



Research report 2026:01

Recommendations for revision of maintenance procedures and regulations for removal of damaged wheels

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Executive summary

The present study was carried out within the project *Improved Regulations and Procedures for Damaged Wheels*, funded by the Swedish innovation agency VINNOVA and conducted between 1 July 2023 and 30 June 2026 by representatives from Trafikverket, Chalmers University of Technology, Green Cargo, and SJ. Parts of the research were also supported through the European project TRANS4M-R (Horizon Europe Rail Joint Undertaking, Grant Agreement No. 101102009). The overall objective was to improve regulations, maintenance procedures, and operational decision-making related to damaged wheels in order to reduce infrastructure damage, avoid unnecessary train stops, and strengthen collaboration between infrastructure managers and railway undertakings.

The VINNOVA project was divided into four work packages (WPs). This report constitutes the final deliverable from WP4, while also summarising the main findings and implementations from WP1 – Detectors, WP2 – Simulation Models, and WP3 – Track Damage Assessment.

A central finding throughout the project is that the current practice of assessing wheel damage primarily through geometric criteria, particularly wheel flat length, does not adequately reflect the actual risk posed to railway infrastructure or operations. Extensive analyses of Wheel Impact Load Detector (WILD) data, combined with detailed simulations of vehicle–track interaction, demonstrated that wheel–rail impact loads depend on several interacting factors, including wheel-flat depth and shape, axle load, train speed, wheel–rail contact conditions, and local track characteristics. Consequently, wheel defects of similar size can produce substantially different impact loads and resulting effects on infrastructure and vehicles. In several cases, wheel flats exceeding the current 60 mm intervention threshold generated loads well below the alarm level of 350 kN, while shorter but deeper defects produced considerably higher dynamic forces.

Within WP1, existing wheel impact load detectors were critically assessed and detector data from Swedish railway operations were analysed. The work resulted in improved understanding of detector performance and variability, as well as new guidelines for detector placement, maintenance, and calibration that have been adopted by Trafikverket. The studies highlighted the importance of controlling track geometry and track stiffness to obtain a high measurement quality. It also identified the absence of a robust dynamic calibration procedure as an important area for future development.

In WP2, advanced simulation models were used to investigate wheel–rail impact loading and the resulting infrastructure consequences. The simulations demonstrated that the risk of rail break is governed by a combination of dynamic wheel loads, crack size, rail material properties, temperature conditions, and track support stiffness. The analyses further showed that wheel condition and resulting impact-load distributions can be more important than axle load and train speed in determining infrastructure risk. These findings support a transition from purely geometry-based regulations towards risk-based approaches based on measured loads and quantified infrastructure consequences.

Within WP3, methods were developed for using detector data to predict resulting track damage and rail crack growth. The studies demonstrated that detector systems have significant untapped potential for train fleet monitoring and providing support for predictive maintenance planning. Recommendations were developed for future enhancements, including collection of full load histories, implementation of additional detectors in curves, and integration with wheel-profile monitoring systems. Such developments would improve the detection, classification, and management of wheel tread damage and support more reliable condition-based maintenance.

The results from the first three work packages formed the basis for WP4, which focused on implementation and regulatory development. Revised regulations for more reliable track structures were developed and evaluated by Trafikverket. Based on detector data, simulations, operational experience, and international benchmarking, recommendations were made for a more flexible and risk-informed framework for handling wheel-damage alarms. A notable outcome was the implementation of revised speed-reduction rules for vehicles triggering high-level detector alarms, reducing unnecessary operational disruptions while maintaining safety.

The practical benefits of the project are demonstrated through examples from Green Cargo, SJ, and Trafikverket. The studies show that major wheel damage is a relatively rare but high-impact phenomenon. A single detector alarm can result in substantial vehicle downtime, recovery costs, reduced capacity, and extensive traffic delays. For passenger traffic, even short inspection stops can generate thousands of accumulated delay minutes across the network. For freight operators, incidents may result in costs ranging from tens of thousands to hundreds of thousands of Swedish kronor due to disrupted operations, vehicle transport, and asset unavailability. These examples illustrate the value of early detection, reliable monitoring, and risk-based maintenance planning. The removal of the requirement for on-foot track inspections following a high-level alarm is by itself estimated to generate annual socio-economic benefits of more than 50 MSEK through reduced inspection costs, fewer traffic-disruptive interventions, and improved operational efficiency.

Overall, the project demonstrates that a transition from geometry-based assessment of wheel damage towards load-based and risk-based management is both technically feasible and operationally beneficial. The developed methods, updated detector routines, revised regulations, and improved collaboration between stakeholders provide a strong foundation for more effective infrastructure protection, reduced traffic disturbances, lower lifecycle costs, and improved reliability of the Swedish railway system. The project outcomes also provide valuable guidance for future development of intelligent condition-monitoring systems and risk-based railway maintenance practices both in Sweden and internationally.

Sammanfattning

Denna studie genomfördes inom projektet "Minskade trafikstörningar och skador på spår och fordon genom förbättrade regler och rutiner", finansierat av VINNOVA och genomfört under perioden 1 juli 2023 – 30 juni 2026 av representanter från Trafikverket, Chalmers tekniska högskola, Green Cargo och SJ. Delar av forskningen har även finansierats genom det europeiska projektet TRANS4M-R inom Horizon Europe Rail Joint Undertaking (Grant Agreement No. 101102009). Det övergripande målet har varit att förbättra regelverk, underhållsprocedurer och operativa beslutsprocesser för skadade hjul i syfte att minska nedbrytning av fordon och infrastruktur, undvika onödiga tågstopp och stärka samarbetet mellan infrastrukturförvaltare och järnvägsföretag.

VINNOVA-projektet delades in i fyra arbetspaket (WP). Denna rapport utgör slutleveransen från WP4, men sammanfattar även de viktigaste resultaten och implementeringarna från WP1 – Detektorer, WP2 – Simuleringsmodeller och WP3 – Bedömning av spårskador.

Ett centralt resultat från projektet är att dagens praxis, där hjulskador i stor utsträckning bedöms utifrån geometriska kriterier såsom hjulplattans längd, inte ger en tillräckligt korrekt bild av den faktiska risken för infrastruktur och trafik. Omfattande analyser av data från hjulskadedetektorer (WILD), i kombination med detaljerade simuleringar av fordon–spår-interaktion visar att hjul–räl-krafterna påverkas av flera samverkande faktorer, bland annat hjulplattans djup och form, axellast, hastighet, kontaktförhållanden mellan hjul och räl, samt lokala spåregenskaper. Följden blir att hjulskador av liknande storlek kan ge upphov till mycket olika belastningar och därmed relatera till olika risknivåer. I flera fall genererade hjulplattor med en längd över det nuvarande gränsvärdet på 60 mm hjul–räl-krafter långt under larmnivån på 350 kN, medan kortare men djupare skador gav upphov till betydligt högre dynamiska krafter.

Inom WP1 genomfördes en kritisk granskning av de hjulskadedetektorer som används i Sverige. Arbetet resulterade i en förbättrad förståelse av detektorernas prestanda och variationer samt nya riktlinjer för placering, underhåll och kalibrering, vilka har implementerats av Trafikverket. Studierna visade samtidigt att spårgeometri och spårstyvhet har stor påverkan på mätresultaten samt att en robust metod för dynamisk kalibrering fortfarande saknas.

I WP2 användes avancerade simuleringsmodeller för att analysera hjul–räl-krafter och deras konsekvenser för infrastrukturen. Resultaten visade att risken för rälsbrott bestäms av en kombination av dynamiska hjullaster, sprickstorlek, materialegenskaper, temperaturförhållanden och spårets styvhet. Analyserna visade också att hjulens tillstånd och den resulterande lastfördelningen ofta har större betydelse för infrastrukturen än axellasten och tåghastigheten. Detta stärker argumenten för att ersätta rent geometribaserade regler med riskbaserade metoder som utgår från uppmätta laster och kvantifierad påverkan på infrastrukturen.

Inom WP3 utvecklades metoder för att använda detektordata för bedömning av risk för spårskador och spricktillväxt i räl. Studien visade att dagens detektorsystem har en betydande outnyttjad potential för tillståndsovervakning och för att stödja planeringen

av prediktivt underhåll. Rekommendationer togs fram för framtida utveckling, bland annat insamling av fullständiga lasthistorier, installation av ytterligare detektorer i kurvor samt integrering av hjulprofilmätningar. Detta skulle förbättra möjligheterna att upptäcka, klassificera och hantera hjulskador samt möjliggöra mer träffsäkra underhållsinsatser.

Resultaten från de tre första arbetspaketen utgjorde grunden för WP4, som fokuserade på implementering och regelverksutveckling. Trafikverket tog fram och utvärderade reviderade regler för att öka spårstrukturens tillförlitlighet. Med stöd av detektordata, simuleringar, operativa erfarenheter och internationella jämförelser utvecklades rekommendationer för ett mer flexibelt och riskbaserat regelverk för hantering av hjulskador. Ett konkret resultat är införandet av reviderade hastighetsrestriktioner för fordon som utlöser högnivåalarm, vilket minskar onödiga trafikstörningar samtidigt som säkerheten bibehålls.

Projektets praktiska nytta illustreras genom erfarenheter från Green Cargo, SJ och Trafikverket. Studierna visar att hjulskador är relativt ovanliga men kan få mycket stora konsekvenser. Ett enda detektorlarm kan leda till omfattande fordonsbortfall, höga återställningskostnader, kapacitetsbegränsningar och betydande trafikförseningar. För persontrafiken kan även korta stopp ge upphov till tusentals ackumulerade förseningsminuter, medan godstrafiken kan drabbas av kostnader på tiotusentals eller hundratusentals kronor till följd av driftstörningar och fordonsbortfall. Dessa exempel understryker värdet av tidig upptäckt, tillförlitlig övervakning och riskbaserat underhåll. Enbart avskaffandet av kravet på spårbesiktning till fots efter ett högnivåalarm bedöms ge årliga samhällsekonomiska vinster på över 50 MSEK genom minskade besiktninganskostnader, färre trafikstörande insatser och förbättrad operativ effektivitet.

Sammantaget visar projektet att en övergång från geometribaserad bedömning av hjulskador till en last- och risk-baserad hantering är både tekniskt möjlig och operativt fördelaktig. De utvecklade metoderna, de uppdaterade detektorrutinerna, de reviderade regelverken och det fördjupade samarbetet mellan berörda aktörer skapar goda förutsättningar för ett mer robust järnvägssystem med bättre infrastrukturskydd, färre trafikstörningar, lägre livscykelkostnader och högre driftsäkerhet. Resultaten ger dessutom värdefull vägledning för den fortsatta utvecklingen av intelligenta tillståndsovervakningssystem och riskbaserade underhållsstrategier, både i Sverige och internationellt.

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Preface

The work presented in this report is performed as a Parallel Special Project (SP37) within the Centre of Excellence CHARMEC (www.charmec.chalmers.se). The aims of the project are improved regulations and procedures to avoid traffic disruptions caused by infrastructure failures and unnecessary stopping of trains. It should also promote an increased collaboration and understanding between infrastructure owner and rolling stock operators. The project duration is 2023-07-01 – 2026-06-30.

Financial support was provided by VINNOVA (Sweden's innovation agency), contract no 2023-01218 together with Trafikverket (The Swedish Transport Administration) as co-financier, contract no TRV 2023/33606. This report summarises the work in the fourth work package (WP4) of the project.

Göteborg in June 2026

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1 Introduction

Wheel flats constitute a common form of local wheel tread damage in railway operation and are known to generate high dynamic wheel–rail contact forces. These impact loads can accelerate deterioration of both rolling stock and track components. To mitigate associated risks, railway administrations typically apply a combination of visual inspection criteria, most notably maximum permissible wheel flat length, and measurements from wayside Wheel Impact Load Detectors (WILDs). However, the relationship between wheel flat geometry and measured impact loads under real operating conditions is not well established.

2 Results and implementations in WP1 – Detectors

The work in WP1 focused on evaluating and improving the use of wheel damage detectors in Sweden. A critical assessment of existing detectors was carried out, alongside a statistical analysis of detector data to identify correlations between wheel damage, operational parameters, and measured loads. The study also examined the occurrence and causes of rail breaks, as well as the infrastructure impact of out-of-round wheels. In addition, the number of train stops and related costs were analysed. Based on the findings, a routine for the calibration and placement of detectors was developed by Trafikverket. Key deliverables include a comprehensive report on detector performance [15] and a practical guideline for their calibration and installation [7] developed by Trafikverket.

2.1 Routine for calibration and placement of detectors by Trafikverket

The placement of a wheel impact load detector (WILD) has a significant influence on both the quality and accuracy of the measurements and on the operational consequences of detector alarms. Consequently, Trafikverket has specified a set of requirements and recommendations to be considered when selecting the location of a new WILD installation; see [67], which recently replaced [2]. The selected detector location must also be approved by the detector manufacturer.

To minimise operational delays caused by alarms, the detector should be located between two stations or railway yards equipped with sidings and road access. This enables damaged vehicles to be shunted and maintained without disrupting surrounding railway operations, while also ensuring accessibility for maintenance personnel and equipment. Particular importance is assigned to locating the detector on a track section that is as straight and flat as possible and where the vehicle is neither hunting nor undergoing acceleration or deceleration. Consequently, the detector should be installed on a straight track section with a maximum gradient of 5‰ and at a sufficient distance from signals that may induce braking or acceleration. In the latest TDOK specification [7], the required distance between the detector and nearby signals is no longer fixed but instead depends on the maximum permissible speed of the track section. Locations prone to snow accumulation shall be avoided. Furthermore, transition curves, switches, crossings, bridges, defective sleepers, and rail joints shall not be located in the vicinity

of the detector. Within 50 m of the detector, neither thermite welds nor rail surface defects are permitted. Additional requirements apply to the local track quality. In the vicinity of the detector, the track gauge deviation from the nominal gauge of 1435 mm may range between +3 mm and -2 mm, the track cant shall not exceed 2 mm, sleeper deflection under train passage shall not exceed 10 mm, and the minimum soil compressive stress shall be 60 MN/m². However, different requirements apply at different distances from the detector. Compared with the previous specification [2], the updated TDOK [7] places greater emphasis on operational performance, compatibility with modern signalling systems, and stricter track geometry requirements rather than fixed-distance criteria.

The updated TRVINFRA-00358 specification [6] defines a general strategy for the placement of wheel impact load detectors. According to this document, freight vehicles should pass at least one WILD every 250 km, and detector locations shall be selected such that damaged railway vehicles cannot enter tracks intended exclusively for passenger traffic. The same document also specifies target distances between hot wheel detectors as a function of the maximum permitted axle load and whether the line consists of single or multiple tracks. A similar philosophy may potentially be adopted for WILD systems in the future.

According to recommendations issued by detector manufacturers, WILD systems should undergo maintenance annually [1]. In addition, the condition of the surrounding track, including track stiffness, track geometry, and rail surface condition, should be carefully assessed during scheduled track maintenance activities. Detector maintenance is typically performed during the warmer months of the year. During maintenance, the voltage levels and integrity of the electrical equipment are verified at several measurement points, and enclosed equipment cabinets are inspected for humidity. Sleeper positions are checked and adjusted if displacements exceeding 30 mm are detected. For strain-gauge-based detectors, the insulation resistance, strain-gauge resistance, and measurement output signals are inspected. For optical detectors, the hardware, cabling, and optical sensors are verified. Battery capacity is measured and batteries are replaced when necessary. After completion of the maintenance procedure, the technicians must verify that the measurement data from the first train passage are correctly stored in the system [1]. Maintenance personnel are required to report all faults identified during the inspection and to confirm that faults reported during previous inspections have been rectified. To maximise detector availability, detector suppliers are further required to verify the quality of the detector output data every second week in accordance with procedures defined by the supplier's technical support.

Calibration of each Wheelscan detector is performed either using a service computer or directly at Schenck headquarters in Darmstadt, Germany. Calibration coefficients for the strain gauges are determined from a series of test runs conducted in both running directions at the installation site using a train consisting of wagons with different axle loads. The train is required to operate throughout the entire designated speed range, for example from 20 km/h to 200 km/h in increments of 10 km/h [7]. However, this procedure only enables calibration of the measured static loads. A separate procedure

for calibration of dynamic loads was developed at a later stage. This method employs a freely falling 25 kg mass impacting the rail at the detector location. Nevertheless, the procedure does not account for the influence of the quasi-static wheel load associated with normal train passage and is therefore not fully representative of operational loading conditions.

Calibration of zentrak detectors requires an external calibration device and must be performed during installation. Since speed determination, train recognition, and axle-spacing calculations depend on accurate sensor positioning, the distance between sensors must be carefully verified. Once correctly installed, the system initiates a continuous self-calibration process based on passing trains, thereby eliminating the need for additional calibration procedures [9]. To date, however, no dedicated procedure for calibration of dynamic loads measured by zentrak detectors has been developed nor presented publicly.

As part of the procurement process for new wheel flat detectors in 2006, extensive field testing was conducted by Banverket [8]. The Track Loading Vehicle (TLV) was used to generate several forms of excitation, including cosine ramp excitation (0.5 Hz), swept-sine excitation (1–20 Hz and 10–200 Hz), and random excitation in the frequency range 10–100 Hz. In addition, impulse excitation up to 1000 Hz was applied using a sledgehammer. However, no procedure for dynamic calibration of the detector systems was found. At present, Trafikverket has no established procedure for calibrating detectors with respect to dynamic load variations superimposed on static axle loads. The development of such a calibration methodology would increase confidence in detector measurements for wheel-flat detection and, in particular, improve the assessment of whether severe or mild operational restrictions should be imposed on damaged vehicles. A robust dynamic calibration procedure would therefore provide substantial benefits both for Trafikverket and for railway undertakings by enabling more reliable condition-based maintenance planning based on detector data. Consequently, development of such a methodology should be prioritised in future research activities.

2.2 Critical assessment of detectors used in Sweden

In [15], extensive WILD data from heavy freight traffic was analysed, with particular focus on the influence of wheel flat length, axle load, train speed, and detector-specific characteristics. The analysis was based on measurements from six WILD installations located along the freight route between Luleå and Borlänge (StålpPENDeln). The route is predominantly used for steel transport and includes both loaded and unloaded freight wagons. All detectors are of Schenck type. The dataset comprises 823 detector passages corresponding to 149 individual wheelsets with confirmed wheel flats, documented during workshop inspections prior to wheel reprofiling. Data were collected between December 2022 and March 2023. Wheel flats were grouped according to their measured length, and only detector passages at speeds above 40 km/h were included to ensure robust wheelset identification.

For each passage, the maximum vertical wheel–rail contact force per axle was selected, consistent with operational alarm evaluation procedures. The dataset includes

both loaded wagons, with axle loads in the range of approximately 17–25 tonnes, and unloaded wagons, with axle loads of about 4.5 – 6 tonnes. The results show a pronounced scatter in measured peak impact loads for all investigated wheel flat lengths and train speeds. No distinct speed-related maxima in impact loading could be identified. When peak loads are analysed as a function of wheel flat length, a weak tendency of increasing loads with increasing flat length can be observed, but the correlation is poor and the dispersion is substantial for both loaded and unloaded wagons. This variability is attributed to several uncontrolled factors, including unknown wheel flat depth and shape, edge rounding, variations in wheel–rail contact position relative to the flat, and local differences in track stiffness and geometry at detector sites.

A key outcome of the analysis is illustrated in Figure 2.1, which presents cumulative distributions of peak impact loads for different wheel flat length intervals for loaded wagons. The figure demonstrates that even wheel flats well above the commonly applied removal limit of 60 mm do not result in peak loads exceeding the high alarm threshold of 350 kN. This finding directly challenges the effectiveness of wheel flat length as an independent criterion for assessing damage potential.

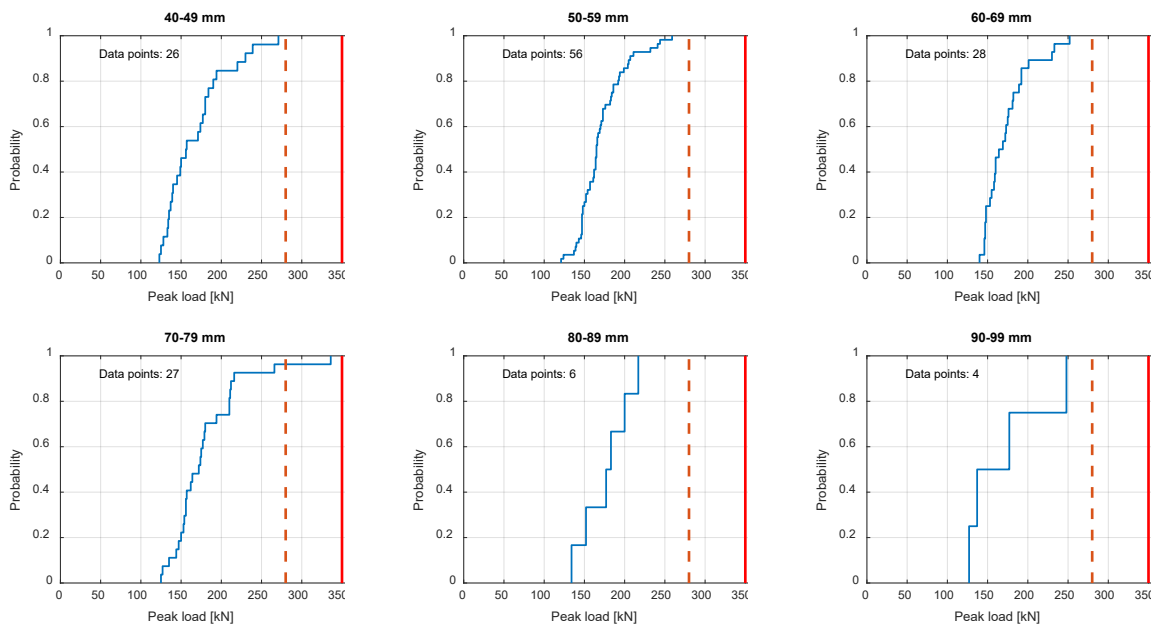


Figure 2.1. Cumulative distributions of peak load for different intervals of wheel flat length: loaded wagons with axle loads 17 – 25 tonnes. From [13]

Passages of the same wheel flat over multiple detectors reveal significant variations in measured peak loads between detector sites. For a single wheel flat of 75 mm length, consistent differences of several tens of kN were observed despite constant vehicle properties. This indicates that detector-specific effects may influence the measured impact loads. To investigate the role of track conditions, stiffness and geometry data obtained from track recording cars were analysed. Figure 2.2 shows that the detector located at Degerbäcken is situated in a track section with relatively uniform foundation

stiffness and geometry well within recommended limits. In contrast, Figure 2.3 illustrates that the detector at Skorpéd is located in a track section exhibiting larger variations in both stiffness and geometry. Such variations are expected to influence vehicle–track dynamic interaction and can partly explain the observed detector-dependent scatter in measured impact loads.

The combined results presented in [15] indicate that wheel flat length alone is a weak predictor of measured wheel–rail impact loads under real operational conditions. Although longer flats increase the likelihood of higher loads, local track–detector characteristics may play an important role. A central implication is that wheel flats exceeding 60 mm in length do not necessarily pose a significant risk in terms of impact loading, provided that measured loads remain below established alarm thresholds. Basing operational decisions more directly on measured impact loads rather than on visual inspection of geometric criteria alone could therefore reduce unnecessary wheel reprofiling and traffic disruptions without compromising infrastructure safety.

However, the study also highlights that such a load-based approach requires high confidence in WILD measurements. This includes reliable calibration procedures, continuous monitoring of track conditions at detector sites, and transparent, well-understood post-processing of detector data. Without these measures, detector-dependent variability risks limiting the practical applicability of impact load-based regulations.

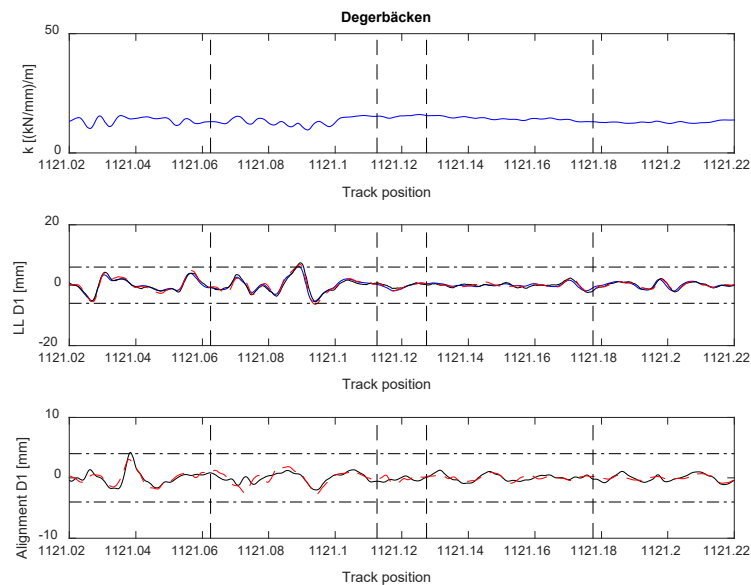


Figure 2.2: Foundation stiffness, longitudinal level (bandpass filtered 1 – 25 m) and alignment (1 – 25 m) measured over a distance of 200 m in the WILD at Degerbäcken. Blue curves were measured on 2022-06-07. Black (left rail) and red (right) curves were measured on 2023-05-31. The inner pair of vertical lines indicates detector area 1 (15 m), while the outer pair of vertical lines indicates detector area 2 (50 m on either side of detector area 1). Horizontal dash-dotted lines indicate suggested tolerances in terms of planned maintenance for tracks with maximum allowed speed up to 160 km/h

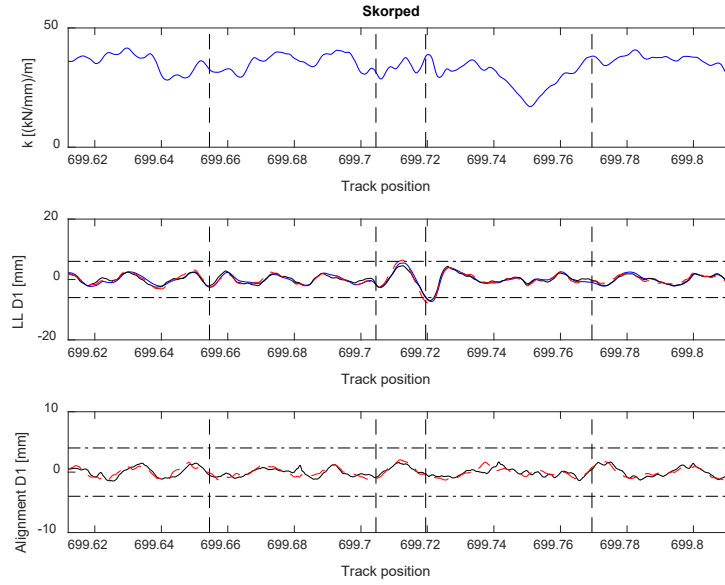


Figure 2.3: Foundation stiffness, longitudinal level (bandpass filtered 1 – 25 m) and alignment measured in the WILD at Skorped.

Blue curves: 2022-10-05. Black and red curves: 2023-08-13

3 Results and implementations in WP2 – Simulation models

Over the years, several models for simulating dynamic vehicle–track interaction have been developed within the CHARMEC competence centre. Two of these models, DIFF and WERAN, have been employed to predict wheel–rail impact loads generated by out-of-round wheels. By coupling the dynamic interaction models with a linear elastic fracture mechanics framework, a comprehensive model for predicting the probability of rail break has been established.

3.1 Models for prediction of risk of rail break and infrastructure damage caused by out-of-round wheels

A comprehensive simulation-based framework for predicting the probability of an instant rail break initiated at a pre-existing rail head crack due to dynamic wheel–rail impact loads generated by out-of-round wheels is presented in [14]. The model integrates measured wheel load spectra from WILDs, vehicle–track dynamic interaction, and linear elastic fracture mechanics within a probabilistic setting. Its primary objective is to provide a physics-based and statistically grounded method for quantifying infrastructure risk associated with wheel tread irregularities, such as wheel flats, under realistic traffic and environmental conditions. At the core of the approach is the recognition that rail breaks are rare but high-consequence events, typically occurring when extreme dynamic wheel loads coincide with unfavourable combinations of crack

depth, material fracture toughness, track support stiffness, and low rail temperature. The model therefore treats rail break as a probabilistic failure event governed by multiple stochastic variables rather than as a deterministic consequence of a single exceedance of a load threshold.

Dynamic wheel–rail contact forces are generated using the validated time-domain model of vertical vehicle–track interaction, DIFF. The model accounts for high-frequency dynamics and potential loss of wheel–rail contact, which are essential for representing impact loads caused by discrete wheel tread irregularities. The vehicle is represented primarily by the unsprung wheelset mass, while the track is modelled as a discretely supported rail with rail pads, sleepers, ballast, and subgrade, see Figure 3.1.

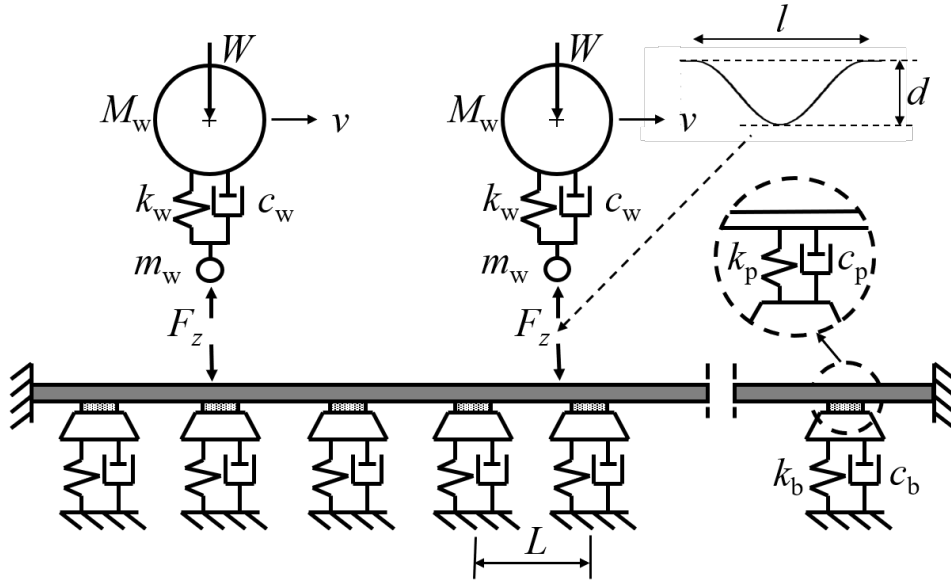
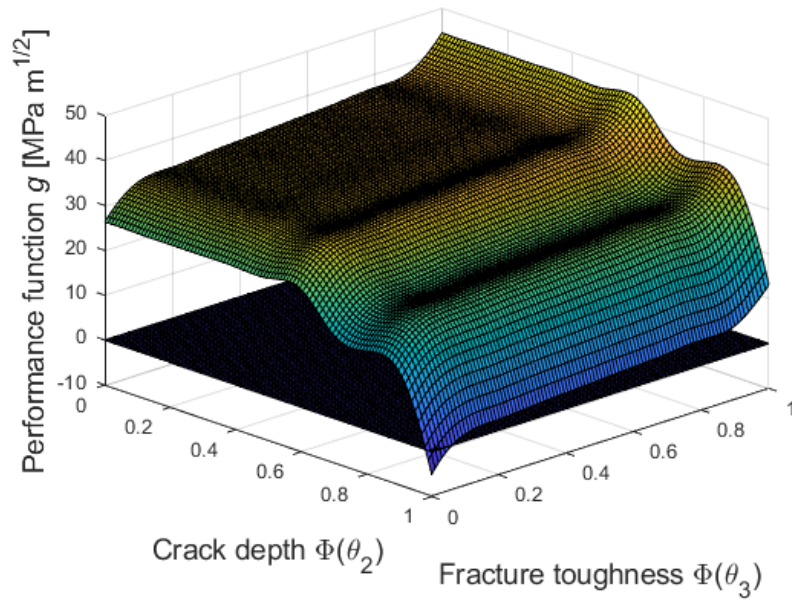


Figure 3.1: Model for simulation of vertical dynamic vehicle–track interaction accounting for a tread irregularity with length l and depth d on the leading wheel

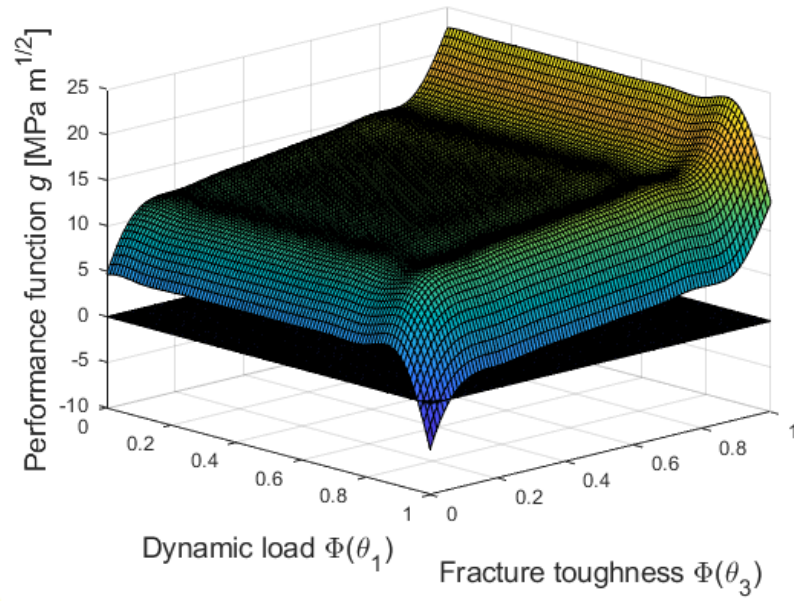
Measured load spectra from wheel impact load detectors (WILDs) are used as statistical input to the analysis. These spectra include a representative proportion of high-magnitude dynamic loads caused by out-of-round wheels on the line. The risk of rail break is evaluated using linear elastic fracture mechanics applied to a pre-existing rail head crack that has already deviated into transverse growth. The stress intensity factor at the crack tip is calculated as a superposition of contributions from dynamic rail bending and thermal stress arising from restrained contraction in continuously welded rails. Fracture is assumed to occur when the maximum stress intensity during a wheel passage exceeds the fracture toughness of the rail material.

Crack depth and fracture toughness are treated as stochastic variables based on field measurements and laboratory data, respectively. The combined effect of dynamic loading, crack geometry, and material resistance is formulated through a performance function, where negative values correspond to failure (i.e. instant rail break). The probability of failure is then defined as the probability that this performance function becomes negative within the multidimensional stochastic parameter space. Direct

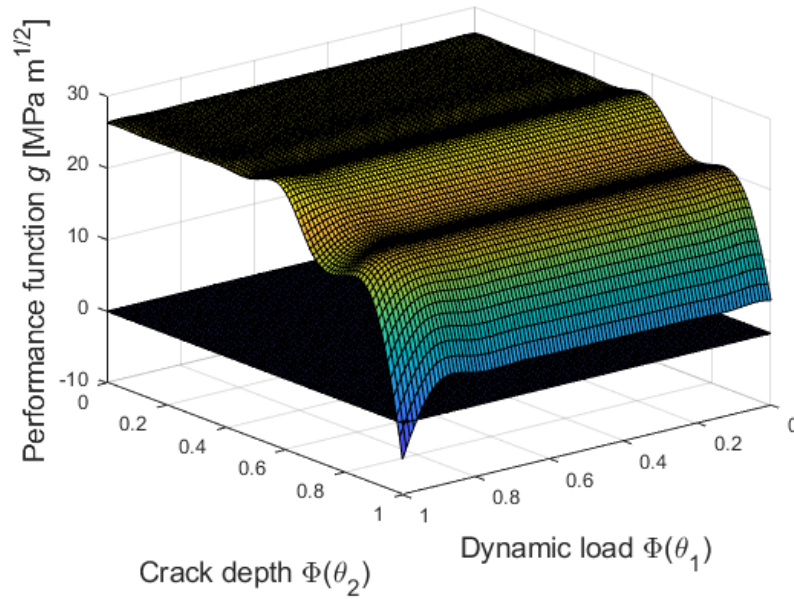
evaluation of the performance function for all combinations of stochastic variables would be computationally prohibitive. To address this, the study introduces a meta-model based on poly-harmonic spline interpolation. This meta-model approximates the overall performance function governing rail failure. Figure 3.2 illustrates an example of such a meta-model for the performance function, visualised in three different projections of the stochastic space. The figure shows that failure occurs only in a very small region where dynamic wheel load and crack depth are near their upper extremes while fracture toughness is near its lower bound. This highlights the rare-event nature of rail breaks and justifies the probabilistic treatment.



(a)



(b)



(c)

Figure 3.2: Example of meta-model of performance function $\hat{g}$ evaluated for cumulative distributions of dynamic load, crack depth, and fracture toughness. Freight traffic model with axle load 25 tonnes and train speed 100 km/h

To efficiently estimate very low probabilities of failure, the subset simulation algorithm is employed. This method decomposes the rare failure event into a sequence of more frequent conditional events, allowing accurate estimation of rail break probabilities that would be infeasible to obtain using standard Monte Carlo simulation.

The model has been used to demonstrate how rail temperature difference and ballast/subgrade stiffness influence the probability of an instant rail break. Figure 3.3 summarises the predicted probability of failure as a function of rail temperature difference and track support stiffness for a representative freight traffic scenario. The results show that rail break risk increases strongly with decreasing rail temperature (i.e. increasing tensile thermal stress) and decreasing ballast/subgrade stiffness. For moderate temperature differences and sufficiently stiff track support, the predicted probability of failure is effectively zero, even in the presence of relatively deep cracks. Conversely, combinations of low temperature and soft track support lead to a sharp increase in predicted risk. These findings quantitatively confirm the critical role of winter conditions and poor support stiffness in rail break occurrence.

The framework was further applied to compare the risk of rail break for different traffic types, as shown in Figure 3.4. Freight traffic and heavy iron-ore traffic are analysed using different axle loads, speeds, and measured dynamic load distributions. Despite significantly higher axle loads, iron-ore traffic is shown to pose a substantially lower risk of rail break than freight traffic under comparable thermal and track conditions. This result is explained by the markedly better wheel condition in the iron-ore fleet, which generates much lower dynamic impact loads, as evidenced by WILD measurements. The lower operating speed of iron-ore trains further reduces dynamic excitation. For each traffic type, the risk of rail break increases with axle load, but the quality of the wheel population and the associated dynamic load spectrum are shown to be more influential than axle load alone. This demonstrates the importance of wheel condition monitoring and effective maintenance strategies for risk mitigation.

The results support a shift from purely load-based or geometry-based alarm limits toward a risk-based approach, where acceptable wheel impact loads are defined in relation to track condition, temperature, and crack population. In this way, the model offers a powerful tool for improving regulations, maintenance planning, and the cost-efficient management of wheel tread irregularities while maintaining a high level of railway safety.

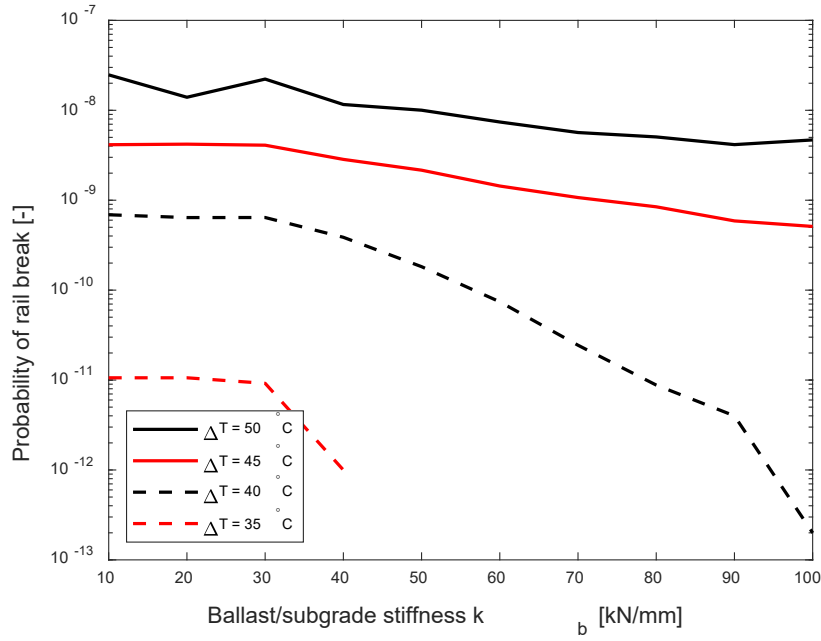


Figure 3.3: Example of evaluated influences of ΔT and ballast/subgrade stiffness on probability of rail break.
Freight traffic model with axle load 25 tonnes and train speed 100 km/h

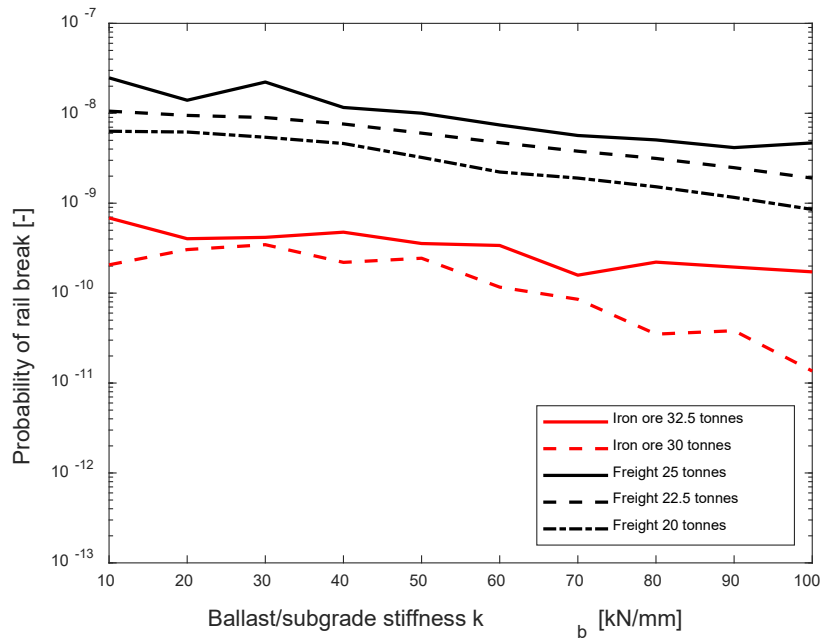


Figure 3.4: Example of evaluated influences of traffic type and ballast/subgrade stiffness on probability of rail break.
Freight traffic model with axle load 20, 22.5, or 25 tonnes and train speed 100 km/h.
Iron ore traffic model with axle load 30 or 32.5 tonnes and train speed 60 km/h

3.2 Simulation of influence of operational conditions on dynamic loads for different sizes and types of wheel damage

A numerical investigation of wheel–rail impact loads induced by wheel flats has been conducted in [12], with particular emphasis on how detailed wheel flat geometry influences the resulting dynamic interaction. Instead of relying solely on wheel flat length and depth as severity indicators (as in DIFF), the work focuses on three-dimensional tread geometry, axle load, train speed, and the lateral position of the rolling circle as key parameters governing impact load generation.

Two wheel flats were selected for detailed analysis and characterised using high-resolution three-dimensional laser scanning. The scanning procedure provided accurate representations of the wheel tread surface, allowing both the longitudinal extent and the local depth variations of the wheel flats to be captured with sub-millimetre accuracy. The resulting geometries were prepared for direct input into time-domain simulations of wheel–rail interaction using WERAN.

The measured tread deviations are illustrated in Figure 3.5, which shows the radial deviation relative to an undamaged wheel profile for the two investigated wheel flats. Although both flats exceed the same length-based regulatory limit, their geometric characteristics differ markedly. One wheel flat has a length of approximately 75 mm and a maximum depth of about 1.4 mm, whereas the second flat is considerably longer, around 120 mm, but shallower, with a depth of approximately 1.2 mm. The shorter flat exhibits steeper gradients at its leading and trailing edges, while the longer flat displays more gradual transitions. These differences reflect the combined influence of initial flat formation and subsequent plastic deformation and wear, which tend to lengthen the flat without significantly altering the depth. These observations demonstrate that wheel flat depth does not scale directly with flat length, contrary to what might be expected from idealised geometric considerations. As a result, wheel flat length alone provides limited information about the potential of a given defect to cause high dynamic wheel–rail loads.

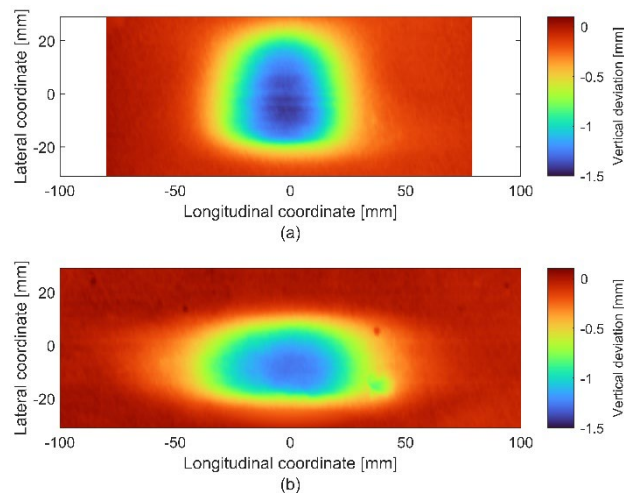
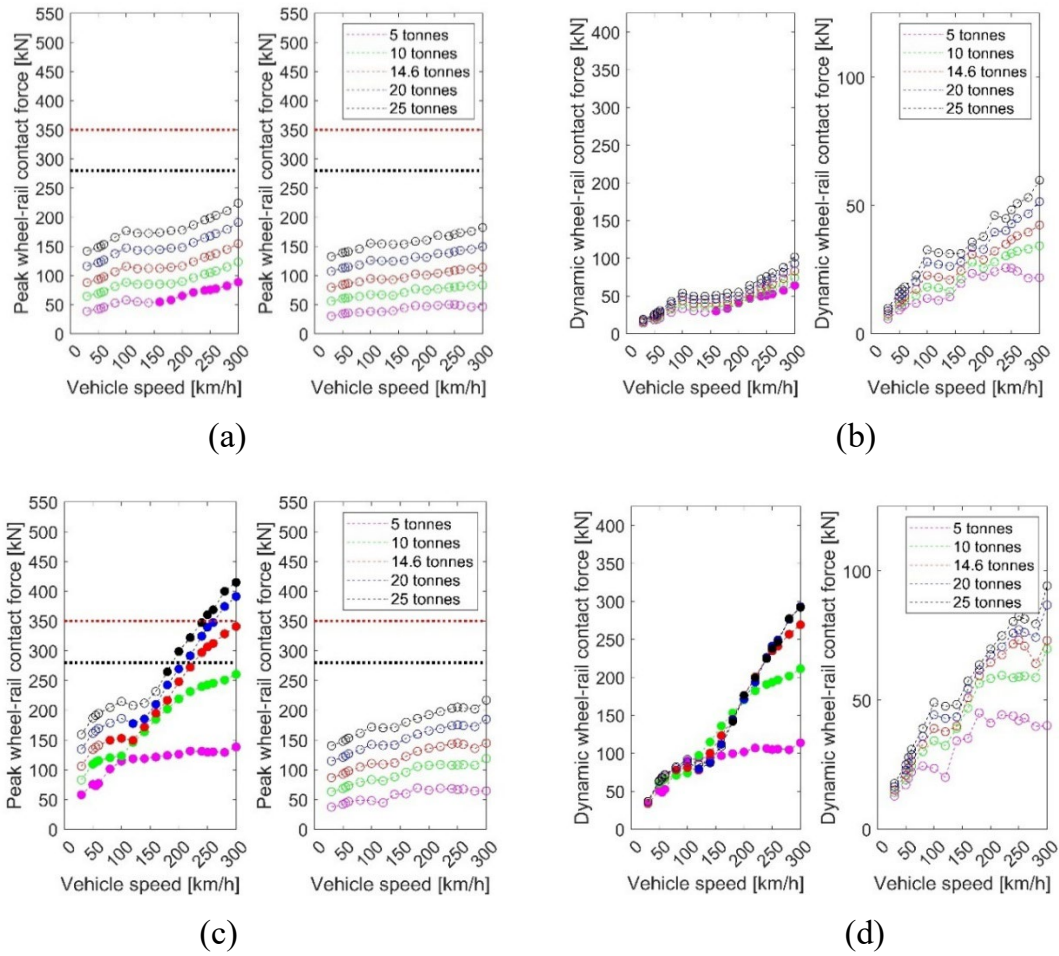


Figure 3.5: Vertical (radial) deviation from wheel profile for (a) wheel flat 1, and (b) wheel flat 2. The nominal rolling circle (70 mm from flange side of wheel rim) is at lateral coordinate 0 mm. Positive lateral coordinate is towards the wheel flange

To quantify the dynamic response associated with the measured geometries, the scanned wheel flats were implemented in WERAN. The simulations were performed in the time domain using a three-dimensional dynamic model of a wheelset running on a discretely supported railway track with realistic rail, pad, sleeper, and substructure properties. Non-linear elastic wheel–rail contact was assumed, and the interaction between wheel and track was resolved using moving Green’s functions. The simulations covered a wide range of operating conditions, including different train speeds, axle loads corresponding to loaded and unloaded wagons, and several lateral rolling-circle positions relative to the wheel flat. This approach allowed the sensitivity of impact loads to both geometric and operational parameters to be systematically investigated.

The simulated peak wheel–rail contact forces are summarised in Figure 3.6 for three representative lateral rolling-circle positions. A key outcome of the simulations is that the shorter but deeper wheel flat consistently generates higher peak impact loads than the longer, shallower flat, despite the latter having a significantly greater length. This behaviour is observed across a broad range of speeds and is particularly pronounced under loaded operating conditions.



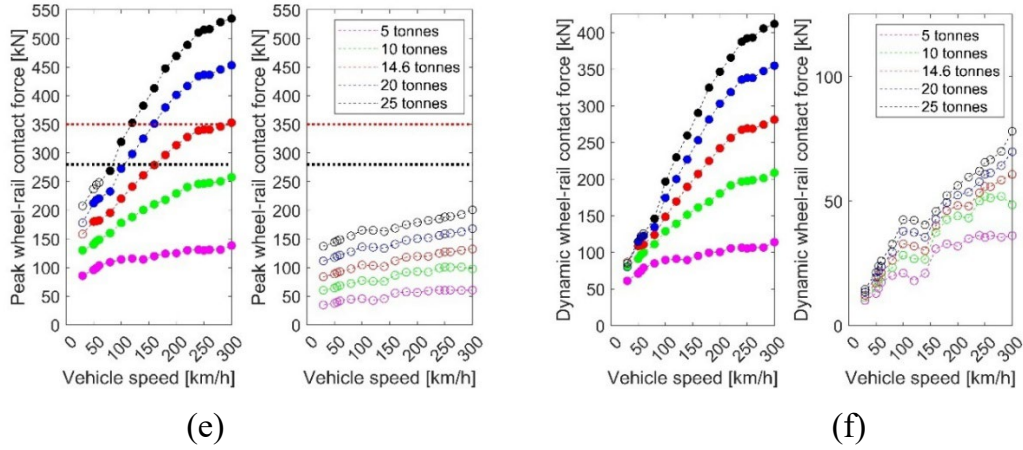


Figure 3.6: Influence of vehicle speed and axle load on simulated maximum wheel–rail contact force (peak load and dynamic load). Filled markers indicate momentary loss of wheel–rail contact before impact.

Lateral position of rolling circle at (a,b) 90 mm, (c,d) 80 mm, and (e,f) 70 mm from the flange side of the wheel rim. In each subfigure, left graph: wheel flat 1, right graph: wheel flat 2.

In (a,c,e), black horizontal line: alert level 280 kN, red horizontal line: alarm level 350 kN.

Note different scales in the plots illustrating dynamic loads

The underlying reason for this difference lies in the dynamic wheel trajectory induced by the wheel flat geometry. For the shorter flat, the steep gradients at the flat edges cause an abrupt vertical displacement of the wheel as it enters and exits the flat. Under certain speed and load combinations, this leads to a brief loss of wheel–rail contact, followed by a high-velocity re-impact with the rail. The resulting impulsive force dominates the peak load response. In contrast, the longer flat typically allows continuous wheel–rail contact to be maintained, leading to lower dynamic excitation despite its greater extent.

Axle load is shown to play a crucial role in determining the severity of these effects. When loss of contact occurs, increased axle load leads to a substantial amplification of peak impact forces. This is clearly visible in Figures 3.6 (a,c,e), where the peak loads for the deeper flat approach or reach operational alert limits at certain speeds under loaded conditions. The simulations further reveal that the lateral position of the rolling circle relative to the wheel flat has a noticeable effect on impact load generation. Depending on whether contact occurs closer to the centre or towards the edges of the flat, both the duration and severity of the excitation can change. This sensitivity contributes to variability in impact loads observed in practice.

Overall, the results demonstrate that the dynamic response to a wheel flat is governed primarily by the relationship between flat depth, flat length, and contact conditions, rather than by flat length alone. Shorter but deeper flats can be dynamically more severe than longer, shallow flats, even when both exceed the same regulatory length threshold. This finding provides a mechanical explanation for the large scatter commonly observed in measured wheel–rail impact loads and questions the effectiveness of length-based wheel removal criteria. The combined geometric

measurements and simulations support a more physics-based assessment of wheel flat severity, in which impact load potential is evaluated with consideration of detailed geometry, axle load, and operating conditions. Such an approach would offer a more reliable basis for maintenance decisions than visual inspection criteria based solely on wheel flat length.

4 Results and implementations in WP3 – Wheel load detector data assessment for prediction of track damage

WP3 investigates how wheel load detectors can be used to identify damaged wheels that may cause excessive damage to railway track. The full report [10] presents an overview of relevant forms of wheel and track damage, examines the limitations and potential enhancements of current detectors, proposes stepwise procedures for detecting and classifying damaged wheels, and demonstrates how detector data can be used to predict rail crack growth and fracture.

4.1 Assessment of track damage and derailment risks

- Rail crack growth and risk of rail breaks

Crack propagation in rails is analysed using linear elastic fracture mechanics. The stress intensity factor at a crack tip is driven by two components: a quasi-static thermal stress arising from restricted contraction of continuously welded rails, and a transient bending stress caused by passing wheels. Fracture occurs when the combined stress intensity exceeds the rail's fracture toughness.

A key finding is that for rail head cracks – typically the most common case – the impact force from a damaged wheel has only a moderate influence on crack propagation. Crack growth accumulates linearly, so although growth rates scale approximately with the cube of the bending stress range (Paris law exponent $m \approx 3$), a single overload has little effect on overall crack life. In contrast, repeated loading from, e.g., wheel polygonisation on multiple wheels is more consequential. A nine-step procedure is outlined for predicting crack growth from a given load spectrum, track stiffness, temperature history, and initial crack size.

- Other forms of track damage

Three further damage modes are addressed:

- *Sleeper cracking*: Bending moment and reinforcement stress ranges both increase approximately linearly with wheel impact load, but sleeper cracking is more of a cost and maintenance concern than a direct safety issue.
- *Ballast settlement*: Impact loads from wheel damage have limited effect on ballast because they are not occurring frequently and the load is spread across several sleepers. General wagon overloading is the more relevant cause but is outside the scope of this study.

- *Flange climbing*: Skewed or unbalanced loading combined with track geometry faults can cause flange climbing and derailment. Current detectors can handle the distribution of average (quasi-static) loads reasonably well, but individual wagon identification is challenging. This is also considered outside the main scope.

4.2 Uncertainties in detector measurements

Significant scatter exists in wheel load detector measurements. Three categories of uncertainties are identified:

- *Stochastic measurement uncertainties*: Fundamental signal noise that is difficult to separate from other sources.
- *Systematic measurement deviations*: Caused e.g., by detector placement in curves, soft track beds, or changing track geometry. Calibration can partially compensate for different estimations of quasi-static loads, but not reliably for dynamic impact loads.
- *Deviations related to impact load characteristics*: Impact load magnitude depends on axle load, speed, lateral position of the defect on the wheel tread, and the position along the detector. If a wheel flat forms outside the nominal running band, it may go entirely undetected on tangent track. Studies show that measured peak loads from the same wheel flat at similar speeds can vary by a factor of approximately two across different detectors.

The recommended approach to reduce uncertainties is to first eliminate systematic and stochastic deviations through calibration, then reduce impact-characteristic deviations by analysing load histories and, where feasible, adding detectors in curves and wheel profile measurements.

4.3 Framework for categorising wheel tread damage

Wheel impact load detectors can only detect tread damage that affects the vertical load. The following damage types are reviewed:

- *Indentations (gravel imprints)*: Only detectable if large. Generally benign and prone to wear off. Minor risk of exceeding load limits.
- *Wear (tread and flange)*: Not detectable by impact load detectors. Has minor influence on vertical forces, though hollow and flange wear affect steering and contact conditions.
- *Polygonisation*: Detectable. Produces moderate-magnitude, narrow-band periodic loads. If extensive, can exceed alarm limits.
- *Surface initiated Rolling Contact Fatigue (RCF)*: Large-scale cases may be detectable. Progressive material fall-out can lead to dangerous RCF clusters, see below.

- *Subsurface initiated RCF*: Undetectable until propagation (close) to fracture. Once a chunk detaches, very high impact loads ensue with major risk of exceeding alarm limits.
- *RCF clusters*: Detectable. Load magnitude increases over time. Major track damage risk for large (long) clusters.
- *Thermal facets*: Possibly detectable. Low initial impact load but can initiate RCF clusters. Even small facets may require reprofiling.
- *Wheel flats*: Detectable. High impact load that peaks immediately, then tends to decrease as edges round off. Long flats can be very hard to detect visually but readily exceed alarm limits. Flats formed in curves may evade tangent-track detectors.
- *Thermal cracks*: Generally not detectable unless very large. Only fractured or severely cracked wheels pose a major track damage or derailment risk.

4.4 Recommended procedures

Currently, detectors are used mainly to detect wheel flats and RCF clusters based on maximum load magnitude. This captures the most dangerous damage types but provides limited support for proactive maintenance planning. A stepwise enhancement is proposed:

- *Load history collection* (first priority): Collecting the full load time history during each wheel passage from existing detectors would enable classification of polygonisation wavelength and depth, growth tracking of RCF clusters, and length estimation for wheel flats and thermal facets. This requires only minor detector modifications but would imply more sophisticated data analysis and storage.
- *Detectors in curves*: Adding load detectors on curved track would help capture defects initiated outside the nominal tangent running band. These are generally smaller defects, so detectors need not be highly precise, but individual wheel identification would be essential.
- *Wheel profile detectors*: Full circumferential profile scans would provide damage shape, position, and wear information for all tread damage types, independently of load magnitude. Combined with numerical simulations (potentially AI-assisted), they would enable highly precise condition assessment of individual wheels. Line based profile detectors provide a sample cross-section of the wheel. This is of use in e.g., identifying tread or flange wear, but may miss point-wise defects such as wheel flats.

All extensions are recommended to be tested in simulation before operational deployment, to ensure that data needs and procurement specifications are properly founded.

4.4.1 Assessment of operational scenarios: Rail crack growth example

An example application demonstrates how current detector data (average and maximum loads) can feed a crack growth prediction framework. Because current detectors do not capture the full load history during a passage, a key challenge is translating peak and average loads into a representative load spectrum. The two extremes – using only the peak load for all cycles (over-conservative) or only the average load (unconservative) – bracket the true prediction, but the optimal weighting cannot be determined without load history data.

Rail foot crack growth simulations using Paris law show that crack life is strongly sensitive to temperature and somewhat less so to load magnitude. A key practical result is that approximately 75% of a crack's service life is spent growing from 1 mm to 5 mm; beyond 5 mm, growth accelerates rapidly toward fracture. This has important implications: detecting and removing foot cracks early is critical. For rail head cracks, frequent grinding to keep cracks small and slow-growing is also beneficial in principle even though the case is more complicated.

Analyses with variable amplitude loading and seasonal temperature variations show that cycle-by-cycle integration captures seasonal effects, which an equivalent-stress numerical approach cannot. While the full framework for operational crack life prediction already exists in its component parts, what is needed is a coherent, comprehensive system that collects data, integrates the models, and supports decision-making at a network scale. Such a system should be introduced incrementally.

4.4.2 Concluding remarks

The main conclusions of the WP are:

- Methods exist to predict rail crack growth and fracture risk from detector data, but the required data collection, calibration, and modelling framework must be assembled into a coherent operational system.
- Single overloads have limited influence on rail crack growth; the scatter and spectrum of repeated loads matter more. Nevertheless, detector precision must remain high for regulatory and operational credibility.
- Measurement uncertainties are substantial. Systematic and stochastic deviations should be reduced through calibration; impact-load-related deviations require load history analysis and, potentially, supplementary detection hardware.
- A classification list of wheel tread damage types provides a structured basis for deciding which detector enhancements would deliver the most benefit.

- The recommended enhancement path is:
 - (1) collect load histories from existing detectors;
 - (2) evaluate in simulation;
 - (3) consider curve detectors;
 - (4) consider circumferential wheel profile detectors.

5 WP4 – Revised regulations and implementation

The results presented in the previous sections of this report demonstrate that current regulations for the removal of damaged wheels, which are largely based on geometric criteria, do not fully reflect the actual risk posed to infrastructure or operations. The extensive use of wheel impact load detectors provides a strong basis for shifting towards procedures and regulations that are primarily guided by measured load levels, warning thresholds, and trend-based condition monitoring, rather than immediate removal triggered by visual inspections. This section therefore presents recommendations for revised maintenance procedures and regulatory frameworks, emphasising the systematic use of warning values, improved understanding of detector performance and limitations, and closer integration between infrastructure managers and railway undertakings.

5.1 Revised regulations for more reliable track structures by Trafikverket

Rail breaks caused by high mechanical stresses in the rail material constitute a severe form of infrastructure damage. Such failures may result from abnormal traffic conditions, extreme wheel loads, or latent manufacturing defects. Low ambient temperatures further increase the risk of rail breaks, since thermal contraction increases tensile stresses in continuously welded rails. Rail breaks significantly increase the risk of derailment, which may in turn cause extensive damage to infrastructure and rolling stock, severe traffic delays, and, in the worst cases, personal injury.

High impact loads generated by damaged wheels may initiate rail cracks or accelerate the propagation of existing defects. Although rail breaks occurring immediately after a high wheel impact are rare, such events have been recorded in the Swedish railway network. **Trafikverket** maintains detailed records of the causes and consequences of all reported rail damage events. **In 2021**, a requirement was introduced stipulating that rail sections subjected to five or more impact events exceeding the **high-level alarm threshold of 350 kN (425 kN for locomotives)** should **undergo ultrasonic inspection** to identify potential damage caused by repeated high loads. Since the introduction of this requirement, no maintenance warnings have been issued as a result of ultrasonic inspections triggered by such alarms [5]. Consequently, **the requirement was removed in 2024**. Furthermore, no rail breaks caused by wheel flats or damaged wheels were reported in 2023 [5]. These observations suggest that **a threshold of 350 kN may constitute an adequate fail-safe alarm level for preventing severe crack propagation and rail failure**, although this is also influenced by both neutral rail temperature and ambient operating temperature.

Within the framework of this project, two commonly proposed modifications submitted by the **Swedish railway undertakings (RUs) SJ, Green Cargo, and Hector Rail**, were investigated. These proposals were motivated by the **operators' wish to eliminate the current 60 mm limit for wheel flats**. Their position is that, if a surface defect is detected, the detector measurement should be fully trusted regardless of the defect size. Conversely, if no defect is identified during inspection, the warning should be disregarded, and the vehicle should be permitted to continue normal operation.

The first proposal suggested removing all operational restrictions for vehicles triggering high-level alarms if no wheel damage is identified during the inspection carried out by the driver. The rationale was that, if visual inspection does not reveal wheel damage sufficient to justify the alarm, the detector should be regarded as faulty and reported accordingly through traffic control procedures. This approach presupposes that the entire wheel circumference has been carefully inspected. However, several risks are associated with this proposal:

- drivers may feel operational pressure to continue the journey, potentially affecting safety-critical judgment
- darkness or adverse weather conditions may reduce the reliability of manual inspection
- certain forms of wheel out-of-roundness are not detectable through visual or tactile inspection and may therefore remain unnoticed

An example of the latter was documented in [9] and [11], where a wheel repeatedly triggering high-level alarms was removed from service after clusters of rolling contact fatigue (RCF) defects were identified across the tread surface. Subsequent wheel scanning revealed that the dominant cause of the abnormal impact loads was not the observed RCF damage, but rather a long and deep tread defect approximately 300 mm in length resembling a wheel flat (see Figure 5.1). Owing to its length, the defect could not easily be detected by visual or tactile inspection. For these reasons, the first proposal was not implemented in TDOK 2020:0074 [3]. The dynamic loading effects of this defect were subsequently analysed in [11].

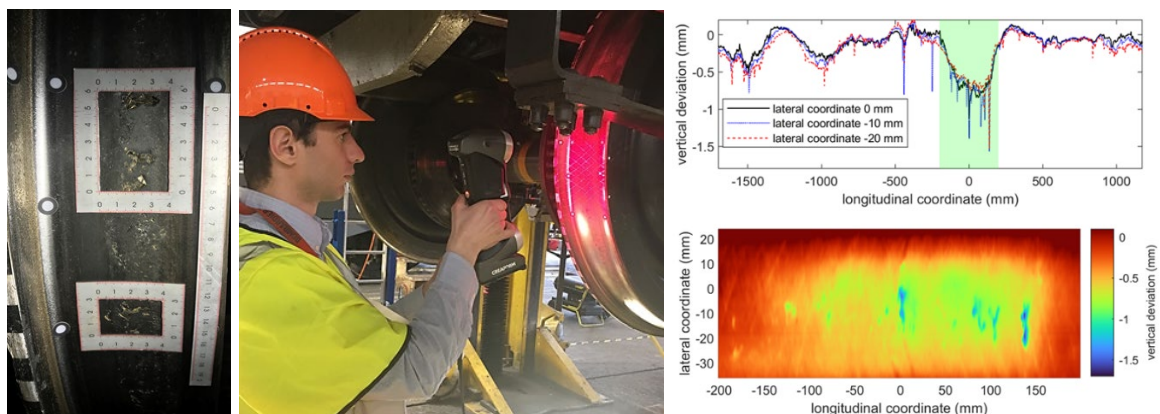


Figure 5.1: The defected wheel (left), the scanning procedure (middle), and the post-processed wheel tread surface (right)

The second proposal concerned the algorithm used to **determine speed reductions for vehicles triggering high-level alarms**. According to TDOK 2020:0074 [3], **for impact loads exceeding 350 kN**, the permissible vehicle speed (in km/h) is reduced by the same numerical amount by which the measured load (in kN) exceeds the threshold. The result is rounded down to the nearest lower multiple of ten. If this calculation yields **a speed below 100 km/h**, an automatic **restriction to 10 km/h** is imposed. This approach was originally introduced to avoid the speed range between 10 and 100 km/h, within which certain studies have indicated that wheel-flat impact loads may increase as speed decreases, depending on wheel-flat geometry and depth [16].

In practice, however, this rule imposed **substantial operational costs on railway undertakings**, particularly freight operators, whose normal operating speeds rarely exceed 100 km/h and who were therefore frequently forced to reduce speed to 10 km/h. Given that large parts of the Swedish railway network, particularly outside major urban areas, consist of single-track lines with limited passing loops, restricted depot access, and few opportunities for vehicle parking, trains operating at 10 km/h caused prolonged line blockages and severe disruption to both freight and passenger traffic. Additional logistical difficulties arose from the need to secure trolley wagons for towing damaged freight wagons at such low speeds. The railway undertakings therefore proposed retaining the same reduction algorithm while modifying the lower threshold such that automatic reduction to 10 km/h would only apply if the calculated permissible speed fell below 50 km/h rather than 100 km/h. A risk assessment was conducted by Trafikverket within this project, taking into account field-test results, numerical simulations from academia, operational experience from Traffic Management, internal RU procedures, and practices adopted by other Infrastructure Managers (IMs) and National Safety Authorities (NSAs).

Field measurements reported in [9] demonstrated an approximately linear relationship between impact load magnitude and vehicle speed, see Figure 5.2, although tests were limited to 10, 55, and 100 km/h. Numerical simulations presented in [11] extended this work (see Figure 5.2) by considering a broader range of operational parameters, including vehicle speed, running direction, lateral wheel–rail contact position, and track flexibility. These studies showed that peak impact loads depend primarily on:

- the position of wheel-flat impact within the sleeper bay
- the lateral wheel–rail contact position
- the direction of travel

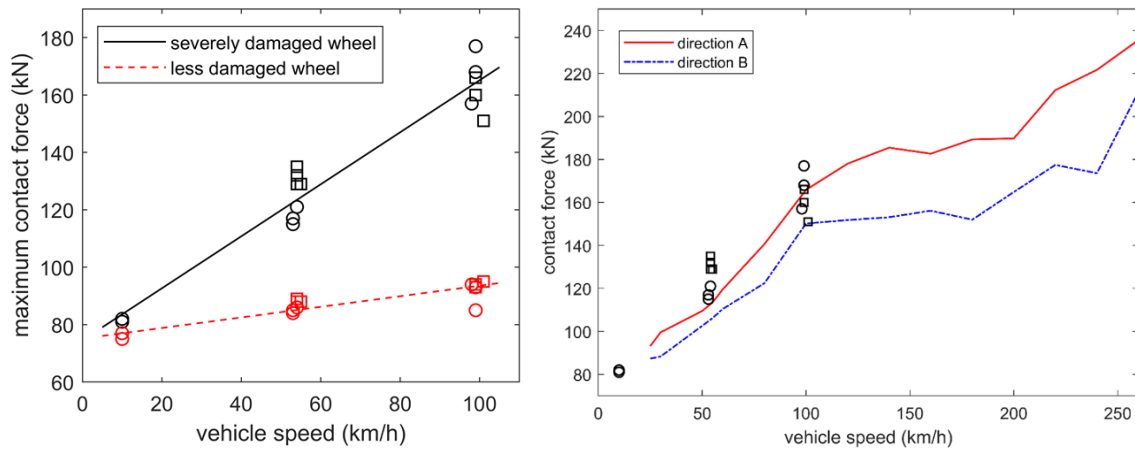


Figure 5.2: Results from the field test in [9] (left) and from the simulations in [11] (right)

Additional simulations were performed within this project using the software WERAN to assess the influence of vehicle speed on impact loads generated by different wheel-flat geometries (see Figure 3.5) and wheelset designs [12].

The simulation results shown in Figure 3.6 and commented in Paragraph 3.2 indicate that **load variation with speed is considerably less pronounced between 10 and 100 km/h** than suggested by earlier studies. Consequently, speed reductions within this interval are unlikely to produce elevated impact loads. Furthermore, wheel flat 1 generated significantly higher impact loads than wheel flat 2. The steeper geometry of wheel flat 1 produces a larger momentum change when the wheel exits the defect and more frequent transient loss of wheel–rail contact. These findings demonstrate that the trajectory of wheel–rail contact, governed by overall defect geometry, is a more critical parameter than wheel-flat length alone.

The Traffic Management unit within Trafikverket assessed that reducing the number of trains required to travel to depots at 10 km/h would improve operational flexibility and increase network capacity. The number of high-level alarms has already decreased significantly since 2018, although certain railway undertakings remain more affected than others. Overall, the Traffic Management unit expressed support for modifications that increase capacity without compromising safety.

Regarding the responsibilities of RUs, more permissive operational rules could potentially be interpreted as reducing incentives for proactive wheel-damage prevention. However, wheel impacts generally pose a greater risk of fatigue damage and crack propagation within the wheel itself than within the track. Railway undertakings therefore retain a strong interest to minimise wheel damage.

Finally, a **comparative review of WILD alarm thresholds and operational restrictions** in other countries was made and it further supported the proposed revision. **Switzerland, Denmark, Spain, and the United States apply higher alarm thresholds** than Sweden and generally **permit higher operating speeds for damaged vehicles**, although Switzerland imposes additional restrictions related to axle load imbalance. **France applies track-dependent alarm thresholds** and comparatively **less restrictive**

operational measures for damaged vehicles. From the perspective of international infrastructure management practice, the RU proposal appeared reasonable.

Based on these findings, and following formal risk analysis within Trafikverket, the **proposed change has been implemented in TDOK 2020:0074 [3]** and incorporated into the corresponding traffic-control procedures.

5.2 Implementation and advantages for GreenCargo

Regarding costs for Green Cargo in the event of wheel damage and other detector alarms that cause delays and wagons to be taken out of service

The costs incurred by operators when vehicles are not allowed to continue their journey vary enormously. It is also very difficult to obtain a clear overview of these costs, as they are distributed across many different areas of the company's accounts, and the connection to the specific incident is often not obvious.

Some examples.

An empty freight wagon was prohibited from continuing after passing Trafikverket's detector in Via south of Sundsvall. The alarm was triggered due to excessive forces from one wheel. **The alarm** was later confirmed to be **faulty**, as the **wagon** was **empty** (five-ton axle load) and had only a **very small wheel flat of 40 mm**. **The total additional costs for this incident** amounted to **80 000 SEK**.

These costs include:

- **delay penalties** for the train
- **workshop costs** for inspection of the damage
- cost of **arranging a new train** to collect the wagon (charged by Trafikverket)
- **track access charges** (per km) for the additional train (to Trafikverket)
- **locomotive kilometre costs** for the additional train
- **driver costs** for the additional train
- **energy costs** for the additional train
- **overtime compensation for the driver** of the affected train that was stopped

In this case, the wagon was empty. If it had been loaded, additional costs could arise, as certain customer contracts include quality clauses. If the stop occurs during the winter, the goods may also be damaged.

Another example concerns an Rc locomotive that developed a wheel flat in Skellefteå. The locomotive's electricity meter showed that it had been used extensively for shunting during the day after arrival. (ABS does not function when the direct brake is used.)

On the way from Skellefteå, the driver heard pounding noises from the multiple-unit locomotive. He stopped and inspected the wheels and found **a wheel flat larger than 60 mm. Trafikverket's limits for wheel flats do not consider either axle loads or wheel diameters.** In this case, the locomotive **wheel diameter is 1300 mm** (freight wagon wheels are **typically between 850–920 mm**).

Wheel replacements on locomotives can only be carried out **in a workshop**. The solution is a “rail wheel trolley” (hjultralla), a small **trolley** on which the **wheelset is placed and moved** as on its own wheels. The availability of underfloor lathes (“undergolvsvarvar”) is limited, which affects the transport distances with these trolleys (the nearest lathe at Notviken in Luleå is **more than 1000 km away**).

The challenges with trolleys are that the speed is very limited, often with a maximum **permitted speed of ≤ 30 km/h**. Over long distances, the transport is carried out in several stages, as train paths are typically only available at night, limiting the distance that can be covered. Workshop personnel usually accompany the transport, and the locomotive is often hauled.

For this incident, it took almost two months to get the locomotive to Notviken for wheel reprofiling. There is no calculated total cost, but a **typical locomotive rental cost is 15 000 SEK per day**. This means that the **rental cost will be 855 000 SEK. Rental costs** for rail wheel **trolleys** vary, but they can cost around **5 000 SEK per day**. The availability of trolleys is also limited, as they are very expensive. During winter, availability often becomes a limiting factor for how quickly the issue can be addressed.

When vehicles are set out on the line, this creates disruptions for other operators, as the vehicles often block passing loops. Many years ago, SJ compiled a summary of the **additional costs** they incurred. **For ten incidents, it was 1.5 MSEK** and it should be noted that none of the detached vehicles belonged to SJ. **The costs consisted of refunded tickets and overtime compensation for staff.**

Improved knowledge of how the size of wheel flats, for different wheel diameters and axle loads, affects the forces on the rails, could help reduce the consequences of wheel flats in the future. Preferably, this should also include wheel flats with rounded edges.

Other **unnecessary faults** that cause disruptions **include damaged detectors**. Trafikverket's detectors have a built-in self-check that is supposed to trigger an alarm when a detector malfunctions. However, recently a wheel damage detector recorded negative forces from the wheels, which is physically impossible. It took **almost two weeks to fix the issue** despite multiple fault reports. **Green Cargo**, which monitors the condition of its vehicles at every detector passage for preventive purposes, **received around 200 internal alarms** from this detector.

In summary, all disruptions on the line lead to high costs. For vehicles that are not allowed to continue as part of a train, these costs become extremely high. Quantifying the total costs of different types of disruptions is almost impossible, as each incident is unique.

5.3 Implementation and advantages for SJ

SJ is the main passenger train operator in Sweden. **Wheel damage** in SJ's operations is a relatively rare but **high-impact problem** that can disrupt the entire railway system. The main issue is not only the technical defect itself, but the **system-wide consequences** triggered when a defect is detected and action is taken. Modern rail networks operate close to capacity, meaning even small disturbances can propagate rapidly.

A key example illustrates this amplification effect: when a detector alarm forces a train to stop for inspection, the delay may initially seem minor. In one case, a **17-minute stop** caused by a wheel damage alarm resulted in **3,368 accumulated delay minutes** for surrounding trains. This corresponds to dozens of affected trains and a large number of delayed passengers. The effect is particularly severe during peak hours, when there is little flexibility in the timetable.

5.3.1 Use of wheel load data and monitoring

To mitigate these risks, SJ relies on wheel impact load detectors (**WILDs**) installed along the track by Trafikverket. These detectors measure the dynamic forces (kN) generated by each wheel as trains pass. High dynamic loads typically indicate defects such as:

- wheel flats
- surface irregularities
- out-of-round wheels

Typical **alarm limits** in the system are:

- **Low-level alarm: ~280 kN**
- **High-level alarm: ~350 kN**

By continuously collecting this data, SJ can monitor wheel condition across its fleet. The data is integrated into a maintenance system called 'Imperium', where measurements from all detector passages are stored and analyzed.

For example, in a normal condition, measured loads are low and stable across all wheels, indicating healthy wheelsets. When values begin to rise or deviate, maintenance can be scheduled early.

This approach has significantly improved performance. Instead of reacting to failures, **SJ can predict and prevent** them, which explains why **only one SJ train was stopped due to wheel damage in 2025**.

5.3.2 Remaining risks and critical scenarios

Despite the success of condition-based maintenance, certain failures remain difficult to prevent. A particularly important example is wheel flats caused by an unreleased parking brake, often due to human error. These defects can develop very quickly and exceed safety thresholds before preventive measures can be applied.

Regulations impose strict limits in such cases. According to **Trafikverket's rules**:

- A **wheel flat ≥ 60 mm** requires immediate stop
- The **train is not allowed to continue**, even at reduced speed

This rule applies regardless of axle load, wheel diameter or traffic conditions. While it **ensures safety**, it can also **lead to disproportionate consequences**, especially if the defect occurs in a critical section of the network.

There have, however, been **improvements in the regulatory framework**. For dynamic load exceedances, slight violations are now tolerated under controlled conditions:

- Example: exceeding **350 kN up to ~ 365 kN**
- **Train may continue at reduced speed**, reducing dynamic impact

This change has shown that **traffic disturbance can be reduced without compromising safety**, highlighting the importance of flexible, risk-based rules.

5.3.3 Maintenance process and data use

SJ follows a structured process when a detector alarm occurs:

1. Trafikverket informs the train driver
2. The driver contacts SJ's technical support center
3. A maintenance work order is created
4. The wheel is inspected and corrective action is taken

Corrective actions include:

- Wheel turning (reprofiling)
- Wheel replacement, if diameter limits are reached

In parallel, the 'Imperium' system continuously processes all incoming detector data. Maintenance thresholds are defined for each vehicle and wheel type, allowing automatic identification of when action is needed.

An important efficiency improvement is that:

- Many work orders are now created semi-automatically
- Maintenance can be scheduled without manual inspection first

Data visualization tools (Power BI) are also used to track:

- wheel degradation trends over 30-day periods
- differences between detectors
- effectiveness of maintenance thresholds

This supports continuous optimization of maintenance intervals and rules.

5.3.4 System-level analysis and collaboration

SJ and Trafikverket collaborate regularly to analyse detector data and its operational impact. A shared tool combines:

- detector alarms (DPCIII)
- traffic delay data (LUPP)

This enables identification of the most disruptive incidents. For example, in one analysed period:

- **30 alarms** resulted in **1,473 delay minutes**
- **total delays** for the year reached **6,158 minutes**

Additional insights from the data (which was collected from 30 detectors) include:

- **80% of alarms** came from **freight trains**
- **20%** from **passenger trains**
- **76.7%** were **high-level alarms** (350 kN)

The analysis also reveals that some detectors or locations contribute disproportionately:

- Example:
 - 2 alarms → 175 delay minutes at one detector
 - 11 alarms → 562 delay minutes at another

This allows stakeholders to focus on high-impact locations and cases, improving overall system performance.

5.3.5 Costs and economic impact

Wheel damage leads to both **direct** and **indirect costs**.

Direct costs include:

- **Emergency** response teams:
 - typically **€2,500–3,500 per incident**
- **Repair** and **recovery** actions

In **more severe cases**, when the train cannot move:

- The **vehicle** must be **transported on trolleys**
- Towed **at very low speeds**, reducing track capacity

An example cost is **~€20,000** for **recovery** and **trolley rental** (excluding internal costs).

These operations are also constrained by network capacity:

- Slow towing occupies track slots

- **Transport** may be **delayed** due to lack of timetable availability
- This **increases vehicle downtime** (unavailability)

Indirect costs are even broader:

- **Passenger delays**
- **Freight disruptions**
- **Network inefficiencies**

These are quantified using Trafikverket's LUPP system and socioeconomic models (ASEK), supporting investment and policy decisions.

5.3.6 Overall conclusion on consequences of wheel damage

Wheel damage is a low-frequency but high-consequence issue. SJ's use of detector data and condition-based maintenance has significantly reduced the number of critical incidents. However, the railway system remains highly sensitive, meaning that **even small technical failures can escalate into major operational disruptions.**

Key lessons include:

- Early detection and data-driven maintenance are essential.
- Small delays can scale into thousands of delay minutes.
- Flexible regulations can reduce unnecessary disruptions.
- Collaboration between stakeholders improves overall system performance.
- Costs extend far beyond maintenance, affecting the entire railway ecosystem.

In summary, **managing wheel damage** effectively requires not only technical solutions, but also **system-level thinking, data integration, and coordinated decision-making** across the railway sector.

5.4 Implementation and advantages for Trafikverket

The primary objective of Trafikverket's detector network is to prevent failures and abnormal degradation of railway infrastructure caused by defective railway vehicles. Detector systems can identify vehicle faults that may lead to derailments and/or damage to the vehicle itself, the track, or the catenary system. Consequently, these systems contribute to improved safety and robustness of the railway system while simultaneously reducing the risk of delays affecting both passenger and freight traffic.

Operational experience indicates that vehicles, and freight wagons in particular, tend to generate different WILD responses depending on bogie type. Detector specialists at Trafikverket have observed that freight vehicles equipped with Y25 bogies are overrepresented in detector data associated with load unbalances, i.e. differences in mean wheel load between the left and right wheel of the same axle. Such load unbalances may arise either from uneven loading of the freight wagon or from deficiencies in the suspension system. However, if uneven loading were the dominant cause, the

occurrence of unbalanced wheel loads would not be expected to depend strongly on bogie type. Detector data therefore have the potential to reveal systematic deficiencies associated with specific bogie designs or suspension systems.

Figure 5.3 presents all freight-train axle passages recorded between 2022 and 2024 for which at least one axle exhibited an unbalance ratio, defined as the ratio between the mean loads of the two wheels on the same axle, equal to or greater than 1.7. The analysis includes only vehicles equipped with either Y25 or NACO bogies.

The detector data originate from WILD installations located along the Stålpändeln corridor, a mixed-traffic line used by SSAB for steel transportation between Luleå and Borlänge. As expected, Y25 bogies are substantially more common overall. However, when the dataset is filtered to include only axles with an unbalance ratio exceeding 1.7, more than 2.5% of axles mounted on Y25 bogies exhibit significant unbalance, compared with less than 1.5% for NACO bogies. If the threshold is increased to an unbalance ratio of 2.0, the overrepresentation becomes even more pronounced, with approximately 1.5% of Y25-equipped axles exceeding the threshold compared with roughly 0.5% for NACO bogies. The data therefore indicate that load unbalances within the same axle occur more frequently in freight wagons equipped with Y25 bogies. Regarding detector location, most detectors along Stålpändeln register similar frequencies of unbalanced axles. However, the detectors located at Jörn and Bodsjön appear overrepresented for unbalance ratios exceeding 1.7 and 2.0, respectively.

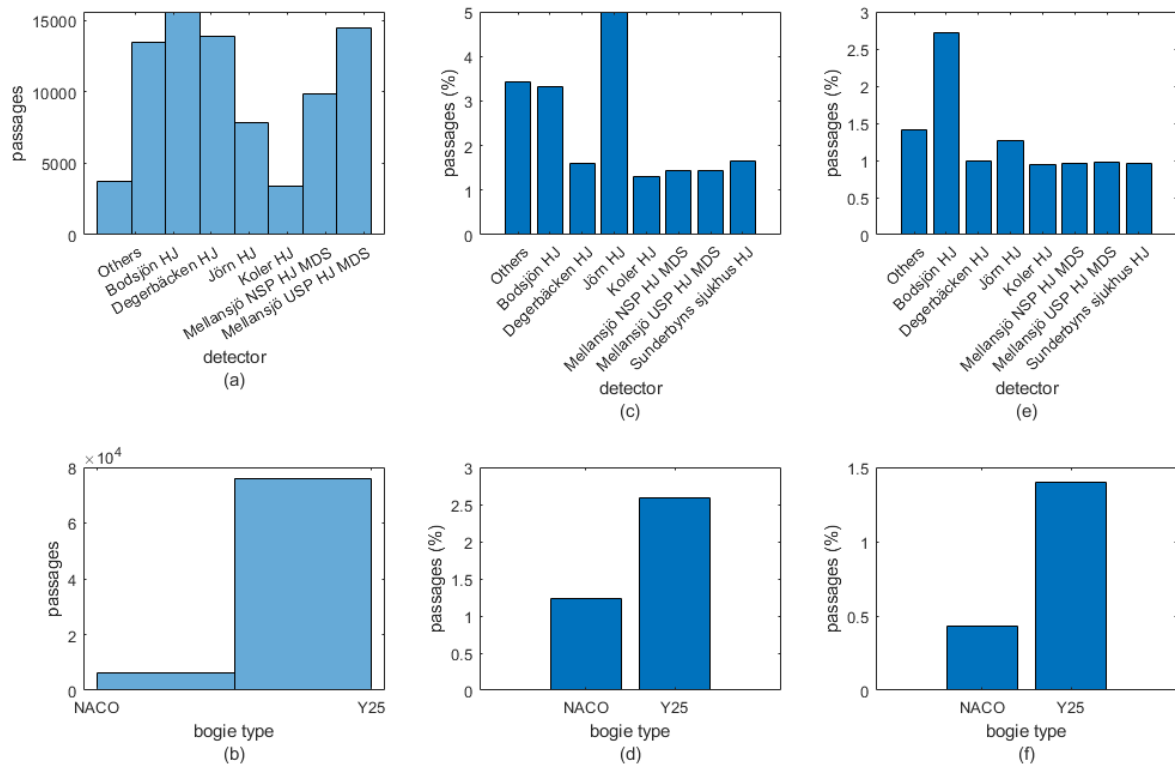


Figure 5.3: Amount of axle passages for freight trains with at least one unbalanced axle per WILD location (a) and bogie type (b). Ratio of axles per WILD location and bogie type showing an unbalance ratio of at least 1.7 (c,d) and of at least 2.0 (e,f)

In Switzerland, operational restrictions apply to vehicles exhibiting unbalance ratios of at least 1.7, while warning levels are issued for ratios exceeding 1.6. At present, Trafikverket has neither restrictions nor recommendations addressing this specific issue, although such measures may be considered in future work. Nevertheless, the present analysis demonstrates the significant potential of detector-data analysis for identifying suspension-system deficiencies, vehicle-loading irregularities, and possible detector faults.

Trafikverket also provides a service known as “teknisk kontroll av fordon” (technical control of the vehicle), which allows train operators to access raw detector data associated with a given train from all detector systems within the Swedish railway network. The data are updated in real time and include issued warnings and alarms. This service enables railway undertakings to maintain improved operational awareness of fleet condition during service.

Trafikverket quantifies the operational consequences of abnormal wheel–rail contact forces using accumulated train delay hours. However, little established methodology currently exists for converting these delay hours into a direct economic cost. In general, trains delayed or stopped as a consequence of WILD alarms or warnings generate larger amounts of accumulated delay when operating in densely populated regions or near major urban centres, where traffic density is significantly higher. Although freight trains account for only approximately one tenth of all train movements in the Swedish railway network, freight traffic generates approximately twice as many total delay hours as passenger traffic.

According to **Trafikverket statistics for 2023** [4], railway undertakings accounted for approximately **45 000 hours of delay**. **Accidents, incidents, and external causes**, such as trespassing on tracks, contributed approximately **37 000 hours**, while **infrastructure-related causes** accounted for roughly **23 000 hours**. **Additional causes** contributed approximately **32 000 hours of delay**. Among these, inspections of vehicles or tracks (such as those occurring after alarm/warning levels) caused 1000 hours of delay in 2023, compared with approximately 300 hours in 2013. Thus, the **total number of delay hours in 2023** was in the order of **45 000 + 37 000 + 23 000 + 32 000 = 137 000 hours**.

To assess the economic benefits of the revised speed reduction regulations for trains exceeding alarm load limits, Trafikverket's cost database and methodology for socioeconomic valuation (*Analysmetod och samhällsekonomiska kalkylvärden*) [17] was used. **Assuming** that, of the **1000 delay hours** caused by vehicle and track inspections, one third are attributable to passenger traffic and two thirds to freight traffic, it was **estimated that restrictions triggered by WILD alarm loads result in annual costs of 55–75 MSEK**. These costs include delays to other trains, vehicle inspections, workshop costs, personnel overtime, compensation paid to passengers and logistic operators, as well as disruptions to the supply chain. **The total costs can vary significantly depending on the traffic density of the route and the train's load factor**.

6 Concluding remarks

This project has significantly improved the understanding of wheel tread damage, wheel impact load detection (WILD), and the relationship between wheel defects, infrastructure degradation, and operational performance. The combined results from field measurements, detector data analyses, numerical simulations, risk assessments, and operational experience demonstrate that wheel damage management can be substantially improved through a more data-driven and risk-based approach.

A central conclusion is that the current reliance on geometric criteria, such as wheel flat length, does not adequately reflect the actual risk posed by a damaged wheel. Both detector measurements and simulation results show that wheel–rail impact loads are influenced by several interacting factors, including defect depth and shape, wheel diameter, axle load, vehicle speed, wheel–rail contact conditions, and local track characteristics. Consequently, wheel defects of similar length can generate very different impact loads and therefore very different levels of risk. The results consistently indicate that measured impact loads provide a more relevant indicator of infrastructure loading than defect size alone.

The project has also highlighted the importance of reliable WILD measurements. While detectors already are essential tools for condition-based maintenance and operational decision-making, the analyses revealed significant variability between detector sites caused by differences in track geometry, track stiffness, and detector characteristics. Trafikverket's updated requirements for detector placement, maintenance, and monitoring represent important steps towards improving measurement consistency. However, further work is needed to establish robust methods for dynamic calibration and validation of detector measurements under operational conditions.

The simulation studies have provided valuable insight into the mechanisms governing wheel–rail impact forces and infrastructure damage. In particular, the developed risk-based framework demonstrates that rail breaks are rare events caused by the combined influence of dynamic loads, crack sizes, material properties, rail temperature, and track support conditions. The results show that wheel condition and the resulting dynamic load spectrum are often more important than axle load alone. This supports future development of regulations and maintenance strategies based on quantified infrastructure risk rather than fixed geometric thresholds.

From an operational perspective, wheel damage remains a low-frequency but high-consequence issue. The examples provided by SJ and Green Cargo illustrate how a single detector alarm or damaged wheel can generate substantial costs, vehicle downtime, network disruption, and large volumes of accumulated delay minutes. In a railway system operating close to capacity, even minor disturbances can propagate throughout the network and affect both passenger and freight services. These findings underline the value of proactive condition monitoring, efficient maintenance planning, and operational rules that balance safety with system performance.

An important achievement of the project has been the successful implementation of revised regulations within Trafikverket. The results have contributed directly to a more flexible and risk-informed framework for handling wheel impact load alarms, enabling reductions in unnecessary traffic disturbances while maintaining a high level of safety. The project has also demonstrated the benefits of close collaboration between infrastructure managers, railway undertakings, researchers, and detector suppliers in developing practical solutions based on scientific evidence and operational experience.

The project results have been actively disseminated throughout its duration through technical reports, meetings with industry stakeholders, presentations within the railway sector, and continuous dialogue between the participating organisations. A particularly important activity was the final dissemination workshop “Förbättrade rutiner för skadade hjul” (Improved regulations for damaged wheels) hosted by Trafikverket in May 2026, where the key findings, recommendations, and implemented measures were presented and discussed with representatives from Trafikverket, SJ, Green Cargo, CHARMEC/Chalmers. The workshop provided an opportunity to share experiences, review the practical implications of the project outcomes, and identify priorities for future developments in wheel damage detection, risk assessment, and maintenance strategies. The strong engagement from stakeholders confirmed the relevance of the project and contributed to a shared understanding of the challenges and opportunities associated with condition-based wheel maintenance.

Overall, the project demonstrates that a transition from geometry-based assessment towards load-based and risk-based management of wheel damage is both feasible and beneficial. Measures to this end have already been implemented and shown to be highly profitable – a rough estimation is that the societal benefit only from being able to limit manual inspection of the track is on the order of 50 MSEK/year. Continued development of detector technology, calibration methodologies, data analytics, simulation tools, and collaborative maintenance processes will enable even more effective infrastructure protection, reduced operational disruption, lower lifecycle costs, and improved railway system reliability. The knowledge, methods, and recommendations developed within the project provide a strong foundation for future implementation of intelligent condition-monitoring systems and risk-based regulations in Sweden and internationally.

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