping, exploring possibilities for automation, data analytics, and real-time monitoring to optimize overall railway infrastructure management.

Conclusions

In summary, this research has revealed crucial insights into the tamping process, ballast compaction, and the interaction between the tamping tine and ballast matrix. The contributions made, including the introduction of a novel measurement method and the proposal of a Smart tamping tool concept, have significant implications for the future of railway maintenance. By embracing these advancements, there is potential for increased efficiency, sustainability, and an overall improvement in the quality of railway track systems. The call to action is clear: continue the momentum of research and implementation for the betterment of railway infrastructure worldwide.

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Train Based Automated Inspection for Railway Fastening System

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Key words: Rail fastening system; visual inspection; differential eddy current sensor; machine learning; anomaly detection.

The current demand on the railway industry necessitates heightened capacity utilization, adding stress to the infrastructure and imposing time constraints on maintenance activities. At the same time, there is a mandate to preserve or enhance the performance and operational capacity of the existing infrastructure. A cost-effective and feasible way of improving capacity utilisation of the current infrastructure can be ensured by successive improvement of the maintenance and renewal process. With the increase in capacity utilisation the track is subjected to higher traffic load and speed, thus leading to a reduction in infrastructure quality and degradation to its components. Failure of components leads to unplanned corrective maintenance activities resulting in delay and reduction in capacity utilisation. Hence the track and its components need to be periodically inspected to decrease interruptions of train operation, reduce cost, and ensure safety.

Monitoring the condition of railway fasteners is essential to ensure train safety, as failures of fasteners may lead to train derailment due to gage widening or wheel climb. In Sweden, the intervals for fastener inspections are fixed by the Swedish Transport Administration (Trafikverket) based on the traffic load and speed subjected to the track and are carried out manually by trained maintenance inspectors or by using measurement cars. Manual inspections are laborious and time-consuming and pose safety concerns for the maintenance personal involved. Fastener inspections employing vision methods on measurement car requires track possession and thus has limited capabilities in terms of inspection frequency. A previous study has shown that the winter season in Sweden has the largest problem with train delays due to the failure of components in track and S&C (Asplund 2014). The inclement weather conditions during the month of November-March, especially in the north of Sweden, inhibits regular fastener inspection that depends on the above-mentioned traditional inspection methods. Hence, the focus of this research performed for this thesis has been directed on finding an automated method for fastener inspection that can be carried out using vehicle-mounted measuring equipment operating in regular traffic.

Firstly, a study was carried out to determine the effectiveness of automated visual-based solutions for fastener state detection. An anomaly detection model combining image processing techniques and deep learning algorithms was developed to detect the fastener state from rail images captured during the vision-based inspection. The model had a high capability of detecting the fastener state from the rail images. However, the model had difficulties detecting the fastener when there were instances of occlusions of fasteners due to the presence of snow and ballast stones and when the image brightness was low. In Sweden, specifically the northern part of it, the fastening systems are covered under snow for up to six months and thus can inhibit regular fastener inspections that rely on such automated visual inspection methods.

To overcome these challenges, this research aims to develop an automated monitoring system based on an in-service train installation, artificial intelligence and a robust magnetic field sensor to enable continuous monitoring of track components during regular operation. Controlled field measurements were carried out along a heavy haul railway line in the north of Sweden to determine the effectiveness

of the proposed differential eddy current measurement system. An anomaly detection model based on a supervised machine learning algorithm was developed to detect the fastener state from the controlled eddy current measurements. Further, to test the effectiveness of the eddy current sensor during real-time measurements, the proposed sensor system was mounted on an in-service freight train, and measurements were carried out along the iron ore line of Sweden. An anomaly detection model using unsupervised machine learning algorithms was developed to facilitate fastener state detection and detect other anomalies from the real-time measurement data.

The proposed differential EC measurement system was able to detect fastener signatures when mounted on an in-service train, 110mm above the railhead. The proposed anomaly detection model was able to segregate the normal fastener instances from the anomalous points and detect missing clamps within the fastening systems. The measurement system also exhibited an ability to detect other track components (such as weld joints, insulation joints) that exhibits magnetic properties, from real time measurements. Further, eddy current sensors are not affected by the presence of non-conductive materials in the sensor-to-target gap and can thus overcome major challenges associated with visual inspection systems and can be used in regular traffic.

The future of this research focuses on enabling continuous monitoring of multiple railway track components to minimize failures, delay and prevent accidents by using in-service train as a career of the condition monitoring system. This reduces cost, increases safety and reliability and increase uptime of infrastructures, thus ultimately reducing consumption of resources and increasing the utilization of the current investments. The future trajectory of this research also involves integrating Multiphysics simulation models of the magnetic field interaction with track and data-driven models (data from the measurement system) to create a powerful hybrid system, to enhance the efficiency of detecting multiple track components using the proposed eddy current measurement system, revolutionizing the field of railway maintenance.

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3D Printed Continuous Fibre Composite Structural Components for Impact Energy Absorption

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Key words: Additive Manufacturing (AM), Carbon Fibre Reinforced Thermoplastics (CFRTP), Energy Absorption Structures (EAS), Impact.

ABSTRACT

Broadening knowledge about future materials and manufacturing processes will serve to develop high value-added products that respond to major societal challenges. Additive manufacturing (AM) is one such process and demonstrates great potential to contribute to enhanced product customization, digitalization of manufacturing, and the circular economy (EC).

Sustainable design is currently one of the criteria in the development of automotive components; with lightweight design, energy savings and efficient use of raw materials the subject of much research. In parallel with environmental concerns, safety remains a critical factor, and manufacturers must strive to ensure or improve the safety of vehicle occupants in impact situations. To satisfy both these requirements, the increase of energy absorption properties by means of complex structure design and non-conventional fibre orientations in cFRTP composite materials is the main objective of the present thesis. To this end, new concepts of structures and metamaterials with predefined or programmable properties addressing specific needs/functionalities within the vehicle structure were analysed and developed using composite AM technologies. 3D printing - FFF of continuous fibre permits greater design freedom and flexibility in terms of fabrication of cFRTP structures, since the fibre can be oriented in the direction of the load, increasing performance and material utilization.

The present work **focuses** on broadening knowledge in three fundamental blocks:

The first block investigates increasing the energy absorption properties of fabricated structural components through geometric profile design and selection of continuous fibre printing trajectories. For this purpose, microstructural characterization and identification of printing defects due to the FFF process was carried out, and the relationship between geometry (Fold profile), fibre printing pattern, and the nature of the reinforcement filament (cCF/PA, cGF/PA and cKF/PA) in the generation of these defects was analysed. At the same time, the fracture mechanisms that induce stable collapse modes of printed profiles were identified, analysing the position and typology of the defects and their relationship with the load direction. This work facilitates the conversion of a weakness/discontinuity in the structure (printing defects) into initiators of stable collapse. The cCF/PA profiles achieved an axial and radial static *SEA* of 30.1 kJ/kg and 9.0 kJ/kg, respectively.

In the second block, the response of printed materials reinforced with continuous fibre cFF (carbon, glass, and Kevlar©) at different test speeds was studied. The results proved that there are differences in the nature of the PA matrices that cover the fibres, which explains their greater sensitivity to the strain rate and improvement of their impact resistance (Kevlar©). It was also demonstrated that poor impregnation of the fibres or lack of consolidation of the printing material causes certain failure mechanisms based on fibre fracture, delamination, and friction between the layers and the printing beads. The cGF/PA profiles shown an axial and radial dynamic *SEA* of

20.0 kJ/kg and 12.8 kJ/kg, respectively. Moreover, the strain-hardening effect enhanced impact resistance of cCF/PA material, whereas in cCF/PA not.
The third block was centred on the identification and characterization of auxetic filling structures that improve the transverse behaviour of tubular profiles, and that produces a synergistic effect on the absorption capacity of the profile-core. The results of this study also showed that the collapse mode of the RSH auxetic core (star-shape re-entrant) increases the load capacity of the profile and controls of the profile progressive collapse mode during its densification. A synergetic effect has been observed for every profile filled with the RSH auxetic core. The cKF/PA filled profile achieved the highest radial impact *SEA* value (20.6 kJ/kg).

Conclusions

3D printing is one of the Industry 4.0 enabling technologies identified in the RIS3 smart specialization strategy of Euskadi. It was selected because it easily integrates into the circular economy through the use of recycled materials (filament or pellet), however it remains underutilised because of its high cost and long manufacturing time. Hybridization in thermoplastic composite manufacturing technologies responds to these challenges by: (i) achieving high levels of lightweighting and material utilization, (ii) reducing the operational cost of parts, and (iii) increasing productivity.

Future works and perspectives

In the near future, RECHARGE RECYCLING TO PROTECT, our innovative startup, is poised to lead the way in rail transport safety. Our focus on delivering long-lasting anti-ballast impact protection system for rail wheelsets holds transformative potential. This robust solution not only ensures durability but also enhances resilience against external impacts, making a significant contribution to the overall efficiency and sustainability of railway systems (Chapter 7-BMC).

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Mechatronic aspects of an innovative two-axle railway vehicle

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Keywords: Mechatronic two-axle vehicle, active wheelset steering, active ride comfort control, wheel wear.

1. Objective of the work

Within the Shift2Rail research program, goals for a sustainable growth of the railway sector are set. Among these are a substantial reduction of Life Cycle Costs, improved reliability and energy efficiency, the reduction of noise emissions, and the achievement of full interoperability of the rolling stock. Therefore, a new generation of running gear is envisioned.

An innovative two-axle metro vehicle with single axle running gear is developed to reduce investment and maintenance costs, as well as weight, and energy consumption considering the key aspect of Shift2Rail Innovative Program 1; "*[…] innovations […] should also derive from an entirely new way of thinking on product development. […]*" [1]. Due to large axle distance and only one suspension step, the performance of the two-axle vehicle is inferior to the one of a standard bogie vehicle. To provide as good ride comfort and as little wheel and rail damage as in a conventional bogie vehicle, active suspensions are incorporated in the vehicle design making it a mechatronic solution. The vehicle is designed for the project partner Metro Madrid, and especially line 10 of the network due to the unique challenges of that operation: a high speed for a metro system (120 km/h) and high concentration of small curve radii.

In this framework, a series of aspects are analysed to provide a competitive alternative to standard vehicles in terms of dynamic performance. Among those, innovative components, such as a composite material bogie frame, a new type of suspension-actuator combination, and control strategies to improve ride comfort and steering capability are developed.

The main objective of the work is to demonstrate the applicability of mechatronic solutions to develop non-standard railway vehicles aiming at a future railway operation with reduced cost, maintenance and energy emission.

2. Contributions

The main contribution of the work is the concept development of the innovative two-axle railway vehicle with only one suspension step under the perspective of mechatronic solutions for wheelset steering and ride comfort control. To achieve this goal, several a detailed virtual demonstrator of the innovative vehicle is built up, considering flexible structural connection elements and actuator dynamics. A flexible connection frame and a steering actuator have been designed, manufactured, tested, modelled, and incorporated in the simulation environment [2], [3].

As mentioned, the two-axle vehicle is a mechatronic solution that is therefore strictly interdependent with the control strategies implemented. In this perspective, a novel feedforward wheelset steering control strategy has been developed to overcome control stability and measurement issues normally involved in solid wheelset steering of railway vehicles [4], [5]. A ride comfort control strategy that adapts with vehicle speed has been implemented based on better knowledge of the vehicle interconnected components ([6], [7]).

The performance of the concept has been validated with help of extensive simulations in terms of wheel wear, showing the great impact it can have on maintenance, expecting a reduction of wheel material loss due to wear of more than 60% in comparison to the standard bogie vehicle nowadays in service on Metro Madrid line 10 [8].

A synthesis of the work performed, together with visualizations of some important results can be found in [9].

3. Future works and perspectives

Two major categories can be distinguished in defining the future work. The first is related to the development of the innovative vehicle itself. Key aspects have been introduced and exploited. Nevertheless, many more aspects, like traction and braking equipment, definition of a carbody structure, and test of controlled systems need more investigation for the future development of the vehicle.

The second category focuses on the development of mechatronic systems in railway vehicles foreseeing the possibility of applying the control strategies introduced in the work to other types of railway vehicles. In this regard, vehicle speed and vehicle position on the line have been found to be simple measurable information that can be beneficial in terms of vehicle dynamic performance and maintenance. Therefore, investigation of these aspects during the development of mechatronic solution for railway vehicles can be beneficial in future development of active control strategies for railway vehicles.

4. Conclusions

The scope of the work is the development of an innovative mechatronic vehicle that could potentially reduce vehicle weight, together with maintenance and investment costs. It is shown that weight reduction is achievable with a novel vehicle configuration. At the same time, it is demonstrated that mechatronic solutions can be designed to overcome the limitations that a non-standard railway vehicle may carry.

Fully active hydraulic actuators can be used to reduce the vibrations transferred from the rail to the carbody of the innovative vehicle making it fulfil todays' performance requirements despite the absence of the second suspension step. The poor wheelset steering capability of the innovative vehicle can be significantly improved when active suspension is implemented. By steering the wheelset in a more correct position, it is possible to reduce the energy dissipated in the contact between wheel and rail reducing the wheel volume lost due to wear in comparison to the standard bogie vehicle for the same travelled distance.

The innovative vehicle presents a unique opportunity to investigate standard railway vehicle aspects with a new challenging perspective.

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IMPROVING ENVIRONMENTAL SUSTAINABILITY OF REGIONAL RAILWAY SERVICES

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Keywords: Regional railways; Advanced propulsion systems; Renewable fuels; Well-to-Wheel; Greenhouse gas emissions.

Main objectives of the PhD thesis

Regional non-electrified railways in Europe are facing significant challenges to improve energy efficiency and reduce greenhouse gas (GHG) emissions. Featuring low transport demand compared to the main corridors, complete electrification of regional lines is often not economically viable. The solutions are being sought in alternative energy carriers and catenary-free propulsion systems. The transition from conventional diesel traction is a complex and context-specific dynamic decision-making process that requires involvement of multiple stakeholders and consideration of numerous aspects. It requires in-depth analyses that include identification of available technology, design, modelling, and assessment of potential alternatives, with respect to the particular case-related constraints imposed by infrastructure, technical and operational characteristics (e.g., track geometry, speed, and axle load limitations, maintaining existing timetables, noise-free and emission-free operation in stations, etc.). Hence, the overarching aim of this thesis is to identify and assess potential solutions in reducing overall (Well-to-Wheel) energy use and GHG emissions from the operation of regional trains, focussing primarily on synergetic adoption of alternative propulsion systems and energy carriers. The case of the Dutch Northern lines with rolling stock and train services of Arriva is used to undertake this research, providing several scientific and practical contributions, which are summarized as follows.

Contributions

First, a backward-looking quasi-static simulation model is gradually developed to encompass various advanced propulsion systems as alternatives for the conventional diesel-electric topology, including hybrid-electric, plug-in hybrid-electric, fuel cell hybrid-electric, and battery-electric. Low-order models of individual main components along the traction chain are coupled with a suitable energy management and control strategy (EMCS) to address the high complexity of hybrid systems reflected in simultaneous operation of multiple power sources. The backward-looking approach enables estimation of powertrain dynamics by capturing typically available main vehicle, infrastructure and operation parameters influencing the energy performance of a train. It offers phased-out influence of the driver's behaviour, lower complexity, and a faster execution time compared to the forward-looking approach. Finally, in contrast to the energetic macroscopic representation approach it does not require field test data, which are often unavailable.

Second, a bi-level multi-objective optimization approach for determining the optimal size of the lithium-ion battery (LB) energy storage system (ESS) in a hybrid-electric vehicle is proposed, that integrates the ESS sizing and control optimization levels. The optimization framework includes most relevant design aspects, such as the requirement of achieving emissions-free and noise-free operation in stations, the trade-off (preference) between lower fuel consumption and hybridization cost, technical constraints related to battery voltage and maximum allowed mass, and the influence of the EMCS. Using derived LB parameters at the cell level, a nested coordination framework is employed, where a brute force search finds the optimal battery size using dynamic programming for full EMCS optimization for each feasible solution. The results indicated significant potential benefits of hybridization in terms of fuel savings compared to the conventional diesel-electric vehicle, while stipulating the need for the integration of different design and optimization levels and further performance improvement of real-time controllers towards the global optimum.

Third, a simulation-based analysis of hybrid-electric and plug-in hybrid-electric propulsion system concepts for diesel-electric multiple unit vehicles is presented, with encompassed LBs or double-layer capacitors (DLCs) as alternative ESS technologies, and newly developed causal and easy-to-implement real-time power control for each concept. The proposed EMCSs are based on a finite state machine control (FSMC), with different defined states and corresponding transition triggers to satisfy the

requirements of removing emissions and noise in terminal stops, and improving fuel economy by maximizing the use of regenerative braking energy, avoiding low load ICE operation, and supporting an internal combustion engine (ICE) by an ESS during high power demand phases. Positive effects from further conversion of a hybrid-electric to a plug-in hybrid-electric system are obtained, reflected in additional fuel savings, GHG emissions and direct energy costs reduction compared to the conventional diesel-electric vehicle, with identified significant influence of the type of service, energy storage technology, electricity production, and charging facilities configuration.

Fourth, a conceptual design of hydrogen-powered propulsion systems for the conversion of diesel-electric trains is proposed. The analysis encompassed technology identification, traction components and hydrogen storage sizing, and the assessment of alternative powertrains in terms of feasibility, fuel economy and produced emissions. An ICE and a fuel cell system are considered as the alternative prime mover configurations, coupled with LB, DLC or a hybrid ESS that combines both technologies. The analysis incorporated constraints related to the slow dynamic response feature of a fuel cell system, available weight and volumetric space onboard, estimated power and energy demand, and a requirement of a daily operation without refuelling. The fuel cell-based hybrid propulsion systems with LB or a hybrid ESS provided the highest fuel-efficiency. The remaining configurations showed higher hydrogen consumption, and reduced vehicle range due to the volumetric and weight constraints. This brings the challenge of implementing efficient refuelling system comparable to that for diesel vehicles, which would prevent compromising timetable fulfilment and daily operation.

Fifth, a framework for the estimation of Well-to-Wheel (WTW) energy use and GHG emissions attributed to the implementation of aforementioned alternative propulsion systems in conjunction with a range of energy carriers is developed. Fatty acid methyl esters (FAME), hydrotreated vegetable oil (HVO), liquefied natural gas (LNG), hydrogen, and electricity are considered as alternative energy carriers to diesel. A bottom-up consumption-based approach is employed, with direct fuel and/or electricity consumption assessed in the Tank-to-Wheel (TTW) stage using the developed simulation model. The obtained estimations are then combined with various energy carriers' production pathways linked to the Well-to-Tank (WTT) stage using energy and GHG emission factors relevant for the Dutch and European context. Overall, the production pathway of the energy carrier is identified as the most significant contributor to the total energy use and produced emissions. Focusing on fuels such as HVO and systems with infrastructure already in place could be an instantly implementable and cost-effective short-term solution for significant energy and GHG emissions savings. This approach would facilitate a smooth transition toward more energy efficient and environment friendly solutions, while providing the time for novel technologies to mature and reach the economy of scale required for their wider adoption, as well as the time required for the development of the supporting infrastructure.

Future works and perspectives

Future research efforts will include investigation of other environmental impact indicators and costs from a life-cycle perspective in comprehensive Life Cycle Assessment (LCA) and Life Cycle Costs (LCC) analyses. In addition, special focus will be on solving design problems linked to the infrastructure development for the new traction concepts, such as the optimal tracks electrification layout for battery-electric trains, or vehicle-to-grid applications for battery-electric and fuel cell hybrid-electric vehicles.

Conclusions

In summary, this thesis provides methods and models for assessing the overall energy use and GHG emissions linked to the implementation of various advanced propulsion systems and energy carriers in non-electrified regional railway networks. The outcomes of this thesis will be leveraged by the railway undertaking and decision-makers in the complex transition process towards energy-efficient and low or zero-emission trains operation.

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Onboard condition monitoring of vehicle-track dynamic interaction using machine learning

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Keywords: predictive maintenance, intelligent fault diagnosis, vehicle fleet, track irregularities, vehicle hunting.

Extended Abstract

Main objectives

The railway sector's reliability, availability, maintainability, and safety (RAMS) can significantly improve by adopting condition-based maintenance (CBM). In the CBM regime, maintenance decisions are driven by asset condition monitoring. The PhD thesis[1] proposes machine learning (ML) based onboard condition monitoring (OCM) algorithms for vehicle-track dynamic interaction monitoring via vehicle response. More specifically, the thesis proposes methods for condition monitoring of vehicle-track dynamic interaction using inertial measurement systems mounted on in-service vehicles operating in regular traffic.

Onboard condition monitoring of track irregularities from onboard accelerations is a cost-effective method for daily surveillance of tracks. Most of the latest research is focused on monitoring vertical irregularity via vertical accelerations. Less attention is given to monitoring alignment level (AL) and cross level (CL) track irregularities. Thus, the first objective of the PhD thesis is "*To develop an algorithm for onboard condition monitoring of track irregularities (TI) via the dynamic response of in-service vehicles.*" Furthermore, high-speed rail vehicles' running instability threatens operational safety and passenger ride comfort. Thus, onboard condition monitoring of vehicle running instability is critical to ensure safety and onboard ride comfort. The latest research focuses on designing OCM algorithms for detecting vehicle running instability, but these OCM algorithms lack fault diagnosis of detected vehicle running instability incidence. Thus, the second objective is "*To develop an OCM algorithm for vehicle running instability (hunting) detection and fault diagnosis via the dynamic response of in-service vehicles.*"

Thesis contributions

The PhD thesis enables the digitalization of vehicle and track maintenance by adaptation of the CBM regime. More specifically, the PhD thesis contributes to knowledge of ML-based OCM algorithms for condition monitoring and intelligent fault diagnosis of vehicle-track dynamic interaction. The detailed contributions of the PhD thesis are documented in four peer-reviewed journal articles and two conference papers. The important contributions are summarized here:

Objective 1: Track Irregularity Monitoring (TRIM)

The PhD thesis focuses on the formulation of an OCM algorithm (Figure 1) designed to assess alignment level (AL) and cross level (CL) track irregularities through the analysis of onboard bogie frame accelerations. By integrating advanced signal processing methods and ML algorithms, the proposed approach attains a notably high level of accuracy in AL and CL track irregularity monitoring based on the acceleration data obtained from the bogie frame. The thesis showcases the efficacy of an ML-based OCM method for qualitative assessment of AL and CL track irregularities.

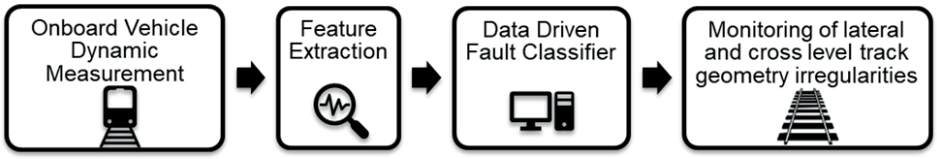

Figure 1 ML-based onboard condition monitoring algorithm of AL and CL track geometry irregularities

Objective 2: Vehicle Running Instability Monitoring (VRIM)

The vehicle running instability (hunting) is a sporadic phenomenon, i.e. an anomaly in the vehicle-track interaction. The thesis proposes an unsupervised anomaly detection (AD) framework,

iVRIDA, which utilizes carbody accelerations for vehicle running instability detection. The *iVRIDA* framework is tested and validated in two independent investigations based on onboard measurements of two high-speed vehicles operating in Europe. Additionally, the *iVRIDA* framework is extended into *iVRIDA-fleet* (Figure 2) for the fleetwide application. The proposed *iVRIDA* framework is generic, where any signal reconstruction-based anomaly detection algorithm can be integrated into *iVRIDA*. Moreover, any unsupervised/supervised clustering/classification algorithm can be integrated for fault diagnosis of the underlying vehicle faults instigating vehicle running instability.

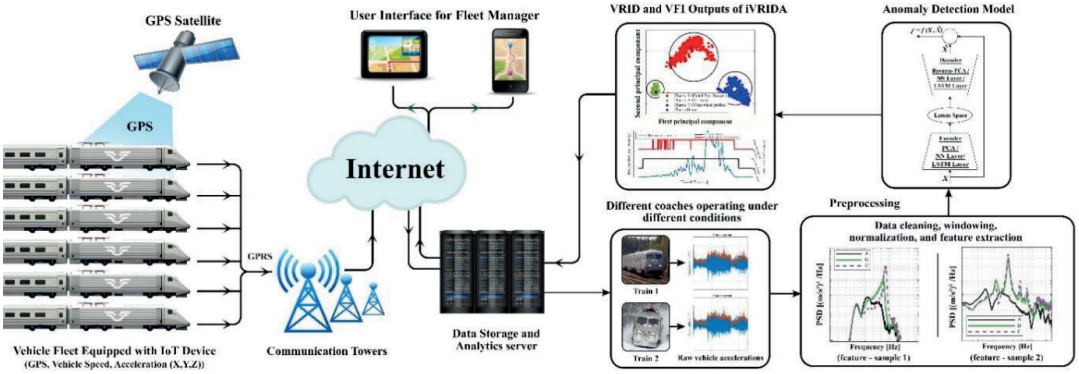

Figure 2 Intelligent Vehicle Running Instability Detection Algorithm (*iVRIDA-fleet*).

Conclusion and Future Work

Objective 1: Track Irregularity Monitoring (TRIM)

The PhD thesis proposes an ML-based OCM algorithm to identify track sections with alignment level and cross level track irregularities exceeding maintenance thresholds (defined in EN14838) via bogie frame accelerations. In this thesis, the OCM algorithm's supervised ML models are trained on BFAs' datasets synthesized with multibody simulation (MBS) of a high-speed diagnostic vehicle. Furthermore, the trained ML models and OCM algorithm are validated with measurements acquired by the same high-speed vehicle. The proposed OCM algorithm shows excellent performance in track quality surveillance only from bogie frame accelerations. Future research should focus on developing a hybrid OCM method, i.e., a combination of model-based and data-driven OCM methods, to leverage their respective strengths and overcome their limitations. The hybrid OCM method is expected to lead to better outcomes and provide a more comprehensive and accurate assessment of track conditions.

Objective 2: Vehicle Running Instability Monitoring (VRIM)

The PhD thesis proposes various OCM algorithms under an "intelligent vehicle running instability detection algorithm" (*iVRIDA*) umbrella to detect vehicle running instability incidences and diagnose corresponding root causes via carbody accelerations. The occurrence of vehicle running instability during in-service operation across a train fleet is an anomaly. Thus, an unsupervised anomaly detection (AD) based *iVRIDA* algorithm is proposed and later extended as *iVRIDA-fleet* for vehicle fleetwide application. The proposed OCM algorithms *iVRIDA* and *iVRIDA-fleet* are verified by onboard measurements of a European high-speed vehicle and the Swedish X2000 vehicle fleet. The results demonstrate the efficacy of *iVRIDA* in various case studies, highlighting its potential for fleetwide implementation in real-world scenarios. Future development of the *iVRIDA* is envisioned through diversifying data sources, including real-time track and vehicle inspection reports, operational information, and additional features from carbody accelerations. It can enhance its performance by expanding the framework to incorporate advanced generative AI models and fine-tuning hyperparameters.

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HAZARDOUS EVENTS DETECTION NEAR TRAIN AUTOMATIC DOORS USING SELF-SUPERVISED DEEP ANOMALY DETECTION NETWORKS

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Key words: safety applications, image processing, deep learning, anomaly detection

• Main objectives of the works

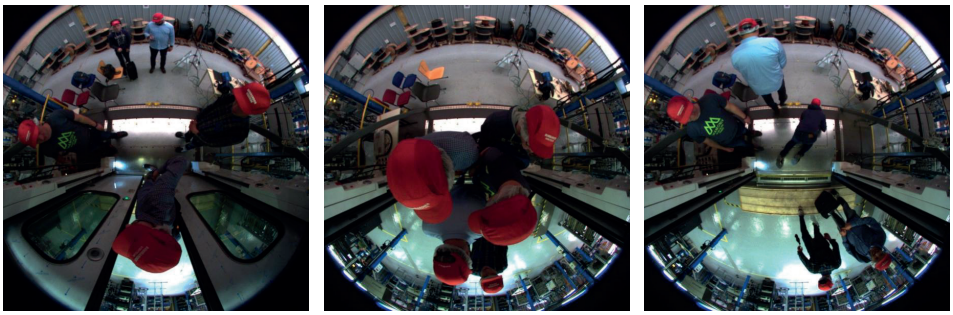
This work is part of a research project to develop an autonomous passenger trains operating on French regional lines (Train Autonome Service Voyageur (TASV) Project). Advanced benefits of passenger train autonomy include optimizing rail capacity, reducing maintenance costs and train energy consumption, and improving system safety.
The developed autonomous train prototype aims for the maximum degree of railway automation (or Grade of Automation 4, GoA 4), for which all train operating functions currently under the responsibility of on-board staff will be handled by technical systems. We focus here on the automation of one of these functions, namely the safe operation of the train's external doors.
This thesis addresses this problem by applying deep neural networks to detect any dangerous events related to pedestrians and doors present in video streams provided by fish-eye cameras installed on the ceiling of the train boarding platforms.

As instances of these dangerous events occur very rarely during train operation, the proposed solution is based on the notion of anomaly, defined as an unknown or unexpected event in a given context. The proposed neural architecture therefore constitutes a model of normality and identifies as abnormal any aberrant data that deviates from it, so as to identify any unforeseen hazardous event.

• Contributions

1) A list of relevant anomalies has been compiled from a preliminary hazard analysis to passengers in the context of modular urban transportation systems produced as part of the MODSafe project[1], and a set of specifications produced by Bombardier Transportation.
These anomalies include, among others, a passenger falling (see fig. 1.c), doors closure failure due to a mechanical mishap or due to the presence of an object (backpack, suitcase, etc.) or a passenger between the doors (see fig. 1.a), an interrupted passenger exchange (see fig. 1.b) when passengers obstruct each other by boarding and disembarking from the train simultaneously, etc.

2) As no image dataset related to our use case exists in the literature, we have collected and annotated two sets of video sequences for training and evaluating neural networks. These sequences depict passengers in the vicinity of a train doors replica (FRailTRI20_DOD dataset[2]) and in a real train instrumented as part of the research project (FADDM dataset, to be disclosed).



1.a 1.b 1.c

Figure 1 : Examples of anomalies seen from a fish-eye camera on the ceiling of the train. Source : [2]

3) We propose a novel architecture[3] that fuses the anomaly detections from two anomaly detection networks focusing on doors-related and pedestrian-related anomalies respectively. A panoptic segmentation network (K-Net[4][6]) first extracts instance-aware pedestrians and automatic doors semantic maps in the input video sequence. Two self-supervised multi-tasks networks based on the work of Georgescu et al.[5] are trained separately on each semantic map sequence and their detections are fused to provide a final interaction anomaly detection. The full network architecture is shown in annex 1. The final model shows great performance for the detection of doors-related anomalies (0.96 AUC-ROC) and to a lesser extent for the detection of pedestrian-related anomalies (0.86 AUC-ROC). We also provide additional results to evaluate our model effectiveness w.r.t each anomaly category and to identify any source of false positives.

• Future works and perspectives

- Development of a new dataset of video streams captured under real conditions (FADDM dataset, to be disclosed)
- Utilization of anomaly scores for anomaly classification

• Conclusions

The model results are very encouraging as they indicate its ability to identify door anomalous movements without any prior knowledge of the door's operation mechanism, and without specifying what constitutes an anomaly. This suggests the potential application of this system to detecting anomalies in other door systems, requiring only to capture door segmentation masks during nominal use.

Further experimentation on a larger dataset and under real conditions is necessary to conclude on the model detection capabilities particularly for the detection of passengers falling.

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Annex 1 : Full neural network architecture

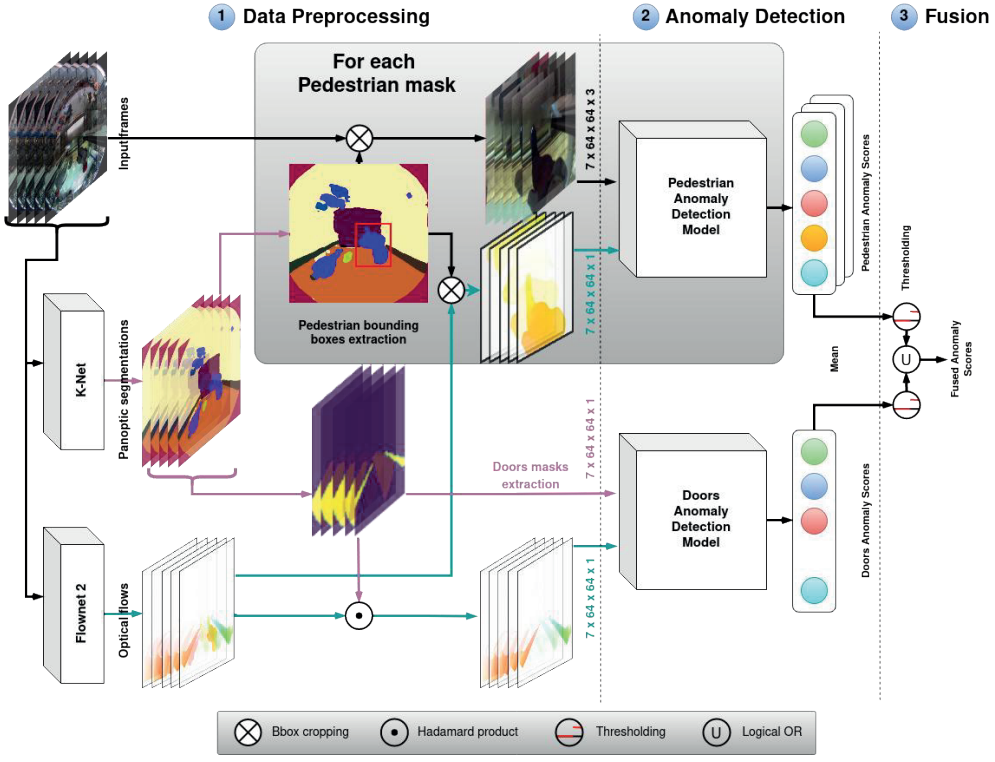

Figure 2 : Full neural network architecture. Source : [3]

Mechanisms of short pitch rail corrugation

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Key words: short pitch rail corrugation, 3D-FE dynamic vehicle-track modelling, differential wear, initial excitation, corrugation initiation, consistent growth.

1. Main Objectives of the Work

1) Investigation of the Corrugation Development Mechanism using a comprehensive 3D dynamic finite element (FE) vehicle-track coupled model that considers the interplay of structural dynamics and contact mechanics.
2) Investigating the Influence of Track Parameters on Corrugation Formation to identify conditions under which corrugation can initiate and consistently grow, and to provide a physical explanation for the mechanism of corrugation formation.
3) Metallurgical Study of Rail Material Damage to examine structural damage in rail material caused by corrugation.

2. Contributions

1) Insights of Corrugation Growth Mechanism [1]
   - This provided a novel approach using a 3D dynamic FE vehicle-track coupled model to study short pitch corrugation.
   - Different from previous assumptions, we found the potential connection between the initiation of corrugation and longitudinal track dynamics.
   - Introduced a consistency condition, emphasizing the consistency in vertical and longitudinal contact forces, that determines corrugation development.
2) Impact of Track Parameters on Corrugation Formation [2]
   - We proposed a hypothesized process for consistent corrugation initiation and growth and verified with numerical simulations.
   - An initial excitation mechanism determined by railpad modelling was identified which causes the high amplitudes initial differential wear.
   - With the initial differential wear, the whole consistent corrugation initiation and growth was reproduced for the first time, and an attenuation state was observed as well when the corrugation peak-to-peak value is above 160 µm.
   - The numerical simulation results are in good agreement with the field observations, confirming the proposed mechanism's applicability to explain real-world scenarios.
   - The initial differential wear is highly correlated with the longitudinal contact force.
   - With different railpad modelling, it was finally found that it is the rail longitudinal compression modes which cause the corrugation formation.
   - The consistency in the differential wear, the resulting corrugation, and longitudinal and vertical contact forces determine the consistent corrugation growth.
   - The explanation of the frequency selection provides a good explanation to the wavelength-fixing mechanism.
3) Metallurgical Study of Rail Material Damage [3]
   - We recognized the existence of Brown Etching Layer (BEL) alongside White Etching Layer (WEL), expanding the understanding of rail material structural changes induced by corrugation.

- BEL was identified as a potential precursor to rail fracture, emphasizing the importance of comprehending its formation mechanism.
- The mechanical and microstructural features of the BEL was characterized experimentally and the formation mechanism and connection with WEL was extensively analysed.

3. Future Works and Perspectives

Building on the foundations laid by this research, future investigations should prioritize:

1) Parametric Variation Studies: to conduct extensive parametric studies to identify additional influential parameters affecting corrugation formation.
2) Optimization of Track Components: to optimize fastening design to proactively address corrugation issues practically.

4. Conclusions

In conclusion, this dissertation extends research on the mechanisms of short pitch corrugation using a novel approach involving a 3D dynamic FE vehicle-track coupled model. Through this innovative method, a new insight has been discovered: the importance of rail longitudinal modes in the initiation of corrugation. Additionally, we introduced an initial excitation concept for corrugation initiation and proposed a hypothesis for a consistent corrugation initiation and growth process. Firstly, we identified an initial excitation determined by railpad modelling, successfully reproducing the entire corrugation initiation and growth process with the adopted hypothesis. The resulting corrugation closely resembles features observed in the field, showcasing the research's capability to explain observed corrugation phenomena. The physical explanation of the initial excitation and the root causes of corrugation initiation lie in the rail longitudinal compression modes. The consistency in the differential wear, the vertical and longitudinal contact forces, and the resulting corrugation determine the consistent growth and wavelength selection of the corrugation. The insights gained not only contribute to mitigating corrugation through track parameter optimization but also provide essential knowledge for the development of future rail technologies. The identification of BEL introduces a novel perspective, opening avenues for further exploration and refinement of strategies to ensure the robustness and longevity of railway infrastructure.

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DEVELOPMENT OF NUMERICAL AND EXPERIMENTAL TOOLS FOR THE SIMULATION OF TRAIN BRAKING OPERATIONS

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Keywords: Longitudinal train dynamics, Digital twins, Adhesion coefficient, Adhesion recovery, Roller-rig

Main objectives of the work

The PhD thesis aims to develop, tune, and validate numerical and experimental tools for the investigation of the dynamics of railway vehicles and trains, with special reference to braking operations. In fact, the need for computationally efficient numerical models intended to simulate the dynamics behaviour of both isolated vehicles (or small groups of vehicles) and long trains, is constantly growing, as nowadays international rules allow the virtual homologation of vehicles [1] as well as the assessment of the longitudinal compressive forces (LCFs) through the generation of statistical train consists [2]. At the same time, the development of reliable laboratory test benches for testing and validation of on-board systems and algorithms is the key to mitigate the high-costs and low reproducibility of on-field tests.

Contributions

A major contribution of the thesis is the development of the in-house LTDPoliTo code for longitudinal train dynamics (LTD) simulations, which is validated against the outputs of an international benchmarking activity [3,4]. The code is developed in MATLAB, and it relies on built-in functions and vectorization strategies to speed up the computation, thus effectively dealing with the nonlinearities in the calculation of the in-train forces on wagon connection systems. As the main limitation of common LTD codes is the inability of estimating the wheel-rail contact forces, the thesis suggests an innovative approach to estimate the running safety indexes, calculated from the wheel-rail contact forces, directly from the outputs of LTD simulations. The approach is based on the derivation of machine learning (ML) kernel regressions from the outputs of a small set of multibody (MB) simulations. Moreover, the LTDPoliTo code is applied in the thesis to calculate quantities of interest that become the inputs of a simplified finite-element (FE) model of a tread braked wheel, which allows to estimate the evolution of the wheel temperature in both drag and stop braking operations.

Focusing on the experimental tools, the activities performed in the frame of this thesis deal with the experimental setup of the multi-axle roller-rig, designed and built by the railway research group from Politecnico di Torino (PoliTo) in previous works [5] and consisting of four scaled wheelsets rolling over the same pair of rollers. The setup includes the connection of the sensors, the development of a LABVIEW data acquisition and bench control software and the implementation of post-processing MATLAB routines. The bench can measure the adhesion curves in different types of tests. Preliminary experimental tests are run to confirm the repeatability of the measurements collected on the bench, while additional tests are run to investigate the adhesion recovery when the roller surface is contaminated with water, showing that in degraded conditions, the adhesion curves feature a hysteresis loop, due to the removal of the contaminant by the sliding forces, which partially restore dry conditions. In a later stage of the activity, the bench configuration is changed to reproduce the UIC freight wagon air brake system in laboratory conditions. With the new configuration, the bench can simulate braking operations of freight wagons, reducing the roller speed based on the deceleration calculated with a simplified version of the equations implemented in the LTDPoliTo code.

Figure: Summary of the main numerical and experimental activities performed within the thesis.

Future works and perspectives

Upgrades of the activities carried out in the thesis are dealing with the integration of wheel and shoe thermal models within the formalism of the SIMPACK commercial MB code, thus allowing to calculate LTD, wheel-rail contact forces and the wheel/shoe temperature in the same computational environment, with no need for the implementation of complex data transfer strategies or co-simulation techniques. Moreover, the calibrated multi-axle roller-rig test bench will be provided with PWM valves so that it can be adopted as a preliminary tool for testing and validation of wheel slide protection (WSP) algorithms and air brake system monitoring units.

Conclusions

In conclusion, the PoliTo railway research group can now count on different reliable and validated tools that can be adopted in future activities to investigate and optimize the operation of railway vehicles in different scenarios.

Firstly, the LTDPoliTo code is validated, and it calculates outputs featuring an excellent agreement with the results obtained by other simulators in the scenarios suggested by an international benchmark, with the advantage of a high computational speed. The computational performances of LTDPoliTo are up to two orders of magnitude faster compared to the implementation of an LTD model in the SIMPACK commercial code. The strategy developed in the thesis to provide LTD codes with digital twins of MB simulations thanks to ML regressions can extend the scope of common LTD codes, which cannot calculate the running safety indexes defined by the international standards.

The experimental activity performed on the multi-axle roller-rig provided the bench with a stable control software, which allows to perform different types of tests. The results of the preliminary experimental tests prove that adhesion recovery phenomena should be considered by wheel slide protection (WSP) algorithms to minimize the braking distances since the work of the friction forces partially removes the contaminant sticking to the wheel and rail surfaces, thus leading to higher adhesion levels as the braking operation goes on.

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Improving the train routing selection for real-time railway traffic management

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Key words: Train Routing Optimization, Real-time railway traffic management, Ant Colony Optimization, Performance evaluation

This PhD thesis investigates research objectives concerning how operational research models and algorithms can help improve train routing selection problem (TRSP) and enhance real-time railway traffic management problem (rtRTMP). The thesis considers the railway infrastructure manager's point of view, which has the task to deal with the real-life unpredictability of operations, by identifying and resolving conflicts during operations. Solving the rtRTMP typically consists in taking retiming, reordering or rerouting train actions in such a way that the propagation of disturbances in the railway network is minimized (Cacchiani at al., 2014). Train rerouting decisions bring one of the biggest benefits to the rtRTMP solution (Pellegrini at al., 2016). At the same time, they pose a major challenge: human dispatchers hardly predict the effect of simultaneous train rerouting decisions, while in advanced technology systems routing variables exponentially increase the number of solutions to explore (Kroon et al., 1997). To this purpose, the TRSP addresses the optimized selection of alternative routes as a preliminary step for the rtRTMP, thus limiting the number of its routing variables.

The main objectives of this PhD thesis are:

1. Develop an algorithm to optimally solve large TRSP instances. The TRSP is generalized as the minimum weight clique problem in an undirected multi-partite graph. This is an NP-hard problem, which for the rtRTMP application requires to be solved in short computation times compatible with real-time traffic management. The goal is thus to achieve efficient solutions within short computation times, especially in complex railway networks.
2. Enhance the mathematical model of the TRSP to increase the correlation between TRSP and rtRTMP solutions. The aim is to enforce that the routes selected in each TRSP solution allow the minimization of the total propagation of train delay in the rtRTMP. In the TRSP, the benefit of using specific subsets of routes in the rtRTMP is assessed by considering estimations of costs. In the state-of-the-art, costs are measured as a function of potential delays between pairs of trains. However, in dense networks, detailed TRSP modelling is essential to account for train interactions and knock-on delays.
3. Extend the applicability of TRSP, considering diverse models, solution processes, and objective functions for the rtRTMP. The thesis evaluates the effectiveness of TRSP in various scenarios, aiming to contribute to improved decision support systems for railway traffic management.

The PhD thesis brings the following contributions:

1. New algorithmic schemes. The thesis study the ant colony optimisation (ACO) for the construction and selection of the minimum weighted clique in a multi-partite graph, comparing it with an exact method (Pascariu et al., 2021). An effective parallel implementation of the metaheuristic is then proposed to better handle large-size instances. Furthermore, two local searches considering different solution neighbourhoods are

introduced to enhance the diversification patterns during the solution search (Pascariu et al., 2022).

2. Model developments. The thesis develops new components for the TRSP model to increase the correlation with the rtRTMP. Two incremental upgrades are proposed for the cost estimation model including train movements performed by the same rolling stock and the impact of delay propagation due to train conflicts (Pascariu et al., 2022). Furthermore, the formulation of several TRSP objective functions is proposed to cope with the plethora of different objective functions used for the rtRTMP.
3. Applications. We extend the application of the TRSP to the rtRTMP. In particular, we assess its general effectiveness for the rtRTMP, regardless: the specific model considered for the rtRTMP, the rtRTMP solution approach used, and the objective function optimized. We carry out thorough campaigns of experiments on realistic case studies, with timetable disturbances and infrastructure disruptions.

Future research directions involve refining the parallel ACO algorithm by mitigating communication overhead, exploring asynchronous communication, and exploring mathematical programming, heuristic, and metaheuristic approaches. Focusing on the model, the thesis shows that the effectiveness of the TRSP depends on the ability to predict the effect that selected routes have in the rtRTMP. Thus to further improve the performance when changing the rtRTMP model and solution process, further customization of the TRSP model and algorithm might be considered. Moreover, according to the actual TRSP model, the route choice is based on the given traffic situation and is highly dependent on the precision with which the cost estimations can model it. Future research may apply a robust optimization model to identify good routes independently from the timetable and possibly to be used at a planning level as well. Finally, the methodology described in the thesis can be equally applicable to all the problems modelled as the minimum weight clique problem in an indirect multi-partite graph.

In conclusion, this PhD thesis advances the TRSP and proves that its application is an effective strategy for the rtRTMP, regardless of the specific model, the solution approach, and the optimized objective function. Practitioners and researchers in the area of real-time rail traffic management should take into account the benefits of the TRSP and increase its deployment. In practice, the TRSP can support dispatchers as a stand-alone software that returns a list of the best routes to choose from based on the current traffic situation, or it can be integrated into a decision support system that suggests optimized decisions to be made on train orders, timings and routes.

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ENABLING INTER-ORGANIZATIONAL CHANGE INTEGRATION IN SOCIOTECHNICAL SYSTEMS

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Key words: systems integration, systems thinking, system definition, railway, interface management

- Main objectives of the works

In railway systems, there is a continuous request for improvement, enabling faster, safer, more reliable, and higher-capacity transport, preferably at low costs. In order to achieve these improvements, changes of various kinds, scales, and complexities are constantly emerging, all of which need to be integrated into the existing railway system context in order to attain the desired system-level qualities. Despite the apparent benefits of these progressions, numerous instances highlight that the integration process doesn't always proceed as smoothly as anticipated. This can lead to financial losses, diminished productivity, harm to reputation, or even casualties. One contributing factor to these challenges is the intricate context within which these changes are intended to be assimilated.

Railway systems like the Dutch railways are sociotechnical and interorganizational in nature and thus characterized by multiple domains such as processes, personnel, technical systems, rules and regulations, with numerous interfaces and interdependencies between those. Additionally, involved organizations and inherent business units, employees, and experts often have diverse views, skills, responsibilities, objectives, and interests, and information and knowledge are dispersed among them. Therefore, obtaining a comprehensive shared perspective of both the railway system and the changes intended for integration proves to be a daunting task. In essence, this suggests that there is a constraint on the extent of enhancements possible when the involved entities cannot collaborate effectively. In addition to this, technological advances are also increasing in size, in complexity, and in their interdependence with other systems that have preceded them. As such, the foreseen changes and the projects that strive to realize them are increasing in scope, and consequently in systemic impacts. Designing a change to one part of the system without considering how this might affect or require a change in the other aspects of the system will limit effectiveness.

These challenges can be overcome by applying systems thinking: understanding how different components of a system are interconnected and how changes to one component could affect the entire system. However, systems thinking appears not to be as self-evidently applied in practical contexts. Therefor this dissertation aims to identify how systems thinking support inter-organizational change integration in the Dutch railway system (M. M. Ramtahalsing, 2023).

- Contributions

Firstly, the dissertation aims to understand the integration challenges and associated needs encountered in the Dutch railway system. The results show that in the event of a change, the investigated integration challenges mainly concern: (1) effectively determining what is being changed, (2) the scope and impacts of this change, and (3) how the change would fit within the existing railway system context. Secondly, the dissertation identifies to what extent well-known systems thinking practices currently support integration in the Dutch railway system. By testing postulates and case study research, several factors emerged: a clear goal, inclusion of multiple experts, synthesizing expertise to obtain mutual integral insights, and focus on managing interfaces. Moreover, the research shows that hard systems thinking approaches which are prevalent in the railway context, do not sufficiently accommodate the various perceptions of reality and the needs of all actors to be included in inter-organizational change integration. Thirdly, the abovementioned factors form the basis of the designed artifacts, which apply systems thinking in the complex sociotechnical railway system: (1) to facilitate scope definition enabling inter-organizational change integration; (2) to changes in system environments with external influences like climate change; and (3) to aid interface management in interorganizational projects. This led to the iterative design and development of three respective artifacts, Management of Sociotechnical and Inter-organizational Change Integration (MOSAIC) analysis (M. Ramtahalsing et al., 2022), a Climate Change Adaptation (CCA) framework (M. Ramtahalsing et al., 2021), and a proposed Interface Management (IM) process.

- Future works and perspectives

Based on this dissertation, future works include:

- Exploring the possible integration of soft systems thinking methods with more traditional approaches in order to address the challenges discussed in this dissertation.
- Developing frameworks and metrics to assess the outcomes and impact of applying systems thinking tools to facilitate change integration. This could involve both qualitative and quantitative approaches to measure the effectiveness, efficiency, and sustainability of changes implemented within sociotechnical systems.
- Examining strategies for knowledge transfer and learning from successful applications of systems thinking to facilitate change integration. This can involve developing best practices, guidelines, and case studies to support practitioners, policymakers, and researchers in applying systems thinking principles effectively in different sociotechnical contexts.

- Conclusions

Integrating inter-organizational changes in the working railway system does not happen automatically. It requires understanding and carrying out the activities and processes in a coherent manner to realize the objectives. However, because of the railway system's inter-organizational and sociotechnical nature, and lack of a designated system-level change integrator, more focused integration efforts are required.

To conclude, systems thinking can support inter-organizational change integration in railway systems by: (1) making the objectives of a change explicit to facilitate focused discussions, (2) using and synchronizing dispersed expert knowledge to gain holistic integral insight into the impacts and scope of change(s), (3) taking a multidomain perspective to organize the collection of information, (4) making inter-organizational interfaces transparent, and (5) condensing interface information by aggregating and visualizing information concerning critical interfaces. Furthermore, in order to accommodate the subjective interpretation in understanding systems and changes, the design research gravitated toward stakeholder engagement and emphasized the importance of learning, especially in the context of inter-organizational collaboration, on top of existing more technical approaches. This dissertation concludes by providing professionals and empirical researchers with the means to apply systems thinking to address integration challenges in a more fitting manner.

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AN ADVANCED MODEL TO PREDICT RAIL CORRUGATION AND ITS EXPERIMENTAL VERIFICATION

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Key words: Rail Corrugation, Wheel-rail dynamics, Receptances, Wear, Experimental Validation

- Main objectives of the work

As it is known, rail corrugation [1] appears in most of the world's railway lines, mostly in tram and metro-type lines. This type of rail defect leads to an increase in noise pollution and in the transmission of vibration to the surrounding area of the line, affecting negatively to people´s live. The only manner to completely remove the corrugation from the rail surface is to carry out grinding or milling processes [2,3], which entail high costs. For this reason, different alternatives have been studied to eliminate or at least reduce the rate of corrugation growth [4-7]. This work describes a computationally very efficient time/space domain model combining the vertical and lateral dynamics of wheelset and track, developed for the prediction of corrugation on a railway line. The advantage, and complexity, of the model developed lies in the introduction of lateral dynamics, as it is of paramount importance in tight curves. In parallel, the evolution of corrugation has been studied experimentally on a metro line since 2018, where this phenomenon developed prematurely after its inauguration. The model has been validated with these experimental measurements. This study aims to obtain feasible solutions against corrugation growth by modifying some of the traffic conditions or track parameters and obtaining the optimal parameters to reduce the corrugation growth on the line under study. Finally, this model can be adapted to any line, considering its characteristics.

- Contributions

This work has resulted in two high impact JCR publications (Q1 in the Journal of Citation Reports) and a number of national and international conferences. Moreover, the computer program of the developed model has been registered under the name OptiTRAIN in the Intellectual Property Register (Ref: 765-1321364).
Publications:

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Recent conferences:

- Congreso Nacional de Ingeniería Mecánica, CNIM2023, Las Palmas de Gran Canaria, Spain, October 25-27, 2023
- International Conference on Contact Mechanics and Wear of Rail/Wheel Systems, CM2022, Melbourne, Australia, September 4-7, 2022

- Future works and perspectives

Some of the future work consists of the experimental measurement of rail hardness after the subsequent grinding operations to study the influence of these grindings on the removal of the hardened layer of the rails. This is of great interest for two reasons. On the

one hand, the optimal period between grindings due to wear can be obtained. On the other hand, this study can provide the wear coefficient that has to be used in the developed model after every grinding process, since it has been observed in the lines under study that after every grinding process, the corrugation development is faster.
In order to get the optimal grinding period, the rail life due to Rolling Contact Fatigue (RCF) [8] should also be considered, since rail life due to RCF is reduced when no grinding process is carried out, whereas rail life due to wear is shortened in case of high material removal. Thus, the intersection of both rail life curves would point out the optimal grinding period.

- Conclusions

The developed model is an efficient tool to study the evolution of rail corrugation in tight curves of railway lines. It has been observed that for the studied cases, lateral dynamics play an important role in the corrugation growth. The model has been validated with the experimental corrugation measurements. These measurements have confirmed the influence of high stiffness of the railpads. The model has been implemented to the line under study modifying some of its parameters, such as the railpad stiffness, obtaining a great reduction of the corrugation growth by just replacing the original railpads with new ones with a lower stiffness. The present model can be adapted to any line, with any characteristics, being an efficient tool to prevent the fast development of rail corrugation and obtaining the best solution to avoid its growth. This model has not only scientific benefits, but also industrial benefits since it has been directly used to solve the corrugation problems of one specific infrastructure manager. In conclusion, corrugation problems appear as a combination of vehicles design, track design, maintenance and trains speed, therefore, the developed model is advantageous for all stakeholders: operators, infrastructure managers and rolling stock manufacturers.

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Coordinated inter-organizational decision-making

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Keywords: *inter-organizational railway projects; complexities; coordination mechanisms; design propositions*

Abstract

The fundamental systems and services that contribute to the economic prosperity and social well-being of a nation, such as public transportation, are highly important for society. According to the European Commission, public transportation in particular, such as the railway system, must become safer, more reliable, and increasingly connected in order to meet the expected increase in demand over the coming years while also dealing with the capacity boundaries of the system. This requires the railway system operators to upgrade their processes, systems and technology, while managing any risks.

In order to reach the aforementioned railway system performance goals of safety, reliability, and interconnectedness, the separate system entities need to be smoothly integrated in increasingly complex projects. One of the complexities of system integration is that it often requires many different stakeholders working together. Decisions have to be made jointly by the diverse system stakeholders in a generally complex inter-organizational and socio-technical context. As such, coordinating inter-organizational projects for effective decision-making is crucial. Concerning this, Williams (2005), in his seminal work on project complexities, revealed that project management needs to take on a wider perspective than the overarching one-size-fits-all, positivistic, and reductionist view it has relied on since the 1960s. This perspective draws particular attention to ensuring that the complexities experienced when tackling system integration challenges are addressed in a more inclusive manner.

This dissertation investigates practical considerations and the complexities experienced in inter-organizational projects in the Dutch railway system. Taking the aforementioned wider perspective on project management revealed that the complexities of railway system projects are diverse in nature. In addition, there is currently a predominant focus on planning & control-based management when coordinating projects. As such, the focus seems to be on a one-size-fits-all approach to coordinating different types of complexity. Finally, project managers are often unaware of how to address context-dependent decision-making complexities with fitting strategies.

For these reasons, this research project investigates “how inter-organizational project coordination can be improved in order to support decision-making concerning system integration challenges across the entire project lifecycle.” To research this, the dissertation is divided into two research themes. The first research theme establishes a thorough understanding of the complex problem context of inter-organizational projects which address system integration challenges. The second research theme aims to improve inter-organizational project coordination in order to achieve more effective decision-making. In order to thoroughly address these two topics, a total of five sub-research questions have been formulated, which are addressed in individual chapters, using methodologies such as ‘Context, Intervention, Mechanism, Outcome logic’ for increased understanding, and ‘design science research’ to develop solutions.

This approach resulted in the implementation of design artifacts, from which several lessons have been learned. These are summarized into six generalizable design propositions (GDPs) which can be used in other complex system contexts.

Design propositions GDP1-GDP3 focus on the context of decision problems in inter-organizational projects specifically, and show that a stronger focus on and more effort toward creating a mutual understanding of the problem before engaging extensively in solution development is prudent. An incomplete understanding of the various stakeholder needs can easily result in sub-optimal solutions. The research results indicate that understanding can be improved through, for example, intervision exercises among the project team, especially when done using a jointly developed process which creates more ownership of decisions. These principles appear to be particularly important in inter-organizational contexts where the various individuals representing the stakeholders have limited understanding of other parts of the system, have technical backgrounds, and/or are not familiar with each other.

Design propositions GDP4-GDP6 appear to be more generally applicable to project coordination in systems integration challenges, and indicate that more awareness of both coordination effectiveness and different coordination options is needed. Identifying individual coordination preferences and comparing and discussing team preferences are two principles that aid increasing coordination awareness. The complexity-response framework aids in matching the experienced complexity with strategies for navigating that complexity. This is especially important in the Dutch railway context, where the awareness of the potential of using coordination mechanisms other than planning & control is generally low.

As such, by improving our understanding of the problem context of inter-organizational railway projects and designing, implementing, and testing tools aimed at improving project coordination, this dissertation provides professionals and empirical researchers with the means to address the project complexities of system integration challenges in a more fitting manner.

The dissertation concludes by presenting the theoretical and managerial implications discovered, for example that the developed artefacts should be considered a toolkit for professionals to assist them in choosing more appropriate responses to complexity they experience. As the social element is becoming increasingly important, the first three design propositions GDP1-GDP3 focus on situations where there is an identified need to build relationships among project participants. This contributes to a better understanding of what happens in inter-organizational projects when managing complexity. The second three design propositions GDP4-GDP6 reveal that effective coordination can be achieved by a better fit at the individual and inter-organizational team level. This will help managers in the railway or similar contexts to increase their effectiveness in coordinating their decision-making activities in increasingly interconnected (project) contexts. Finally, future research opportunities into more effective coordination in inter-organizational railway projects are highlighted, including the suggestion to focus on promoting flexibility and the recommendation to test tools in the pre-project phase within the railway context.

Vibration-based railway track condition monitoring: A physics-based digital twin approach

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Keywords: Digital twin, railway condition monitoring, axle box acceleration, track stiffness, vehicle-track dynamics.

1 Main objectives of the works

Modern sensing technologies mounted on trains and tracks gather a vast amount of vibration data, offering insights into the condition of railway infrastructure. Traditional methods, whether data-driven or physics-based, have limitations in handling this data effectively. While data-driven approaches are faster, they face challenges such as a lack of 'labelled data' for effective training, and limited interpretability and predictive power. Physics-based approaches, on the other hand, are computationally intensive, making them unsuitable for processing large data volumes.

This thesis introduces a physics-based digital twin approach for vibration-based railway track condition monitoring, combining the efficiency of data-driven methods with the interpretive and predictive power of physics-based models. The objectives of this thesis are to **propose** and **implement** such a digital twin, as well as to demonstrate its capabilities and effectiveness through real-world **applications**.

2 Contributions

2.1 A Digital Twin Framework

The first contribution of this thesis is proposing a physics-based digital twin framework for the vehicle-track interaction (VTI) system. It combines a physics-based VTI model for forward mapping from track parameters to vibration signal features, and a data-driven model for inverse mapping, see Appendix A. This framework allows for dynamic updating of track parameters based on measured vibration features.

The framework relies on three essential components for successful implementation and application, i.e., a set of interpretable features identified from measured vibrations, an accurate physics-based model to solve the forward problem and an efficient data-driven approach to solve the inverse problem. This thesis has made contributions in all the three aspects as summarized in sections 2.2, 2.3 and 2.4, respectively.

2.2 Mapping frequency features of vehicle-track dynamics through field measurements

Each component in the vehicle-track system serves specific functions and possesses distinct vibration features. Identifying the relevant vibration features for each track component from measurements is crucial for targeted condition monitoring and maintenance.

The thesis's second contribution is the creation of a detailed frequency feature map for the vibrations of the VTI system between 50 Hz and 3000 Hz, which can be used to identify, sequence and interpret the multiple frequency features measured by different techniques. To construct the map, extensive field measurements were carried out using three different measurement techniques, i.e., hammer tests (in both unloaded and loaded conditions), track-side, and axle-box acceleration (ABA) measurements. A total of sixteen resonances are identified and sequenced based on an underlying physical principle: track and VTI system resonances occur at the bounding frequencies of propagating track waves, see Appendix B.

With this frequency feature map, peak frequencies identified by different measurement techniques can be associated with the corresponding resonances of the VTI system in a consistent and well-founded manner. The sequence patterns can serve as a key feature of a track or VTI system, and be used subsequently for evaluating model accuracy (see section 2.3) and monitoring track conditions (see section 2.4).

2.3 Evaluating model assumptions for vehicle-track dynamic simulations

For the digital twin to effectively reproduce measured vibration features (see section 2.2), a physics-based VTI model that balances accuracy and efficiency is essential. This balance depends on the model assumptions.

The third contribution of this thesis is quantifying the effects of various model assumptions made in the wheel, contact and track models on the simulated vibration features. A comparative study was conducted for two types of commonly used VTI models, i.e., a beam model and a 3D finite element (FE) model. The capabilities of each model to reproduce the frequency features (section 2.2.) were evaluated. The study focused on wheel-rail impacts at rail squats

for various vehicle speeds and defect sizes. It is found that the local inertia in the contact patch and stress wave propagation in solids, which can be considered in the 3D FE model but not in the beam model, are critical factors that have been overlooked in previous research. As a result, the beam model is found to be only comparable to the 3D FE model up to approximately 800 Hz, instead of the conventionally believed 1500 Hz. Comparisons with field observations also suggest that the 3D FE model is more accurate, see Appendix C.

The findings from this study not only enhance the understanding of vehicle-track dynamics but also guide the development of VTI models by choosing model assumptions that lead to a balance between accuracy and efficiency for a given problem.

2.4 Robust, efficient and high-resolution track stiffness evaluations

The proposed digital twin is applied to two inverse identification problems, i.e., evaluating dynamic track stiffness in unloaded tracks by hammer tests and in loaded tracks by ABA. Using the frequency feature map (section 2.2), the stiffness of each track layer is related to distinct vibration features. A beam model (section 2.3) was developed to establish the forward mapping. Gaussian process (GP) regression models were used to establish the inverse mapping.

The last contribution of the thesis is demonstrating how the proposed digital twin approach enables high-resolution, robust and efficient track stiffness evaluations. Compared to existing techniques, the proposed approach enables evaluating the stiffness of multiple track layers (i.e., the railpad/fastening and ballast) simultaneously at high resolutions (i.e., at sleeper spacing level), see Appendix D. In addition, track stiffness evaluations by ABA are robust to changing track irregularities and speeds. Furthermore, the proposed approach is capable of performing rapid assessments of track stiffness due to the efficiency of the GP models.

3 Future works and perspectives

In the literature, different VTI models have been compared through benchmark tests for different problems. However, 3D FE models were excluded from these benchmarks. This provides the opportunities to apply the two models developed in this thesis for the available benchmark problems, especially those wheel-rail impact problems, e.g., at insulated joints, wheel flats and crossings.

In future studies and practical applications, a more comprehensive understanding of the rate at which track stiffness changes can be gained by integrating frequent ABA measurements with in-track validations, utilizing the techniques demonstrated in this thesis. The technology can be used to monitor track stiffness and its changes over time due to degradation, maintenance (e.g., tamping) or seasonal effects (e.g., groundwater level and temperature).

The proposed digital twin framework provides a generic approach for broader applications in railway condition monitoring. For instance, by using the digital twin framework, the ABA technique can be extended to detect and quantify multiple track degradations simultaneously. The fundamental principle is to identify unique ABA features that correspond to a particular degradation. This will allow for integrated condition monitoring of the track structure, such as for rail top defects, track geometry, fastenings, ballast, and substructures (e.g. track stiffness).

4 Conclusions

- The proposed digital twin framework combines data-driven and physics-based methods to overcome their individual limitations. The framework requires three key elements: clearly defined vibration features, an accurate physics-based forward model, and an efficient data-driven approach for inverse problems.
- A frequency feature map is established through field measurements, which identifies peak frequencies that can be linked to specific resonances of the VTI system. The identified frequency features are essential for validating the physics-based model and for railway condition monitoring applications, e.g., evaluating track stiffness.
- Two physics-based models - a beam model and a 3D FE model - are compared for reproducing the frequency features of wheel-rail impact at squats. The beam model is accurate up to about 800 Hz due to its inability to consider local inertia in the contact patch and stress wave propagation in solids.
- Using the frequency feature map, a beam model and GP models, the proposed digital twin approach enables robust, efficient and high-resolution track stiffness evaluations.

Monitoring Dynamic Properties of Railway Tracks Using Train-borne Vibrometer Measurement

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Date of PhD defense: December 4, 2023

Keywords: Laser Doppler vibrometer; Train-borne infrastructure monitoring; Load-response relationship; Train-track dynamics; Speckle noise.

Main objectives of the thesis

Dynamic properties of railway tracks affect the safety and quality of train operations. Load-response relationship over a wide frequency range is a normalized and informative characterization of track dynamic properties. Such a relationship is typically measured by impact modal tests, which are time-consuming and labor-intensive and cannot be applied on a large scale. The goal of this thesis is to continuously measure such load-response relationships at every location along a track from an instrumented train. With the excitation from the moving dynamic train load, a non-contact sensing device – laser Doppler vibrometer (LDV) – is utilized to scan track structures and measure their vibration response. To accomplish this goal, the following research questions are addressed in this thesis.

- How to mitigate speckle noise in LDV signals when scanning rough track surfaces?
- How to interpret operational vibration response without load information?
- How to characterize the performance of a train-borne LDV at different speeds?
- How to estimate the load-response relationship from a moving vehicle?

Contributions

The overall contribution of this thesis is the development and validation of a new technology based on train-borne LDV for measuring the vibration and load-response relationship of railway tracks over a wide frequency range. It consists of the following four cornerstones.

Cornerstone 1: A three-step framework for speckle noise mitigation. Speckle noise has long been a major obstacle to open-path scanning of LDV on rough surfaces. Speckle noise is extremely irregular and broadband in nature, and its characteristics vary significantly at different scanning speeds. This thesis develops a framework to mitigate speckle noise at the post-processing stage based on the study of the noise characteristics. It consists of three main steps – spike detection, imputation, and smoothing. The framework can effectively remove the speckle noise in train-borne LDV signals while preserving the target track vibrations. The extracted track vibrations are consistent with those measured by trackside accelerometers [1].

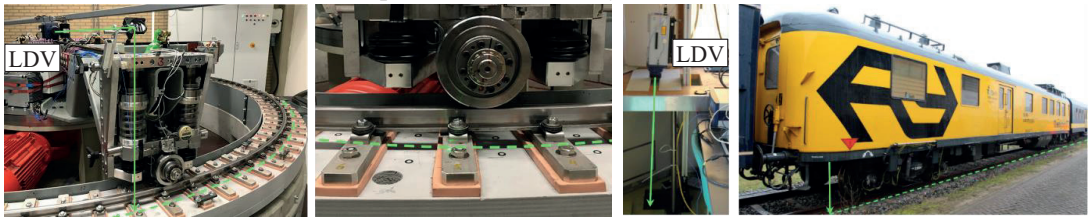
Cornerstone 2: An interpretable operational modal analysis method in time-frequency representation. The lack of dynamic loading information makes the interpretation of structural vibrations and the identification of dynamic parameters challenging, especially for nonstationary track-track responses under time-varying loads and conditions. Therefore, this thesis develops an interpretable operational modal analysis method. This method can extract a global view of modal characteristics over time and frequency and also estimates of modal parameters. The identified natural frequencies and mode shapes are in good agreement with those measured by impact hammer tests over a broad frequency range [2].

Cornerstone 3: A systematic investigation in the speed-dependent characteristics of signal-to-noise ratio. Train speed is a key factor affecting the performance of a train-borne LDV since both track vibration and speckle noise vary significantly with it. This thesis combines simulations and measurements to characterize a train-borne LDV system. The framework in Cornerstone 1 is adapted to separate track vibration and speckle noise in signals measured at different speeds. The speed-dependent characteristics of the signal-to-noise ratio are investigated, and the optimal speed ranges with high signal quality are determined in the different scenarios [3].

Cornerstone 4: A response-only methodology for estimating load-response relationship of track structures. Based on Cornerstone 1 and 3, a train-borne LDV can extract pure track

response from a moving vehicle. To fill the gap of unknown train loads, accelerometers are mounted on the vehicle for dynamic load estimation. The method in Cornerstone 2 is applied to identify the modal parameters of the vehicle, which are then used to estimate wheel-rail contact force from vehicle vibrations. A transfer function is further estimated for each short track section along a track using the estimated wheel-rail force as input and the extracted track vibration as output. The results are in good agreement with the results of trackside hammer tests [4].

Based on the four cornerstones, the train-borne LDV technology has taken its shape in continuously and efficiently measuring the load-response relationship of railway tracks. As the instrumented vehicle moves, track vibrations are captured, and transfer functions at every location along a track are estimated. This technology is tested on the V-Track test rig at TU Delft and on the CTO measurement train in the Netherlands. In the laboratory test, the highest speed tested is 20 km/h, and the track vibration up to 1,000 Hz is analyzed. In the field test, the highest speed of 30 km/h and the track vibration up to 300 Hz are analyzed.



Laboratory and field tests of the train-borne LDV technology.

Future works and perspectives

This thesis makes the following recommendations for future research.

- The train-borne LDV technology needs to be tested at higher speeds where more severe speckle noise, lower frequency resolution, and more uncertainties are expected.
- The operational modal analysis method needs further improvements in terms of accuracy for nonlinear and highly-damped structures and robustness to short signal lengths.
- In addition to measuring sleepers and ballast, the laser beam of a train-borne LDV can be adapted to measure other structures, such as embankments and bridges. There may be additional challenges due to rougher surfaces, lower reflectivity, and large inclinations.
- Future development should be aligned with its potential application to rail infrastructure monitoring. The goal is to achieve large-scale monitoring from instrumented operational trains on a daily basis, thus allowing effective lifespan control with predictive maintenance.

Conclusions

The developed train-borne LDV technology is capable of directly measuring the track vibrations from the moving vehicle. The measured track vibrations are further combined with the wheel-rail contact force estimated from the measured vehicle vibrations to successfully estimate the transfer function of the track structure over a wide frequency range. The train-borne LDV technology can be potentially applied to a wide range of structures, thus enabling more efficient and informative rail infrastructure monitoring.

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Mechanisms and mitigation of short pitch rail corrugation

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Key words: short pitch corrugation, rail longitudinal vibration modes, rail fastening design, 3D finite element modelling, the downscale V-Track test rig.

Main objectives of the PhD works

Short pitch corrugation is a (quasi-) periodic rail surface defect with shiny crests and dark valleys. It primarily occurs on tangent tracks and gentle curves with a typical wavelength in the range of 20-80 mm [1]. Short pitch corrugation excites high-frequency wheel-rail dynamic forces and generates a high level of noise and vibration, which is a nuisance to both the passengers and the residents near the railway lines, as well as a main track degradation drive.

The goal of this dissertation is to better understand the formation mechanism of short pitch corrugation and develop the root-cause solutions to mitigate it. To achieve this goal, the research works in this dissertation were conducted in three steps, as shown in Fig. 1.

1. The operating deflection shape (ODS) approach and the synchronized multiple-acceleration wavelet (SMAW) approach are employed to investigate rail vibration modes and wave propagation in free conditions (Chapter 2) and under fastening constraints (Chapter 3), which are crucial to short pitch corrugation formation.
2. The influence of fastening parameters on the development and mitigation of short pitch corrugation is numerically studied, employing a 3D FE vehicle-track interaction model (Chapter 4). In light of these results, a new rail constraint is designed to suppress rail longitudinal compression modes and mitigate short pitch corrugation (Chapter 5).
3. A dynamometer is developed in the V-Track test rig to measure the wheel-rail contact forces for short pitch corrugation experiments (Chapter 6). Afterwards, the V-Track test rig is used to reproduce short pitch corrugation to understand and validate the corrugation development mechanism proposed in [2] (Chapter 7).

The research outcomes in each Chapter have been published in peer-reviewed international journals, as listed in Annexes.

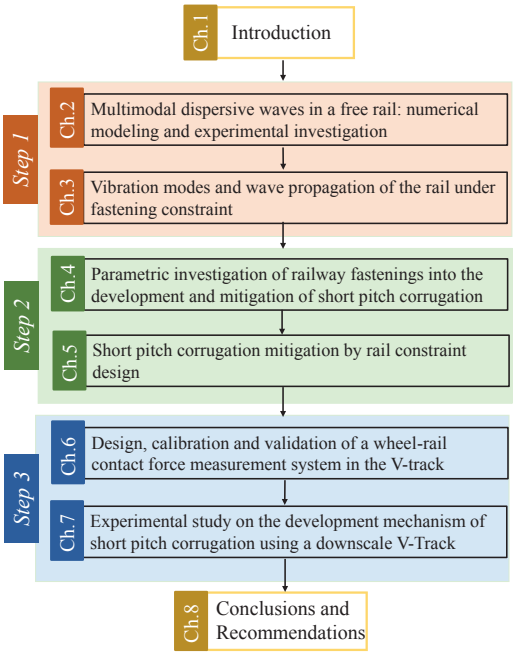

Fig. 1. Outline of this PhD dissertation.

Contributions

The major contribution of this dissertation is threefold, as follows,

1. A better understanding is obtained of vibration modes and wave propagation of the rail in free condition and under fastening constraint by ODS and SMAW measurement, which is essential for understanding and mitigating short pitch corrugation;
2. A new rail constraint is designed which can effectively suppress rail longitudinal compression modes and mitigate short pitch corrugation;
3. Experimental evidence is provided for the first time to demonstrate that initial excitation and longitudinal compression modes play a significant role in the consistent development of short pitch corrugation.

Future works and perspectives

Based on the research in this dissertation, the following aspects are recommended to be further investigated:

1. The current work investigates the corrugation formation mechanism using numerical simulations and the V-Track tests in the laboratory. For future work, field tests and monitoring are recommended to further validate the findings from this work.
2. In the current work, a new rail constraint is designed and its validity on short pitch corrugation mitigation is numerically evaluated employing a 3D FE vehicle-track interaction model. However, it should be noted that this new rail constraint is still a concept design in the current stage. In future research, it is recommended to experimentally assess the effectiveness of the new rail constraint on short pitch corrugation mitigation. Besides, it is necessary to investigate the influence of the new rail constraint on other track components, such as sleepers and ballast layers for its field application.
3. Fastening parameters and modelling play an important role in understanding short pitch corrugation development. To better grasp the corrugation features in the field and reliably predict corrugation in the simulation, it is suggested to examine the service conditions of fastenings in different stages and characterize them with appropriate parameters. More advanced fastening models are recommended to be developed to consider the nonlinear properties of railpads.

Conclusions

This dissertation focuses on three aspects to better understand the development mechanism of short pitch corrugation and develop effective solutions for its mitigation. They are 1) to investigate rail vibration modes in free condition and under fastening constraint which determine the formation of short pitch corrugation; 2) to design a new rail constraint to suppress rail vibration modes and mitigate short pitch corrugation; 3) to experimentally validate the corrugation development mechanism using a downscale V-Track test rig. The major conclusions are summarized as follows.

1. In Chapter 2 of Step 1 (see Fig. 1), novel experimental methods (i.e., SMAW and ODS) to distinguish different wave modes and measure wave propagation and dispersion characteristics were proposed and demonstrated in a free rail.
2. In Chapter 3 of Step 1, rail vibration modes and wave propagation under fastening constraint in three directions were studied using the SMAW and ODS methods. It is found that the existing fastening constraints suppress the longitudinal rail vibrations less effectively, compared to the vertical and lateral directions. The change of fastening stiffness and damping can control rail mode frequencies and their vibration amplitude, and influence the wave propagation velocities and attenuation along the rail.
3. In Chapter 4 of Step 2, a parametric investigation of fastenings was performed employing a 3D FE vehicle-track interaction model to better understand the corrugation development mechanism and gain insight into its mitigation by fastening design. It is found that the fastening longitudinal constraint to the rail is the major factor that determines the corrugation development because the rail longitudinal modes, which are responsible for the corrugation initiation, are a type of compression/rarefaction vibration in the longitudinal direction. The increase of fastening constraint in the longitudinal direction helps to mitigate corrugation.
4. In Chapter 5 of Step 2, based on the identified corrugation initiation mechanism and insights in Chapter 4, a novel approach was proposed to mitigate or even eliminate corrugation. That is to design a new rail constraint that can effectively suppress rail longitudinal compression modes so that the induced longitudinal contact force fluctuates much less, differential wear can barely accumulate, and corrugation can hardly initiate.
5. In Chapter 6 of Step 3, a force measurement system named a dynamometer was developed for the innovative downscale V-Track test rig to reliably measure and control the wheel-rail contact forces in three directions. The V-Track would be used for rail corrugation experiments.
6. In Chapter 7 of Step 3, an experimental study of short pitch corrugation was performed using the V-Track test rig. The experimental evidences validated the hypotheses about rail longitudinal vibration modes and the consistency condition for short pitch corrugation development [2].

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An electronic version of this PhD dissertation is available at

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Benchmarking with aviation to develop maintenance paradigm shift from preventive to predictive for rail freight wagons

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Keywords: maintenance strategy, digital transformation, rail freight, aviation

• Main objectives of the works

This work is part of my PhD thesis, which focuses on the research topic of "cross-industry digital innovation in asset maintenance", supervised by professor Olivier Bareille and defensed in December 2023 at Ecole Centrale de Lyon, France. My PhD thesis is a cross-disciplinary research aiming to bridge mechanical engineering and innovation management, and a cross-industry innovation research aiming to improve the competitiveness of rail freight industry by benchmarking the best practice of maintenance strategies in aviation industry. As a pillar of my doctoral thesis, the main objective of this work is to propose a condition monitoring-based predictive maintenance architecture for rail freight wagons, based on the findings we get from both the industrial practice and the literature review.

• Contributions

This work summarizes and compares the maintenance strategies of rail freight wagons and aircrafts both in practice and in literature, showing that, maintenance strategies for aircrafts and wagons are different, and wagon maintenance lags far behind aircraft maintenance in terms of efficiency, reliability, and digitalization. This work proposes that the maintenance strategy of rail freight wagons will undergo an imperative paradigm shift from preventive to predictive, especially in terms of utilizing digital technology and data management. Thus, this work contributes to developing a condition monitoring-based predictive maintenance architecture for rail freight wagons, taking into account the realities of wagon maintenance as well as the characteristics of condition-based and predictive maintenance technologies.

From sociotechnical system perspective, leveraging digital technology to transform maintenance business of rail freight wagons is not only a technical issue of how to make good use of digital technology to improve maintenance efficiency, but also a strategic issue of how to innovate business model to generate value growth for the rail freight industry. So, in addition to focusing on the technical maintenance architecture, my PhD thesis also considers the strategic maintenance ecosystem, especially focuses on the leasing business of freight wagons. My thesis reveals that with the emergence of new digital maintenance landscape, the business models of the main players in the wagon maintenance ecosystem will change accordingly. Specifically, my thesis contributes to the value growth of rolling stock(wagon) OEMs, cargo rail operators and wagon keeper.

• Future works and perspectives

With the rail freight sector trying and initiating to implement condition monitoring-based predictive maintenance architecture, the maintenance process will change accordingly. This work advocates that the gradual shift from legacy equipment to new sensor-equipped fleets requires a flexible approach to incorporating digital maintenance insights into decision rules and monitoring the extent to which regulatory requirements are met. As digital tools continue to

evolve throughout the rollout and deployment, the surrounding processes and decision rules will also need to be adapted and incorporated into the maintenance process. Future works could focus on the maintenance process design and decision-making optimization.

• Conclusions

By comparing different maintenance strategies of reactive, proactive, and reliability-centered maintenance, this work argues that systematic predictive maintenance is still far from "ready to implement", instead, gradually shifting from preventive to CBM and then to predictive is much more realistic. In the proposed condition monitoring-based predictive maintenance architecture, three layers of data management are considered: 1) multi-source raw data collection, 2) intelligent condition data analysis and 3) automated maintenance decision making.

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