

FP5TRAN S4M-R

Transforming
Europe's Rail Freight

D29.5

Execution of test for gates installed in Sweden

Project acronym:	FP5-TRANS4M-R
Starting date:	2022-07-01
Duration (in months):	54
Call (part) identifier:	HORIZON-ER-JU-2022-01 (Topic: HORIZON-ER-JU-2022-FA5-01)
Grant agreement no:	101102009
Due date of deliverable:	Month 39
Actual submission date:	2026-05-26
Responsible/Author:	Behzad Kordnejad (KTH)
Dissemination level:	PU
Deliverable Type:	R – Document, report
Doc Version & Status:	V4.0 Submitted

Reviewed: (Yes)



"Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them."

"The project FP5-TRANS4M-R is supported by the Europe's Rail Joint Undertaking and its members."

Document history

<i>Revision</i>	<i>Date</i>	<i>Description</i>
1	2025-08-18	First issue
2	2025-11-27	Version sent for internal review
3	2025-12-17	Final review
4	2026-05-22	Revised and resubmitted after JU's feedback

Report contributors

<i>Name</i>	<i>Beneficiary Short Name</i>	<i>Details of contribution</i>
Behzad Kordnejad	KTH	Lead author, Editor, chapter 1, 3, 4, 7
Ingrid Nordmark	KTH	Editor, chapter 2, 3, 4
Florian Thiery	LTU	Chapter 6.4, 7
Jens Nielsen	CHALMERS	Chapter 6.4, 7
Martin Kjellin	RISE	Chapter 6.1, 6.2, 7
Mats Åkerfeldt	RISE	Chapter 5, 6.3
Francisco Parrilla Ayuso	INDRA	Chapter 5.2, 6.3

Reviewers

<i>Name</i>	<i>Beneficiary Short Name</i>	<i>Details of contribution</i>
Elisa Sengle	DBC	Official Review and Feedback
Thomas Pum	ÖBB	Official Review and Feedback

Disclaimer

The information in this document is provided "as is", and no guarantee or warranty is given that the information is fit for any particular purpose. The content of this document reflects only the author's view – the Joint Undertaking is not responsible for any use that may be made of the information it contains. The users use the information at their sole risk and liability.

The content of this report does not reflect the official opinion of the Europe's Rail Joint Undertaking (EU-Rail JU). Responsibility for the information and views expressed in the report lies entirely with the author(s).

Table of Contents

1. Executive Summary	6
2. Abbreviations & Acronyms	7
3. Background	8
4. Objective/Aim.....	9
4.1. Task Description	10
5. Gates in Sweden	11
5.1. Gate 1 in Gothenburg	11
5.2. Gate 2 in Malmö	13
5.3. RFID at checkpoints.....	14
5.4. Integration with Trafikverket's data infrastructure	16
6. Test results	17
6.1. Manual comparison of images and extracted data from Gate 1	17
6.1.1. Wagon Counts	18
6.1.2. Wagon numbers.....	19
6.1.3. ILU counts	21
6.1.4. ILU codes	21
6.1.5. UN numbers	22
6.1.6. Processing times	22
6.2. Automated comparison of data from Gate 1	22
6.3. Test results for Gate 2.....	23
6.4. Information from classical wayside monitoring systems	25
6.4.1. Quality and rescaling of Wheel Impact Load detectors	26
6.4.2. Wheel impact load detectors and regulations	32
6.4.3. Information related to Hot-box/Hot-wheel	36
6.4.4. Connection to Intelligent Video Gates.....	39
7. Conclusions	40
8. References.....	41

Lists of Figures

Figure 1. Location of the checkpoint in relation to the port of Gothenburg	11
Figure 2. The gate in Gothenburg (Kville) with its two equipped towers	12
Figure 3. Front-end solutions for the gate	12
Figure 4. The gate in Malmö (Svågertorp).....	14
Figure 5. Location of the checkpoint in Malmö, near to the Öresund bridge to Denmark.	14
Figure 6. RFID reader installed along the Swedish rail network.	15
Figure 7. Classical wayside monitoring systems along the rail network in southern Sweden (image cropped) (Trafikverket, 2025)	15
Figure 8. Schematic flow diagram.....	16
Figure 9. A partially occluded wagon number.	20
Figure 10. Sample images from gate in Malmö.....	23
Figure 11. Streaming Visualization Sample.....	25
Figure 12. Types of detector deviation that can affect or delay detection of wheel defects (based on case-study observations).....	27
Figure 13. Real and simplified map of the freight corridor for the case study.....	28
Figure 14. 3D histogram of the dynamic load as function of the axle load	28
Figure 15. CDF of all detectors. Unloaded (left) and Loaded (right) wagon. Detector 1 to 5 (Schenck) use strain gauges, while detector 6 (Phoenix) use fibre clamped to the rail foot	29
Figure 16. Rescaling principle using quantile mapping between two cumulative distribution functions	30
Figure 17. (a) Evolution of the median value of the detectors right side as function of time (b) Evolution of the degradation of the right wheels before rescaling/removal (c) Evolution of the degradation of the right wheels after rescaling/removal.....	31
Figure 18. 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.....	34
Figure 19. Influence of vehicle speed and axle load on simulated maximum wheel–rail contact force (peak load). Filled markers indicate momentary loss of wheel–rail contact before impact. Lateral position of rolling circle at (a) 90 mm, (b) 80 mm, and (c) 70 mm from the flange side of the wheel rim. In each subfigure, left graph: wheel flat 1, right graph: wheel flat 2. Black horizontal line indicates alert level at 280 kN, while the red horizontal line is the alarm limit at 350 kN.....	35
Figure 20. Evolution of bearing and wheel temperatures as function of detector passage	37
Figure 21. K-Value of the wagon bearing as function of the detector passage	38

Lists of Tables

Table 1. Task descriptions and related output in the report.....	10
Table 2. Wagon count results for the set of images analysed by Indra's system.....	18
Table 3. Wagon count results for the set of images analysed by Hitachi's system	18
Table 4. Wagon numbers correctly and incorrectly extracted by Indra's system	19
Table 5. Wagon numbers correctly and incorrectly extracted by Hitachi's system	19
Table 6. Failure types for wagon numbers extracted by Indra's system	20
Table 7. Failure types for wagon numbers extracted by Hitachi's system.....	20
Table 8. ILU count results for the set of images analysed by Indra's system	21
Table 9. ILU codes correctly and incorrectly extracted by Indra's system	21

1. Executive Summary

This deliverable, D29.5 *“Execution of Test for Gates Installed in Sweden”* addresses the execution of tests for gates installed in Sweden in relation to *Task 29.2: Demonstration and evaluation of the installed checkpoints* within WP29 – European Railway Checkpoints (ERC). WP29, as part of the Flagship Project FP5-TRANS4M-R, focuses on the development, deployment, and validation of Railway Checkpoints, which are designed to support the automation of freight train transfers at border crossings and other operational stop points.

This document provides a comprehensive overview of the planning, execution, and analysis of the tests conducted. The purpose of these tests is to assess the performance, reliability, integration, and interoperability of the Railway Checkpoints in Sweden. Two strategic locations have been decided for the installation of gates in Sweden, namely the main gateways to and from Sweden i.e. in vicinity of the Port of Gothenburg, which is Scandinavia's biggest port, and in Malmö in vicinity of the Öresund's bridge, connecting Sweden with the European continent.

The tests in this report are carried out in a comprehensive manner regarding the image analysis for the gate in Gothenburg, and in a slightly less comprehensive manner regarding the newly deployed gate in Malmö. RFID readings of wagon numbers are available for both gates but not yet fully matched with the results of the image analysis. The evaluation of the analysis of the images from the gate in Gothenburg consists of two parts; a manual comparison on a set of images and the data that have been extracted from these images, as well as an automated comparison of data extracted from images and corresponding data from a system called Lupp, which stores data that have been reported by railway undertakings to the rail infrastructure manager in Sweden, Trafikverket. These types of comparisons are made for data that have been produced by two different image analysis systems, one from Indra and the other from Hitachi. Although the results of the comparison are satisfactory on certain detection aspects, further work is needed and currently ongoing in improving the algorithms for image analysis as more images are produced from the installed gates. The gate in Malmö was deployed late March 2026. After that a training period for the gate was launched to train the system to identify all types of EVN, ILU and UN-numbers. At this stage, the system should be considered operational but not yet fully optimized.

This report also identifies paths for exchange and integration of the data retrieved from the checkpoints with Trafikverket's data infrastructure and with classical wayside monitoring systems in Sweden.

Keywords: European Railway Checkpoints (ERC), Intelligent Video Gates (IVG), Image analysis, Data exchange, Rail Freight Transportation, Sweden

2. Abbreviations & Acronyms

Abbreviation / Acronym	Description
CDF	Cumulative Distribution Function
CDM	Conceptual Data Model
ERC	European Railway Checkpoints
EU	European Union
EU-Rail JU	Europe's Rail Joint Undertakings
EVN	European Vehicle Number
FP	Flagship Project (within Europe's Rail)
FA	Flagship Area (within Europe's Rail)
GA	Grant Agreement
HB/HW	Hot-box/Hot-Wheel
ILU	Intermodal Loading Unit (containers, swap-bodies and semi-trailers)
IVG	Intelligent Video Gate
MAWP	Multi-Annual Work Programme
OCR	Optical Character Recognition
PoC	Proof of Concept
RFID	Radio Frequency Identification
UIC	International union of railways
UN number	United Nations number for dangerous goods
WILD	Wheel Impact Load Detector
WMS	Wayside Monitoring System
WP	Work Package

3. Background

The present document constitutes the Deliverable *D29.5: Execution of test for gates installed in Sweden* which is part of Task 29.2: *Demonstration and evaluation of the installed checkpoints* in the framework of the Flagship Project FP5- TRANS4M-R as described in the Europe's Rail Joint Undertakings Multi-Annual Work Programme (EU-RAIL MAWP).

The Standardised Railway Checkpoints are developed to assist with automating Freight Train Transfer detection and inspections at borders or other operational stop points. Specifications for the checkpoint has previously been described in chapter 8 in Deliverable D25.1 *Report on the basic functional and technical specifications for the realisation of the technical enablers of Seamless Freight, also including the final specification input for FP1* (Hildebrandt et al., 2024).

Descriptions of system development and installation process for the gates in Sweden have been published and presented in chapter 5 in D29.1 (Kordnejad et al., 2024). Two strategic locations have been decided for installation of gates in Sweden, namely the main gateways to and from Sweden i.e. in vicinity of the Port of Gothenburg, which is Scandinavia's biggest port, and in Malmö in vicinity of the Öresund bridge, connecting Sweden with the European continent.

The above-mentioned specifications and developments have now been implemented to the state which is described in chapter 5 in this document and ready to undergo the tests that are depicted in chapter 6.

4. Objective/Aim

This document has been prepared to provide the output from the tests executed in Sweden, as part of Task 29.2: *Demonstration and evaluation of the installed checkpoints*.

The aim of the task was to demonstrate and evaluate the development of checkpoints for digitalisation and partial automation of manual processes through innovative sensors, video gates and other devices.

The aim of this deliverable is to provide a comprehensive overview of the planning, execution, and analysis of the tests conducted. The purpose of these tests is to assess the performance, reliability, integration, and interoperability of the Railway Checkpoints in Sweden. D29.1 (Kordnejad et al., 2024) specified four use cases as high level definitions of test cases and the developments in the four countries where ERCs have been installed, are responsible and focuses on one test case each.

1. Condition monitoring – Bogie Analyzer, (Germany)
2. Rolling stock and ILU identification, (Sweden)
3. Identification of dangerous goods, (Netherlands)
4. Integration with On-board systems, (Spain)

The test case considered for the Swedish installations concerns use case 2: *Identification of rolling stock and ILUs*, hence that is the emphasis of the tests carried in this report, whereas the other test cases are out of scope and presented in D29.1 and will be elaborated in other upcoming deliverables of WP29; D29.2, D29.3, D29.4, D29.6 and D29.7.

For the demonstration of European Railway Checkpoints, gates from all four countries will be included and presented in deliverable D29.2 *Demonstration and Evaluation of standardised European Railway Checkpoints at borders or other operational stop points* and showcased within WP33 Showcase Seamless Corridor, presented in D33.2 *Report on the Seamless Corridor*.

4.1. Task Description

Task 29.2 Demonstration and evaluation of the installed checkpoints started in January 2025. The task includes:

Demonstrate and evaluate the development of IVG checkpoints based on the specifications in task 29.1 for cross border traffic, on main lines, at yards and terminals at suggested sites. Final selection and demonstration of use cases.

The output from the tests executed in Sweden is included in this document. Table 1 gives the direct match of the task definition from the proposal with the output and a link to the section where more details can be found.

Table 1. Task descriptions and related output in the report

	Task definition from GA (Task 29.2)	Output of deliverable
	Demonstrate and evaluate the development of IVG checkpoints based on the specifications in task 29.1 for cross border traffic, on main lines, at yards and terminals at suggested sites. Final selection and demonstration of use cases.	Chapter 5 and 6

The evaluations in this report will concentrate on the quality of the image analysis. The project has aimed to improve this quality, since the final evaluation in the previous project, FR8RAIL III, showed that the necessary accuracy level was not reached by then. In D25.1 (Hildebrandt et al., 2024) it was specified that in order to recognise the required detection items, the Checkpoints must meet certain requirements. Only a sufficiently accurate recognition can be used for automatic OCR. Ideally, additional RFID readers should be installed to read out wagons equipped with RFID. In addition, the differentiation of wagons should work unambiguously to enable the use of the technology regardless of the installation location (free track, hump) and at different speeds up to 120 km/h. The recognition target for this use case should be over 95% in order to offer a significant advantage over the current process.

An important delimitation of this report is that the evaluation will consider the above-mentioned use case; “Rolling stock and ILU identification”, thus logistics-related data such as vehicle numbers and ILU codes are considered, while maintenance-related data are out of scope. The evaluation will compare the performance of two different image analysis systems; one developed by Hitachi and the other by Indra.

5. Gates in Sweden

Since the start of Shift2Rail, the Swedish Transport Administration, Trafikverket, together with its partners, has chosen to investigate and build two test facilities for ERCs/IVG. The first was built in 2022 in Gothenburg (Kville) on the line to the Port of Gothenburg, about a 10-minute train run to the port, see Figure 1. As of November 2025, the second one is under construction in Malmö (Svågertorp) on the line to the Öresund Bridge in southern Sweden.

Both gates have the same purpose of capturing logistics information. This information consists of location, time stamp, wagon order, wagon counts, European vehicle numbers (EVN/UIC numbers), ILU counts, ILU codes and dangerous goods codes (UN number). For call 2 of FA5, it is planned that the gate in Gothenburg will also be equipped with new cameras and software to be able to analyse bogies and any risk of damage to them. In addition to the IVGs there are further RFID-readers installed along the Swedish rail networks.

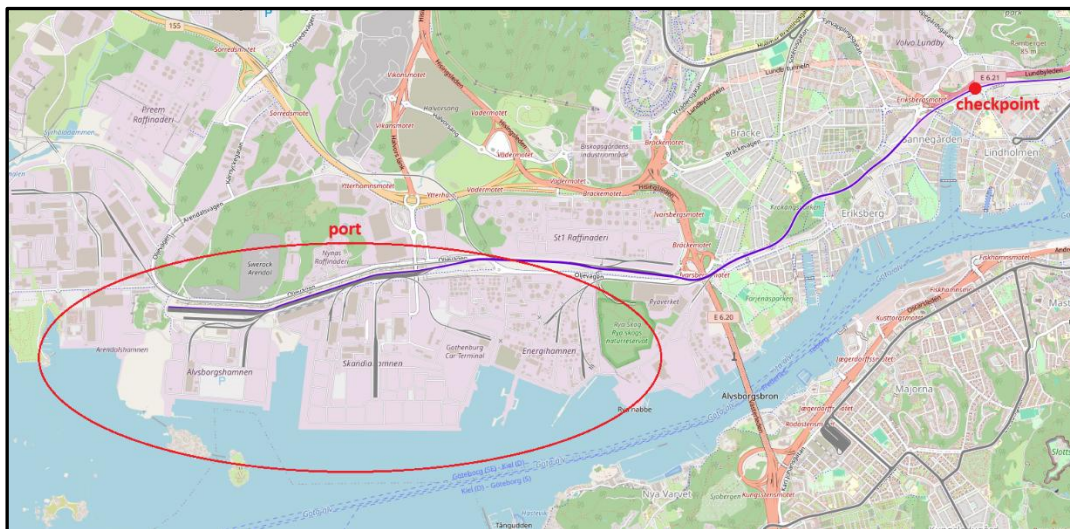


*Figure 1. Location of the checkpoint in relation to the port of Gothenburg
Map data © OpenStreetMap contributors; rendered using OpenRailwayMap (CC BY-SA 2.0)*

5.1. Gate 1 in Gothenburg

The gate in Gothenburg has produced data in varying quantities and quality since it was built. The installation process involved Hitachi, which supplied the hardware for the gate, which produces images that are uploaded to a server on site. From there, Indra can retrieve the images, which are then analysed using Indra's image analysis software. After that Indra makes the analysis results available to the research data platform Deplide. The platform is provided by the RISE Research Institutes of Sweden. So far, logistics data has been handled with some success. It should be noted that Hitachi has developed an image analysis system which is also considered in the tests of this report. The project group is

continuously working on quality improvements in data collection, and new versions of both hardware and software have been launched since installation.



Figure 2. The gate in Gothenburg (Kville) with its two equipped towers

The gate (see Figure 2) consists of two towers standing opposite each other, rotated by a certain degree for the best target image. The towers contain cameras, lighting and screen protection. There is also a RFID-reader assigned to the gate. A technology cabinet located nearby connects captured images to image analysis tools and RFID readings. The data is then stored on local sever in the immediate vicinity. For the image processing of Indra, currently the data is uploading to a cloud server. There is also a separate RFID reader near the towers that complements the images. To start the whole process, a number of axel sensors are used that are located at a certain distance from the towers. The images are taken from both sides when a train passes.

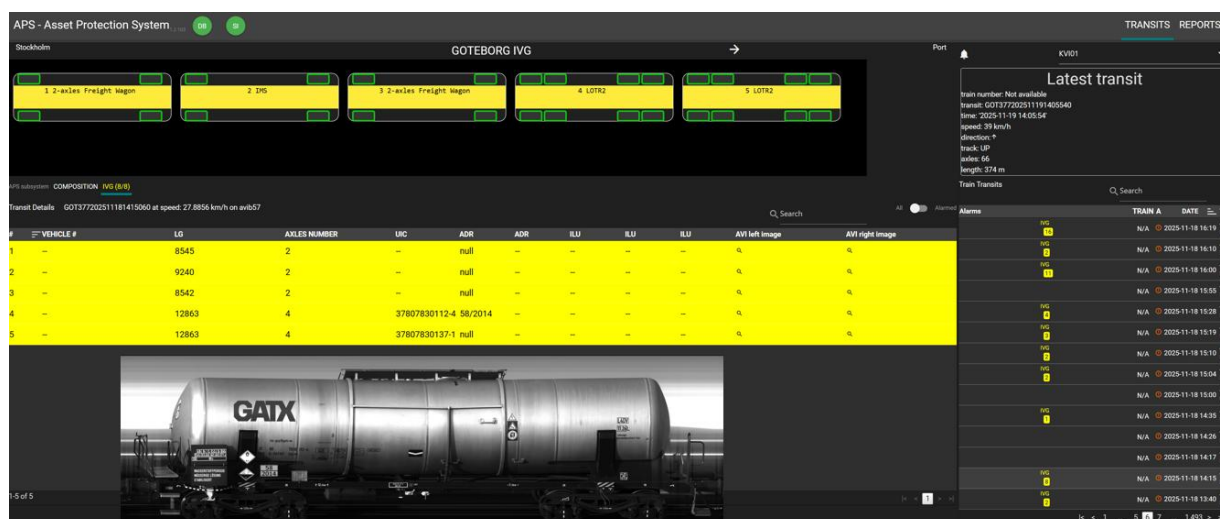


Figure 3. Front-end solutions for the gate

There is a user interface (see Figure 3) where the trains that have passed can be seen with images and with analysed results. The interface is not yet formally available to users but is mainly used by the project for quality control and analysis. In the interface, by clicking on a train passage, one can see all the information that has been captured, i.e. train content, wagon number, etc.

Since the gate in Gothenburg is located close to the port, it can be considered a port and terminal gate. The information from the gate can be used to better plan operations in all parts of the port. Early information allows the activities of the port to be planned more efficiently and contributes to increased productivity. For trains leaving the port, a verification of the train composition can be made when they pass the gate on their way out.

5.2. Gate 2 in Malmö

There is also a gate recently installed in Svågertorp, see Figure 4 on the outskirts of Malmö in southernmost Sweden, near the Öresund Bridge, which connects Sweden and Denmark. It is a five to six minutes train run to reach the bridge and another ten minutes to cross the border to Denmark, see Figure 5. The civil work started in November 2025. The gate was deployed late March 2026. After that a training period for the gate was launched to train the system to identify all types of EVN, ILU and UN-number. At this stage, the system should be considered operational but not yet fully optimized. The system is currently deployed as a functional prototype.

The technical solution is modified compared to the gate in Gothenburg. Among other things, there are no wheel sensors or axle sensors; instead, cameras and Infra-red (IR) sensors are used to prepare and start the gate. IR sensors are also used to monitor whether a train is passing. However, the output from the analysis is the same as in Gothenburg, i.e. logistics information.

The purpose of placing the gate near the Öresund Bridge is to capture logistics information for trains entering and leaving Sweden and to be able to provide reliable information on trains leaving Sweden. The deployment serves to verify the system's capabilities in a real-world environment and to continuously refine the performance of the integrated subsystems. The gate is designed as a specialized product for Infrastructure Managers (IM), Railway Undertakings (RU), and Port Administrators (PA), with two primary objectives:

- Rail Freight Transport Management: Optimizing and automating freight traffic at borders, terminals, and shunting yards. The gate enables real-time composition management, precise identification of Intermodal Loading Units (ILUs) and dangerous goods, and synchronization with Traffic Management Systems (TMS) or Terminal Operating System (TOS) to minimize operational downtime.
- Asset and Rolling Stock Management: Enhancing the monitoring and lifecycle management of assets. By collecting continuous sensor data, the system ensures compliance with international standards, facilitating automated technical inspections and predictive diagnostics.



Figure 4. The gate in Malmö (Svågertorp)

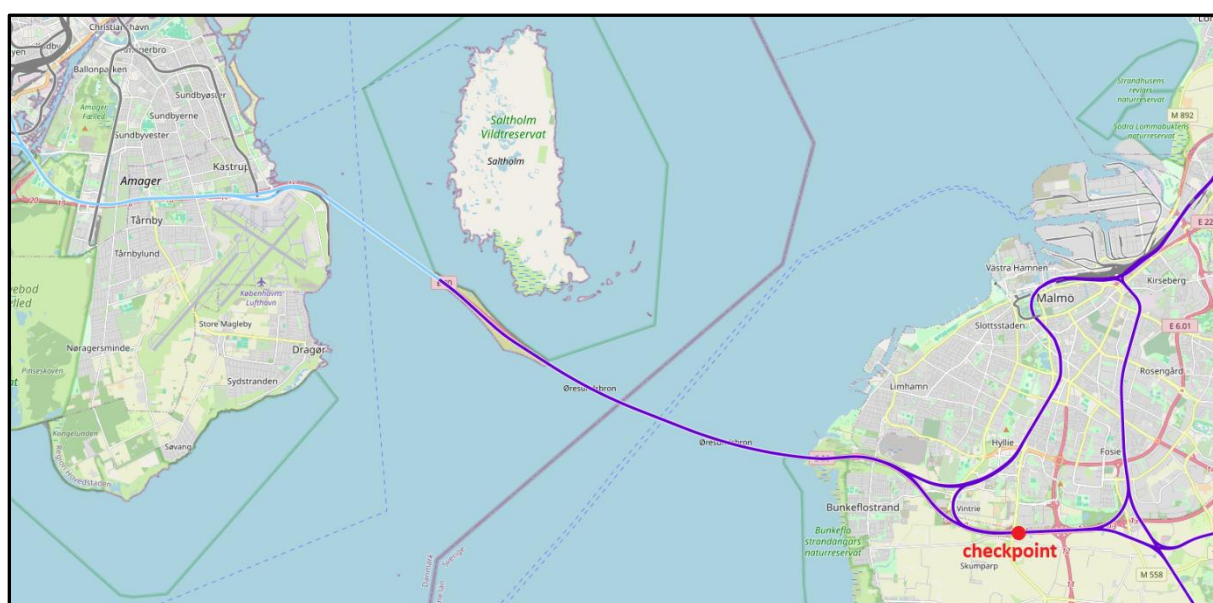


Figure 5. Location of the checkpoint in Malmö, near to the Öresund bridge to Denmark.
Map data © OpenStreetMap contributors; rendered using OpenRailwayMap (CC BY-SA 2.0)

5.3. RFID at checkpoints

Trafikverket has installed approximately 400 RFID reader stations (example in Figure 6) across the country. Tagged wagons that pass the readers are detected and the data is sent via Trafikverket's server to data subscribers. Each station has axle sensors that count the axles that pass. This means that even untagged wagons can be detected and placed in the correct place in the wagon sequence, but without wagon number. RFID readers are installed in vicinity of both IVGs. Approximately half of the RFID stations are equipped with other sensors to read the status of passed wagons. These are hot running/theft brake detectors, wheel damage detectors, derailment detectors and there are also samples with acoustic sensors that can recognise discord sounds, see Figure 7 for southern Sweden.



Figure 6. RFID reader installed along the Swedish rail network.

Together with Image analysis, OCR and RFID, a checkpoint enables several possibilities at the same location. Logistics information from IVG and different outcomes from the sensors in the RFID stations. So far, the two have not been used together, but Trafikverket uses RFID to warn railway companies if the sensors indicate a fault or an elevated value, for example in the hot-running detector. This is further elaborated in chapter 6.4.

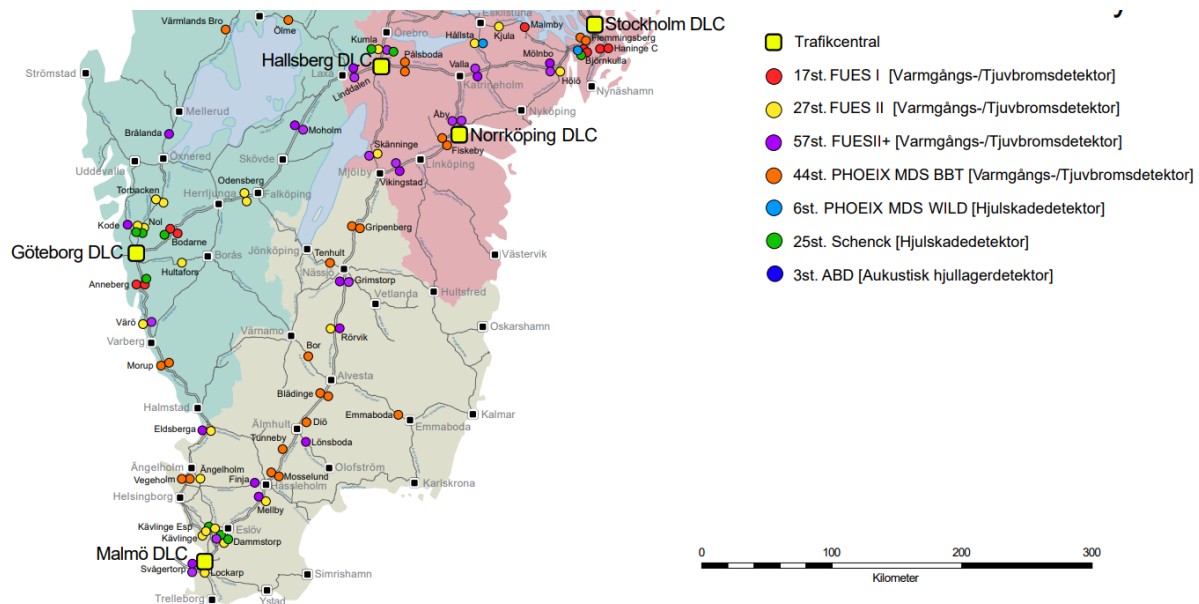


Figure 7. Classical wayside monitoring systems along the rail network in southern Sweden (image cropped) (Trafikverket, 2025)

5.4. Integration with Trafikverket's data infrastructure

Until today, data that can be captured from the gate is sent to Deplide and analysed from there and shared within the project. Next step is to integrate the data from the gates into Trafikverket's data sharing architecture.

Since the deployment of RFID-readers Trafikverket has had a data collection and data sharing policy. The architecture, briefly illustrated in Figure 8, handles the RFID readings in a secure and safe multi sharable way. The RFID data is currently managed in a database, where two options are available for end users to access the information: either through an API interface, which allows users to subscribe to the data, or through a web interface, where users can log in with their credentials and extract the information themselves.

When time has come to integrate the gates into this data infrastructure it would be quite affordable. To start that process the project as a whole must be convinced that the quality and the availability is at a certain stage that the stakeholders will trust the results and can use it to enhance their businesses.

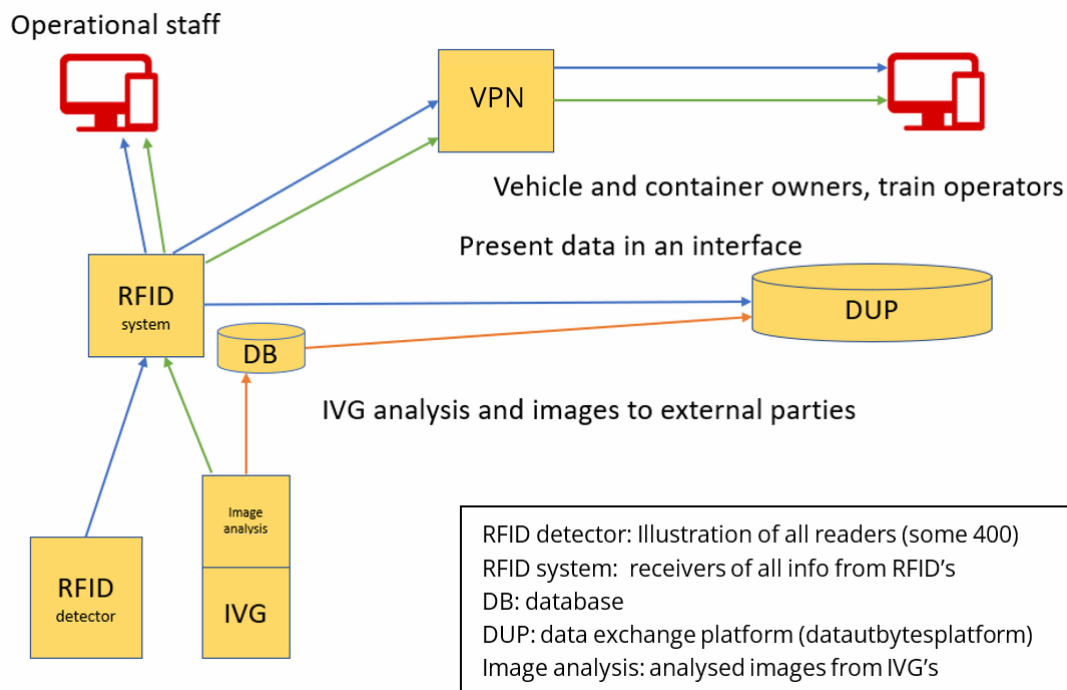


Figure 8. Schematic flow diagram

Note that the figure above depicts the data integration internally at Trafikverket. For data exchange on European level, work has been carried out in D29.1 (Kordnejad et al., 2024) and aligned with FA5 WP32 "Seamless data exchange" as well as with the Conceptual data model (CDM) developed in FA1.

6. Test results

This chapter presents the results of testing from the Swedish gates in Gothenburg and Malmö. Testing is a critical part of the development process, where specification, development, and testing phases form a continuous loop. Feedback from the testing will drive further development and model refinement.

The gate in Gothenburg is equipped with two image analysis systems. One of the systems has been developed by Indra and the other one by Hitachi. The systems have been tested in two different ways. First, images have been manually compared to the data extracted by the systems from these images, see chapter 6.1. Second, extracted data have been automatically compared to corresponding data that have been reported to Trafikverket by railway undertakings, see chapter 6.2.

The gate in Malmö is recently installed and has an image analysis system from Indra. Tests from the initial data extraction is further described in chapter 6.3.

The integration of data retrieved from the ERC with the classical wayside detectors reading the status of passed wagons (e.g. hot running/theft brake detectors, wheel damage detectors, derailment detectors, acoustic sensors) is elaborated in chapter 6.4.

6.1. Manual comparison of images and extracted data from Gate 1

In this section, images produced by the gate are manually compared to output from the image analysis systems. The purpose of the comparison is to test the ability of the systems to correctly extract the following types of logistics data from the images: wagon counts, wagon numbers (European vehicle numbers, EVN), ILU counts, ILU codes, and UN numbers (dangerous goods information). Due to lack of output data, however, Hitachi's system has not been tested for its ability to extract number of ILUs, ILU codes, and UN numbers. Also, the two systems have not been tested on the same set of images, due to lack of overlapping data. As stated in Section 0, there is a requirement that the output from the image recognition systems must be correct in more than 95 % of the cases. Additionally, the processing times of Indra's system have been evaluated.

Usually, the gate produces a pair of images for each wagon (one image for each side of the wagon), but it sometimes happens that one of the images in a pair is missing or completely black. Even so, we consider the information that can be obtained from the images using visual inspection to be the truth. In other words: in case both images of a wagon would go missing without any traces, this wouldn't affect the evaluation. The reason for this choice is that the images are the best source of information that we have.

In the evaluation of Indra's image analysis system, all images of wagons from 11 trains were analysed. These images were produced during one day in November 2025. In total, 190 pairs of images were included in the evaluation. In the evaluation of Hitachi's system,

all images of wagons from 10 trains were analysed. These images were produced during one day in March 2025. In total, 200 pairs of images were included in the evaluation. For both systems, the analysed images were produced in conditions reaching from full daylight to darkness.

6.1.1. Wagon Counts

Each image should display exactly one wagon (that is, the gate should place a cut between images in each gap between wagons, and only there), and the image analysis system should report one wagon per pair of images. The outcome for a pair of images is considered correct if both these conditions are fulfilled. (However, one of the images in the pair can be completely black, provided the other is not.) If all image pairs for a train are correct in this respect, the reported wagon count for the train will also be correct in relation to what is displayed in the images.

If a wagon is incorrectly split between two image pairs, the pair that has the worst analysis is completely excluded from the evaluation (including the following sections). The other image pair is included in the evaluation and considered as incorrect. Since the splitting of images is done before the image analysis and the two analysis systems consistently report one wagon per pair of images, there is no big difference between the results for the two sets of images, as shown in Table 2 and Table 3. In both cases, more than 95 % of the image pairs have been correctly handled.

Table 2. Wagon count results for the set of images analysed by Indra's system

Outcome	Number of image pairs	Percentage of all image pairs
Correct	187	98.4 %
Incorrect	3	1.6 %

Table 3. Wagon count results for the set of images analysed by Hitachi's system

Outcome	Number of image pairs	Percentage of all image pairs
Correct	198	99.0%
Incorrect	2	1.0 %

6.1.2. Wagon numbers

The wagon number (European vehicle number, EVN, also called UIC number) of a wagon is considered correctly extracted if (a) all twelve digits in the number are visible in at least one of the two images of the wagon and (b) exactly twelve digits are reported by the system and all these are correct. (For Hitachi's system, which reports separate analyses for the two images, it is enough that the latter condition is true for one of the images.) Otherwise, the outcome is considered incorrect. As shown in Table 4 and Table 5, Indra's system produces a correct wagon number for 64.7 % of the image pairs, while Hitachi's system succeeds in 63.0 % of the cases.

Table 4. Wagon numbers correctly and incorrectly extracted by Indra's system

Outcome	Number of image pairs	Percentage of all image pairs
Correct	123	64.7 %
Incorrect	67	35.3 %

Table 5. Wagon numbers correctly and incorrectly extracted by Hitachi's system

Outcome	Number of image pairs	Percentage of all image pairs
Correct	126	63.0%
Incorrect	74	37.0%

The failures (incorrect outcomes) can be divided according to type:

- The wagon number may be damaged so that it is not readable to the eye. The number may also be occluded by some part of the wagon in such a way that it is unlikely that using other camera angles would solve the problem (see Figure 9 for an example). These failures are considered to be of the same type, since they are caused by the state of the wagon and not by the image acquisition system or the image analysis system. (In some cases, it is very likely that the image analysis has in fact produced the correct wagon number, but it is not possible to come to this conclusion just by inspecting the image. To be more specific, the problem in these cases is that the leftmost part of a digit which is very likely a "3" is occluded, so that judging from the image, it could just as well be an "8".)
- The image analysis system may not produce the right wagon number, even though there is a number in at least one of the images of the wagon that is fully readable to the eye. The result may be a number that consists of too few or too many digits, a number where one or several digits are incorrect, or an indication that the system couldn't find or read the wagon number.

- In principle, a failure in producing wagon numbers may also be caused by poor image quality, so that there is no number that is readable to the eye. For example, an image could be too dark or too bright, or the wagon number could be occluded due to an unsuitable camera angle. However, no such cases showed up among the images that were included in the evaluation.



Figure 9. A partially occluded wagon number.

Table 6. Failure types for wagon numbers extracted by Indra's system

Failure type	Number of image pairs	Percentage of all failures	Percentage of all image pairs
Damaged or occluded number	15	22.4 %	7.9 %
Image analysis failure	52	77.6 %	27.4 %

Table 7. Failure types for wagon numbers extracted by Hitachi's system

Failure type	Number of image pairs	Percentage of all failures	Percentage of all image pairs
Damaged or occluded number	4	5.4%	2.0%
Image analysis failure	70	94.6 %	35.0 %

As can be seen in Table 6, 7.9 % of the failures of Indra's system are caused by the state of the wagons (damaged or occluded wagon numbers), while 27.4 % are caused by the image analysis system. If the former are excluded, this means that the system produces a correct wagon number in 70.3 % (123 out of 175) of the cases where this should be possible. For Hitachi's system, whose failures are summarised in Table 7, the corresponding figure is 64.3 % (126 out of 196 image pairs). Since these figures are based on data for two limited sets of trains, they are somewhat uncertain. However, it is clear that the evaluated versions of the systems don't meet the requirement of producing correct wagon numbers in more than 95 % of the cases.

6.1.3. ILU counts

The image analysis systems should correctly report the number of ILUs visible in each image pair. As shown in Table 8, Indra's system succeeds in doing this for 54.2 % of the image pairs included in the test set. The requirement of correctly counting the ILUs in more than 95 % of the cases is thus not fulfilled. There are two types of failures in the results produced by the system. First, the system sometimes reports that there is an ILU on the wagon, even though there is actually none (either because the wagon is an intermodal wagon that didn't carry any ILUs when it passed the gate or because it is a covered wagon). Second, the system may report a too small number of ILUs (for example, even though there are actually four ILUs on the wagon, only two or even none may be reported).

Table 8. ILU count results for the set of images analysed by Indra's system

Outcome	Number of image pairs	Percentage of all image pairs
Correct	103	54.2 %
Incorrect	87	45.8 %

6.1.4. ILU codes

The test of the ability of Indra's image analysis system to correctly extract ILU codes includes the ILUs that are both visible in the images and included in the output from the system. That is, ILUs that are shown in an image but not included in the output (corresponding to the system reporting a too small number of ILUs, as described in the previous section) are omitted here and don't affect the result of this part of the evaluation. Likewise, ILUs that are included in the output (without an ILU code) but don't exist in the images are not considered here. Instead, such errors show up in the ILU count results in the previous section.

In total, the evaluation includes 222 ILUs. As shown in Table 9, the system reports the correct ILU code for 204 of these. This corresponds to 91.9 % of the ILUs, which is close to the requirement of producing correct ILU codes in more than 95 % of the cases but doesn't completely fulfil it. All the incorrect outcomes are caused by the image analysis system, since the ILU code is clearly visible in at least one image in every pair.

Table 9. ILU codes correctly and incorrectly extracted by Indra's system

Outcome	Number of ILUs	Percentage of all ILUs
Correct	204	91.9 %
Incorrect	18	8.1 %

6.1.5. UN numbers

UN numbers identify dangerous goods and are written on orange-coloured plates that are attached to wagons and ILUs that contain such substances. In the output used in the evaluation of Indra's system, there are 15 images of wagons that have orange-coloured plates with UN numbers. However, the system always reports that the UN number is the default value "0", since Indra thinks that the detection of this type of numbers doesn't work well enough yet. In other words, the requirement of 95 % correct detections is not fulfilled.

6.1.6. Processing times

Indra's image analysis system typically needs less than five minutes from the point in time when a train reaches the gate until data have been extracted from the images of the train and delivered to Deplide. Since clocks are not synchronised between the different systems, this time is approximate. However, it is clear that the processing time is short enough not to disturb the processes of the users of the extracted data.

6.2. Automated comparison of data from Gate 1

Railway undertakings report to Trafikverket which vehicles (wagons and locomotives) are part of their trains and which types of dangerous goods (if any) the wagons carry. This information is stored in a system called Lupp, but it is known that the information is partly incomplete and incorrect. To get an idea of how much information that could be added or corrected by gates, output from the image analysis systems from the gate in Gothenburg was compared to information from Lupp. For Indra's system, 878 vehicles with an extracted vehicle number were included, and 460 of these vehicles (52.4 %) were found to have passed the gate (within a time margin of two hours) according to the information from Lupp. For Hitachi's system, the corresponding figures were 2 353 of 3 253 vehicles (72.3 %) for the camera with the best result. Since we know that the vehicle numbers extracted by the image analysis systems are not always correct, we cannot say that all the vehicles that were found by the image analysis but that were not present in Lupp would contribute to increased information quality. However, improved versions of the image analysis systems would certainly be of help in collecting complete and correct information about vehicles and dangerous goods.

6.3. Test results for Gate 2

As a functional prototype, the system in Malmö is fully operational and under active development. Iterative improvements are currently being implemented based on the data collected at the installation, focusing on fine-tuning the detection models and system calibration to progressively enhance accuracy and ensure the results meet the highest reliability standards required for the final product. The configuration of both software and hardware is constantly improving as more and more images are stored and the system is trained.



Figure 10. Sample images from gate in Malmö

The latest version of the gate shows a total of 144 train passages, of which 18 were identified as freight trains by the system. However, at least 3 of these detections were incorrectly classified, resulting in a classification accuracy rate of 83.3% for freight traffic.

The identification of alphanumeric identifiers also provided key metrics during this stage:

EVN Identification and Confidence:

- The system detected 266 EVN codes, 67 of them with a confidence of 100%.

ILU Identification and Confidence:

- The system detected 601 container codes (ILUs), 57 of them with a confidence of 100%. It should be noted that this total may include passenger train detections since the passenger/freight discrimination has not yet been fully implemented.

The system performance has been optimized following the updates implemented on 10/04/2026. This analysis compares the baseline period (period 1) with the post-update results (period 2), focusing on classification reliability and tracking continuity.

In terms of the optimization of freight classification and tracking, the refinements in the detection and pre-classifier modules have directly addressed the challenges of identifying complex freight compositions. This progress has enabled the system to maintain high accuracy and stability when processing complex freight compositions:

Error Rate Reduction: The misclassification rate for freight units dropped from 37.5% in Period 1 to just 14.2% in Period 2. This confirms a higher reliability in distinguishing between passenger and freight traffic.

Tracking Robustness: The system has successfully overcome tracking fragmentation. While Period 1 was limited to capturing compositions of up to 16 wagons, the updated system now maintains stable object assignment for long-haul trains of up to 36 wagons.

Impact: This evolution ensures that heavy-haul freight operations are recorded as single, coherent data units, preventing the system from splitting long trains into multiple incorrect detections.

Processing Efficiency: Regarding system processing efficiency, the platform has been recalibrated to ensure more reliable outputs, demonstrating a significant increase in operational efficiency during Period 2. Despite a 19.4% decrease in total traffic volume (191 vs. 237 trains), the volume of processed images grew by 8.5% (102 vs. 94). This improvement reflects a more optimized capture trigger, which allows the system to extract a higher volume of quality data per detection even when faced with lower overall traffic levels.

Throughout this installation, intensive qualitative review of collected images continues to reveal real-world visual challenges, such as extensive graffiti, overexposure, and low-contrast surfaces. These findings highlight the inherent complexity of the operational environment and reinforce the need for stabilized acquisition conditions and high-quality data for reliable code identification



Figure 11. Streaming Visualization Sample

6.4. Information from classical wayside monitoring systems

The wayside monitoring systems (WMS) play a major role for the safety of vehicles running on railway tracks. However, to improve the inspection and optimize the maintenance actions of the operator's vehicles, it is necessary to standardize and harmonize the extracted information from the different types of wayside systems from both a national and international perspective. In general, the wayside monitoring systems across European railways may use different sensor types, signal processing algorithms and calibration methods that will inherently lead to variation of readings for the same condition of components. Hence a strategy should be adopted to align data distribution between the different detector types, but as well based on operational and environmental parameters that can affect specific detectors in more distinct manner. This could contribute to a common reference framework for interpreting data by reducing inconsistencies between different railway networks. The EU railway network aims to enable seamless cross-border traffic, but variations in data collection methods across countries give rise to challenges. Hence a harmonized approach to rescaling ensures that measurement from various national railway infrastructures can be compared and integrated.

Modern railways tend to shift from time-based maintenance to condition-based and predictive maintenance. If the wayside detector outputs are harmonized, railway

operators can develop common threshold values for intervention based on specific levels. This ensures consistent maintenance decisions across different railway operators.

The main objective in this study is to improve the interoperability of wayside data across different networks (international level) or routes (national level). By doing so, it should help for:

- Facilitating predictive maintenance with standardized thresholds
- Helping rail operators and regulatory bodies make data-driven decisions
- Aligning with EU policies on interoperability

6.4.1. Quality and rescaling of Wheel Impact Load detectors

In the case of degraded wheels (wheel flats, pitting or shelling), the use of WILD systems is done to identify wheels that display a high peak or dynamic load when passing through a specific detector. Hence the WILD systems work as an automated inspection system rather than a condition monitoring system.

The advantages of using WILD systems as condition monitoring rather than automated inspection systems are as follow. On one side, from a diagnostics perspective, it will allow to detect changes in an early stage as possible as well as to possibly estimate the extent of the fault. On the other side, the prognostic part will allow to estimate the Remaining Useful Life with a specific confidence interval and better accuracy. Hence sharing information related to low severity from wayside data can be beneficial in several aspects:

- Low-impact readings can indicate emerging issues with the wheelsets but maybe related with other components (bogies, springs)
- Early detection can prevent a defect from causing damage to the infrastructure
- Addressing a small defect early avoids more expensive repairs or service interruptions
- If this information is shared ahead of time (e.g. before a border crossing or a terminal), inspection teams can prepare and intervene quickly and target specific wagons
- Wagon owners, entities in charge of maintenance and operators benefit from better tracking of wear patterns and component lifespan

Instead of relying on safety thresholds during operation, detector systems can apply graduated (level 1 to 5 for instance, with level 1 being the lowest level of degradation), which would allow border or terminal operators to receive pre-alerts for wagons with “suspected issues” to enable a targeted inspection instead of full-train checks.

However, to transition to lower warning levels and target specific wagons, an important factor that comes into play is related to the wayside detectors themselves. The quality of wayside detectors and its deviations (Figure 12) will directly impact the reliability and

usefulness of low-level threshold data. In addition, knowledge related to the quality of the detectors can help targeting and prioritize specific maintenance actions on the detector themselves based on the type of deviations.

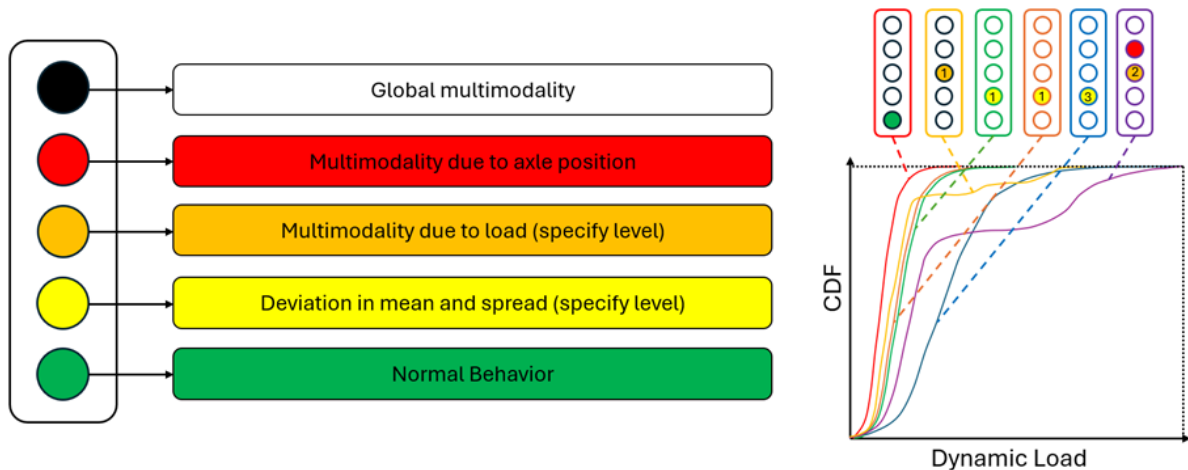


Figure 12. Types of detector deviation that can affect or delay detection of wheel defects (based on case-study observations)

6.4.1.1. Case study: Influence of detector quality and rescaling on wheel degradation detection

The investigation of the detectors' quality is first performed on a specific wagon with heterogeneous detectors on a freight corridor to understand the possible variations of the data at each location without taking into consideration the variation in wagon type.

This preliminary study focuses on a specific freight wagon running on the Iron Ore line (Malmbanan) in Northern Sweden (Figure 13) to illustrate the main concepts and associated challenges. In this case, the wagon of interest passes through detectors D1 to D6 during several years of operation. The values of the dynamic loads are plotted as function of the axle load for the entire study period (Figure 14).

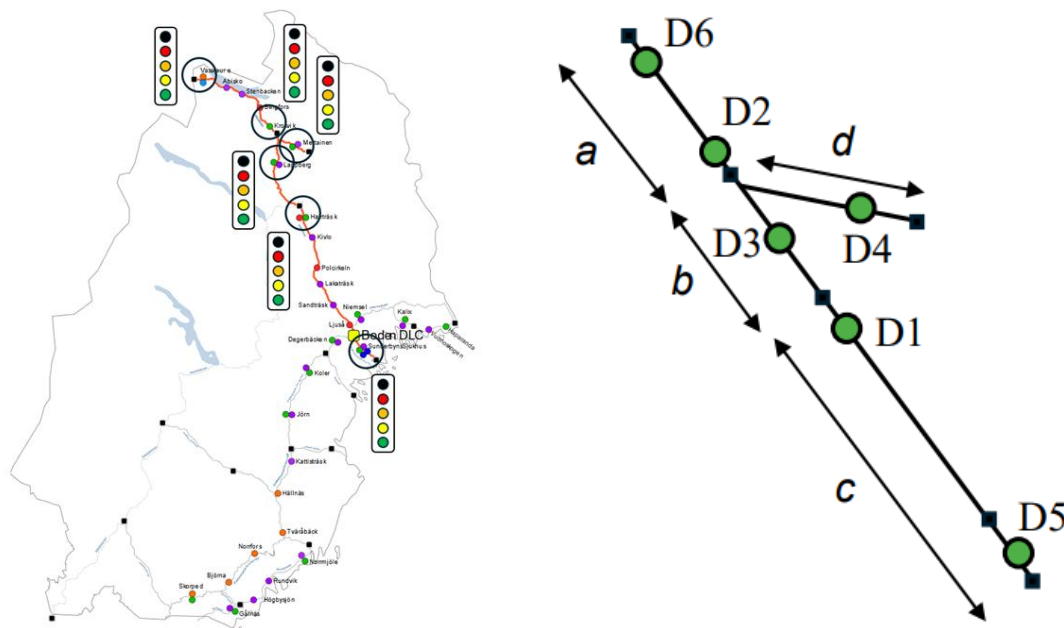


Figure 13. Real and simplified map of the freight corridor for the case study.

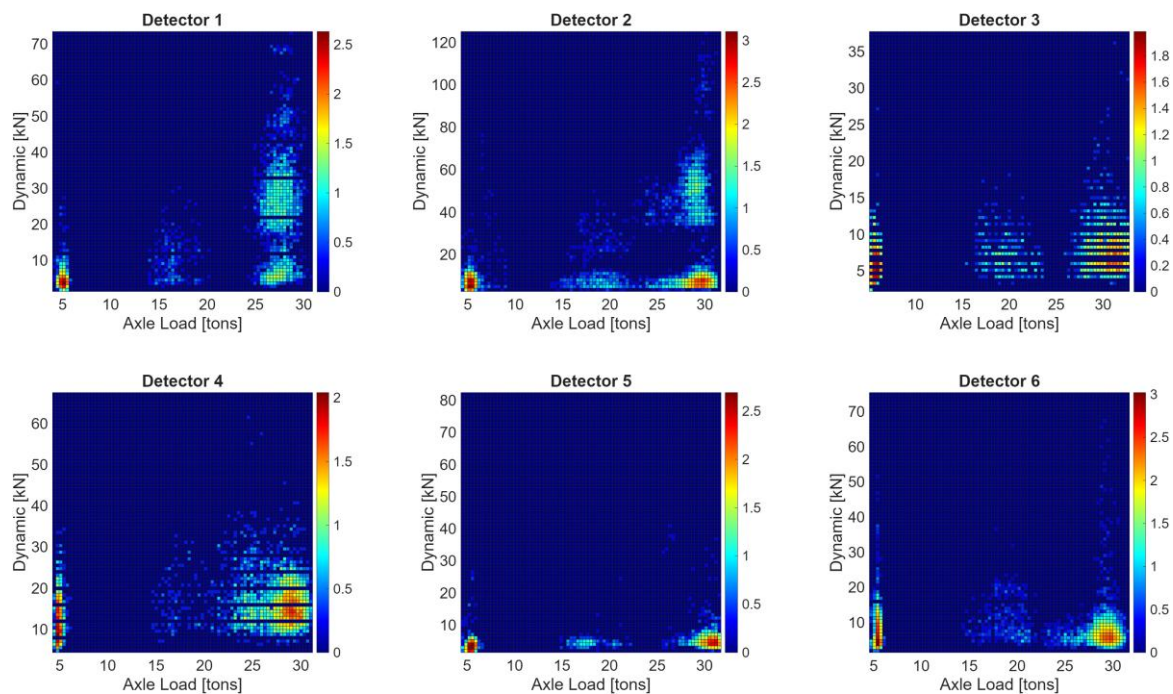


Figure 14. 3D histogram of the dynamic load as function of the axle load

To have a clearer view of the behaviour of the detectors, the cumulative distribution functions (CDF) is plotted for each detector by separating when the wagon is unloaded or loaded (Figure 15).

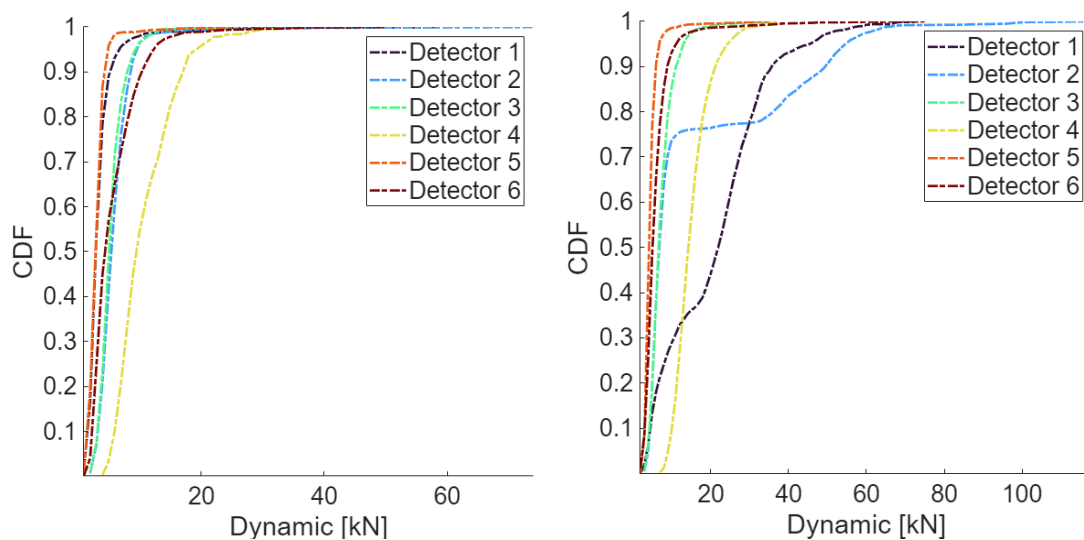


Figure 15. CDF of all detectors. Unloaded (left) and Loaded (right) wagon. Detector 1 to 5 (Schenck) use strain gauges, while detector 6 (Phoenix) use fibre clamped to the rail foot

It can be observed that the detectors behave differently depending on the detector locations and type, showing deviations in mean, spread and even occurrence of multimodality for the loaded case. The summary of the behaviour of the detectors is as follows:

- Detector 2 performs as expected at low axle loads, but for higher loads, its CDF shows that 25% of wheels exceed the first elbow point, indicating elevated dynamic loads.
- Detector 1 shows a comparable pattern to Detector 2, though a larger share of wheels (63%) exhibits elevated dynamic loads, and even its lower-load mean values are higher.
- Detectors 3, 5, and 6 display consistent, normal behaviour across both low and high axle loads.
- Detector 4 also behaves normally across load ranges but exhibits a broader spread and a higher median compared with Detectors 3, 5, and 6.

For the rescaling procedure of the data, Detector 5 is chosen as the reference detector where all other detectors will be scaled upon. The process to rescale the data is based on quantile mapping (Figure 16. Rescaling principle using quantile mapping between two cumulative distribution functions. The Quantile Mapping purpose is to rescale the measurements from one detector to match the statistical distribution of our reference detector by mapping each value to its corresponding quantile in the reference distribution.

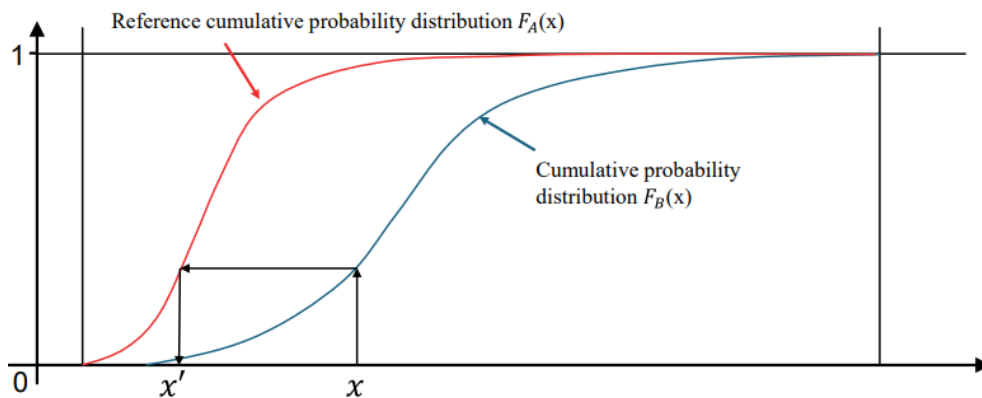


Figure 16. Rescaling principle using quantile mapping between two cumulative distribution functions

Even if straightforward, the method requires strictly monotonic empirical distribution functions and to carefully handle outliers to avoid distortions, limiting the transformation to specific quantile ranges. It is also worth mentioning that Detector 1 and 2 will be entirely disregarded for this test due to their multimodality, even though some sub-datasets could have been kept in the process (for instance the unloaded data of detector 1 and 2 that still behaves normally).

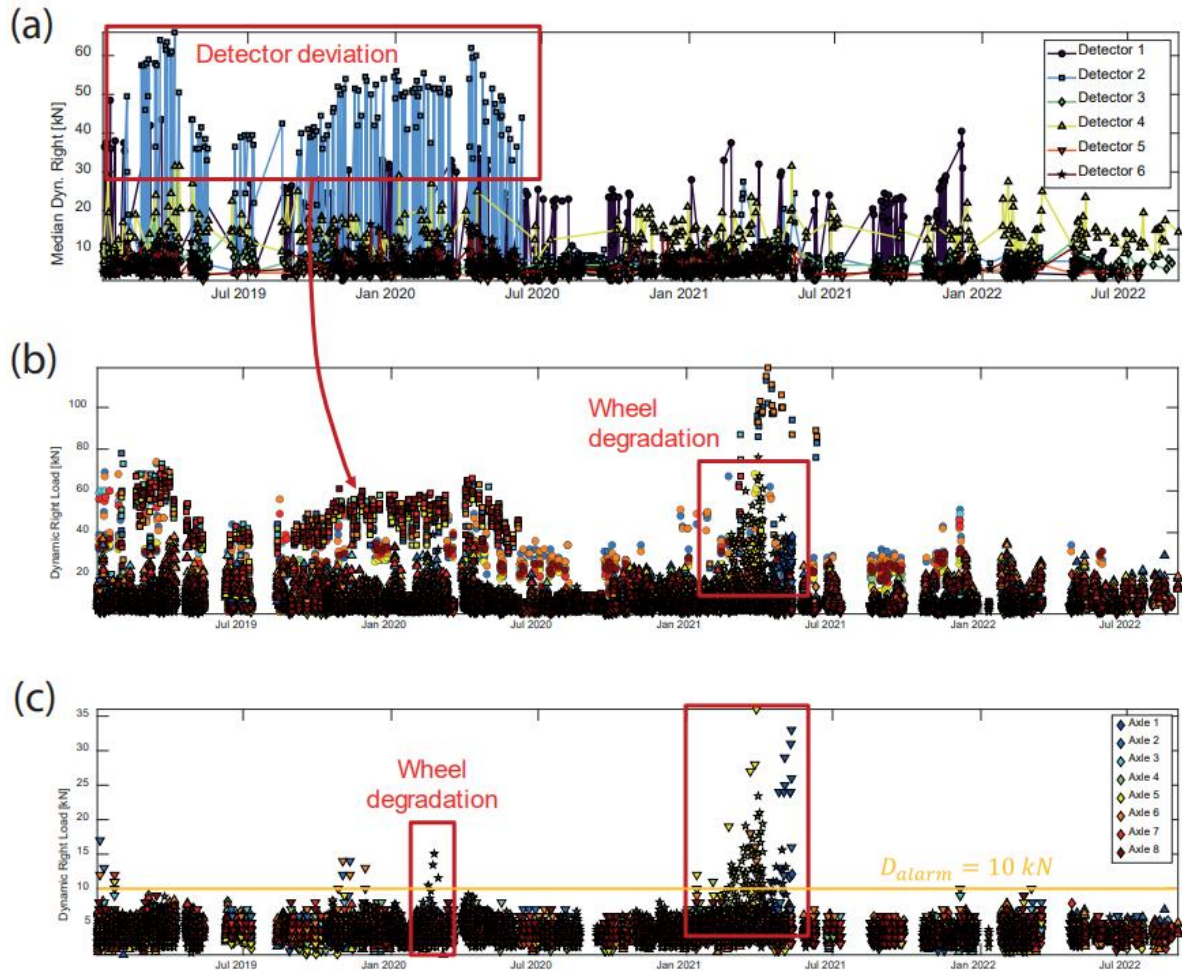


Figure 17. (a) Evolution of the median value of the detectors right side as function of time (b) Evolution of the degradation of the right wheels before rescaling/removal (c) Evolution of the degradation of the right wheels after rescaling/removal

Figure 17 shows that variations in detectors 1 and 2 can mask the early stages of wheel degradation, making defect detection less reliable. After removing and rescaling these detectors, degradation patterns become clearer, enabling the use of lower alarm thresholds with fewer false alarms.

6.4.1.2. Discussions on rescaling procedure

A key question emerging from this pre-study is who should be responsible for selecting the reference detector(s) and performing the rescaling of the data, as well as how often should it be performed. Since the infrastructure managers own and maintain most of the wayside monitoring systems, they should ensure data quality, proper calibration and consistency across the network, while operators depend on the data/information to schedule their maintenance actions. To enable operators to trust and take decision based on the data, each measurement should be followed by standardized quality related

metadata (detector confidence, validity flag). Moreover, because wayside sensors may react differently to different wagon types (due to variations in suspension systems, axle loads, or running behaviour), these differences must also be accounted for when choosing reference detectors and establishing robust rescaling procedures.

In addition, further studies should be made to investigate if the rescaling process adds value to the operator in terms of earlier detection and detecting issues related to other components that were initially missed or not possible to see before rescaling (for instance spring defects, bogie issues or other non-critical issues).

6.4.2. Wheel impact load detectors and regulations

As mentioned in previous section, wheel flats and other forms of wheel out-of-roundness can be detected through measurements of vertical wheel–rail contact force using wheel impact load detectors (WILDs). Condition monitoring based on these force measurements provides operators with essential information regarding the status of their wheel fleet. Commercial wayside WILD systems employ various sensor technologies for indirect measurement of wheel–rail contact forces. These include strain gauge load circuits and fibre-optic sensors for measurements of rail bending, as well as load cells for assessing rail seat loads. Within the Swedish railway network, approximately 30 WILD installations are currently in operation.

Regulations for placement of WILDs were summarised in D29.1, chapter 5 (Kordnejad et al., 2024). For example, Trafikverket specifies permissible limits for track irregularities along the detector section (including gauge, cross level and twist) and the maximum allowable vertical sleeper displacement, which reflects sleeper support conditions and track stiffness. Regular monitoring and rectification of track geometry, together with systematic calibration of the detectors, are key for accurate measurements.

Following post-processing of the recorded signals, WILD systems provide data on the mean and peak loads generated by each passing wheel. The dynamic load contribution and the ratio are also evaluated. The dynamic load is defined as the difference between the peak and mean loads, while the ratio is the peak load divided by the mean load. Peak load values are particularly relevant for operations involving high axle loads to control that the wheels do not induce loads that could damage the track, while the ratio is mainly applied for unloaded wagons to detect wheel damage that could become critical once the wagon is loaded.

To mitigate unacceptable deterioration and prevent safety-related failures, prescribed alarm limits and warning levels are enforced. The UIC recommended alarm limit for peak load mandates an immediate stop of the train if the peak wheel–rail contact force exceeds 350 kN, with an alert level at 280 kN, see D29.1 (Kordnejad et al., 2024). If the alarm limit is exceeded for a passenger coach or freight wagon, the train may proceed at reduced speed to the nearest siding, where the vehicle with the wheel tread damage must be decoupled (Trafikverket, 2024). If the measured peak load, dynamic load, or ratio exceeds

a 'warning' level (but not the peak load 350 kN), the train may continue without regulations to its destination. However, the vehicle cannot resume service until the wheel has been repaired and certified. This regulation applies unless the length of the wheel tread defect exceeds 60 mm.

6.4.2.1. Analysis of Wheel Impact Load Detector data

An assessment of data from six WILDs positioned along the route of the so-called Stålpendeln was described in D29.1 (Kordnejad et al., 2024), see also (Mattsson et al., 2024). All these WILDs were of the same brand and based on load cells for measurement of rail seat load. In total, 823 detector passings by 149 different wheelsets (with at least one of the wheels on the axle being defective) were included in the analysis. For different intervals of wheel flat length, and for loaded and unloaded wagons, the influence of train speed on measured peak loads was investigated. A large scatter in measured loads was observed. Based on these measurements, no evident increase in peak load with increasing train speed for any of the wheel flat length intervals could be found. However, an expected trend indicating higher peak loads with increasing flat length could be distinguished.

There are several potential reasons for the large spread in the data. One reason could be differences in lateral wheel contact position relative to the position of the wheel flat while passing over the different detectors. Other reasons could be related to differences in the position within a sleeper bay where the flat made impact with the rail. Differences in wheelset design, wheel radius and unsprung wheelset mass, as well as variation in track stiffness between different detectors and irregularities in track geometry, are other factors contributing to the scatter in data.

For a given 75 mm wheel flat, all registered loads in the six WILDs along the route of Stålpendeln were studied, see (Mattsson et al., 2024). The data covered the period from when the flat had recently been generated until the wheelset was taken out of service for repair. Two journeys in loaded conditions and three journeys in tare conditions were considered. A large, relatively consistent, variation in measured loads between different detectors during a given journey was observed. This indicates that besides the variation in speed and other influencing variables, the condition of the detectors might have affected the measured loads. The time since calibration, and measurement accuracy, may vary between individual detectors. For one of the detectors, it was found that measured vertical track stiffness was relatively uniform and that the track geometry was within the tolerance limits, see D29.1 (Kordnejad et al., 2024). In another detector, irregularities within the detector area were observed both in terms of track stiffness and track geometry, which could affect the vehicle dynamics while passing through the detector. It is argued that the measured variations in track stiffness and track geometry at the detector sites might have contributed to the scatter in measured peak loads.

6.4.2.2. Numerical simulation of wheel impact load

The 3D geometry of two wheel tread surfaces with wheel flats identified as wheel flat 1 and wheel flat 2, both of which exceeded the regulatory maximum length 60 mm, was scanned using a portable HandySCAN 3D scanner. Each scanned geometry was post-processed in MATLAB to generate a 3D mesh by interpolating the radial deviation from an undamaged wheel tread surface. Wheel flat 1 had a length of approximately 75 mm and a depth of around 1.4 mm. Wheel flat 2 was longer, at 120 mm, but not as deep, measuring 1.2 mm.

For both scanned wheel flats, the influences of axle load, vehicle speed, and the lateral position of the rolling circle (relative to the wheel flat) on wheel–rail impact loads have been simulated using the in-house software WERAN (Maglio et al. 2021). Here, the simulation of vertical dynamic vehicle–track interaction is carried out in the time domain using moving Green’s functions and a convolution integral approach, while the non-linear wheel–rail normal contact is solved using Kalker’s variational method. The input to the simulation software, in terms of measured wheel flats, is illustrated by contour plots in Figure 18.

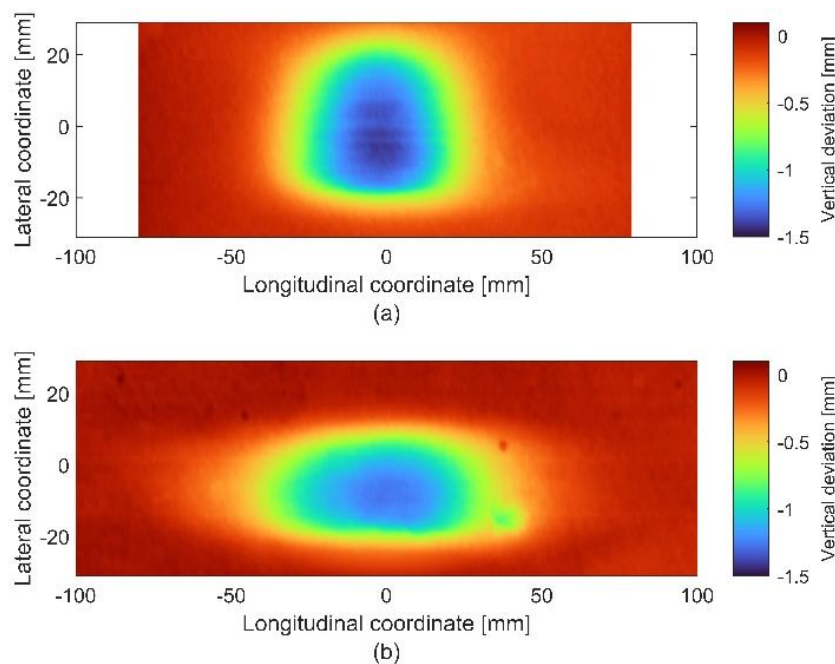


Figure 18. Vertical (radial) deviation from wheel profile for (a) wheel flat 1, and (b) wheel flat 2. The nominal rolling circle (70 mm from flange side of wheel rim) is at lateral coordinate 0 mm. Positive lateral coordinate is towards the wheel flange.

Examples of simulated peak loads, for three different lateral positions of the rolling circle, are presented in Figure 19. It is observed that the peak loads generated by wheel flat 1 are generally significantly higher than those for wheel flat 2. This is because the steeper gradient of the shorter but deeper wheel flat 1 result in a larger variation in vertical wheel centre trajectory, leading to a greater change in momentum after reaching the centre of

the flat. For most studied combinations of axle load and vehicle speed, it is seen that wheel flat 1 generates a momentary loss of wheel–rail contact, as indicated by the filled markers in Figure 19, while wheel flat 2 remains in wheel–rail contact (non-filled markers). It is observed that the influence of axle load on the dynamic load is relatively small for cases with maintained wheel–rail contact. For wheel flat 1, the simulation model, using the given combination of vehicle and track input data, indicates that the alert limit of 280 kN is reached at a speed of 80 km/h in loaded conditions (axle load > 20 tonnes), but not in unloaded conditions at any of the studied speeds. Further, the simulations indicate scatter in dynamic load magnitudes depending on the combination of wheel flat geometry, lateral position of the rolling circle, vehicle speed, and axle load. It is argued that these simulations can improve future regulations on how to handle situations where the alarm limit or alert level have been exceeded.

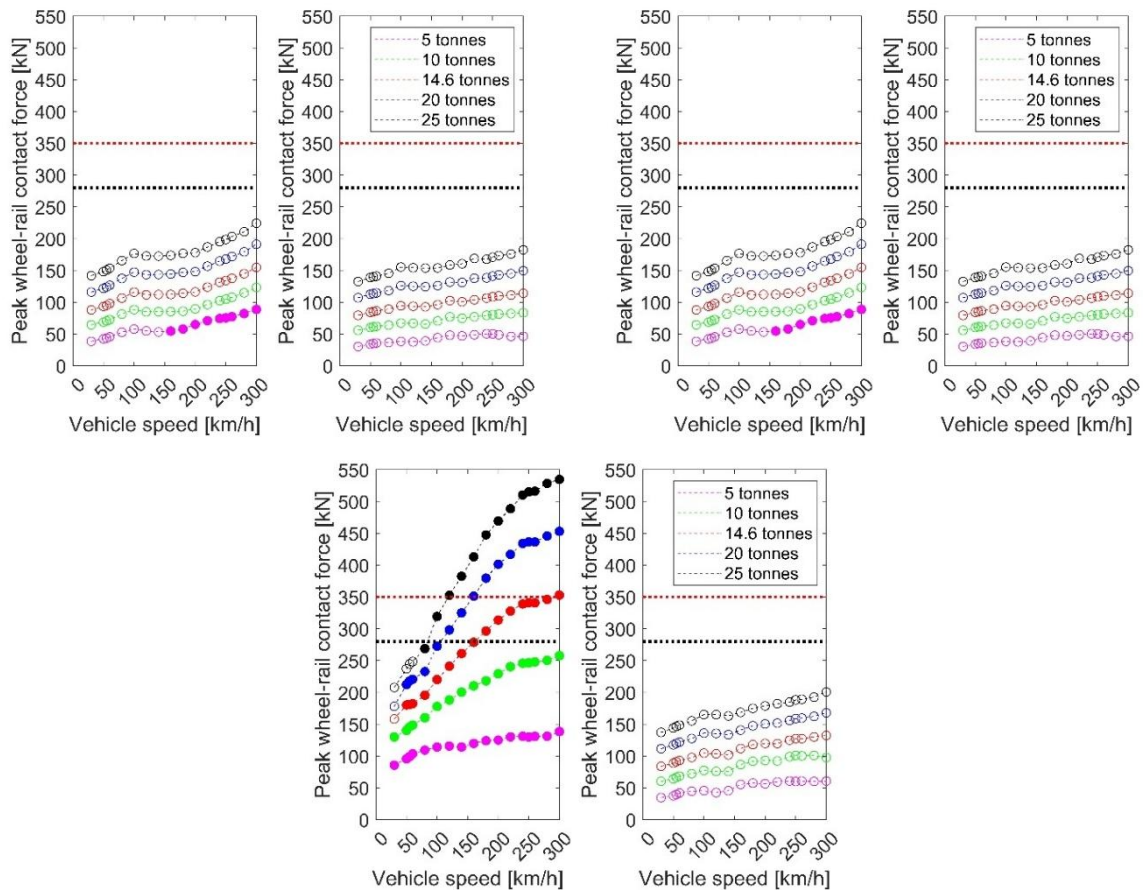


Figure 19. Influence of vehicle speed and axle load on simulated maximum wheel–rail contact force (peak load). Filled markers indicate momentary loss of wheel–rail contact before impact. Lateral position of rolling circle at (a) 90 mm, (b) 80 mm, and (c) 70 mm from the flange side of the wheel rim. In each subfigure, left graph: wheel flat 1, right graph: wheel flat 2. Black horizontal line indicates alert level at 280 kN, while the red horizontal line is the alarm limit at 350 kN.

6.4.2.3. Conclusion of WILD analysis

The critical assessment of WILDs carried out in this work, see also D29.1 (Kordnejad et al., 2024), emphasises that detector data must be reliable and supported by a robust, transparent procedure for calibration and post-processing. Calibration of the mean (quasi-static) load can be performed using passages of axles with known axle loads (typically a fleet of locomotives) at low speed. Calibration of the dynamic load is considerably more challenging, as detector measurements are influenced by factors such as the frequency content of the load, load magnitude, temperature, and other operational conditions. Consequently, calibration should reflect the characteristics of traffic on the line, including axle load, speed, and the proportion of passenger and freight services. In addition, irregularities in track geometry and variations in track stiffness must be systematically monitored and corrected.

In Sweden, regulations mandate the removal or reprofiling of wheels if the wheel flat exceeds 60 mm in length, independent of axle load and train speed. However, the simulation study reveals that the influences of various traffic parameters are considerable. For example, the trajectory of the wheel-rail contact, influenced by the ratio of wheel flat depth to length, is a more critical parameter than the length of the wheel flat. Therefore, it appears more reasonable to base regulations and the removal of out-of-round wheels on measured peak loads than on visual inspection of wheel tread damage and measurement of wheel flat length.

6.4.3. Information related to Hot-box/Hot-wheel

The Hot-Box/Hot-wheels detectors check the condition of the bearing and wheel temperatures of the passing wagons using infrared measurements. The values obtained are usually compared to safety-based predefined static thresholds. The level of this threshold will decide if the train can follow its route or if it should be stopped and go through a detailed inspection.

However, more information could be extracted related to the condition of the bearings and brakes by following the behaviour of the temperature's variation over time. The natural way to re-organize the data is to split in multiple data sets based on the wagon RFID number and ordered with the timestamps and axle number to track individual wheelsets (Figure 20).

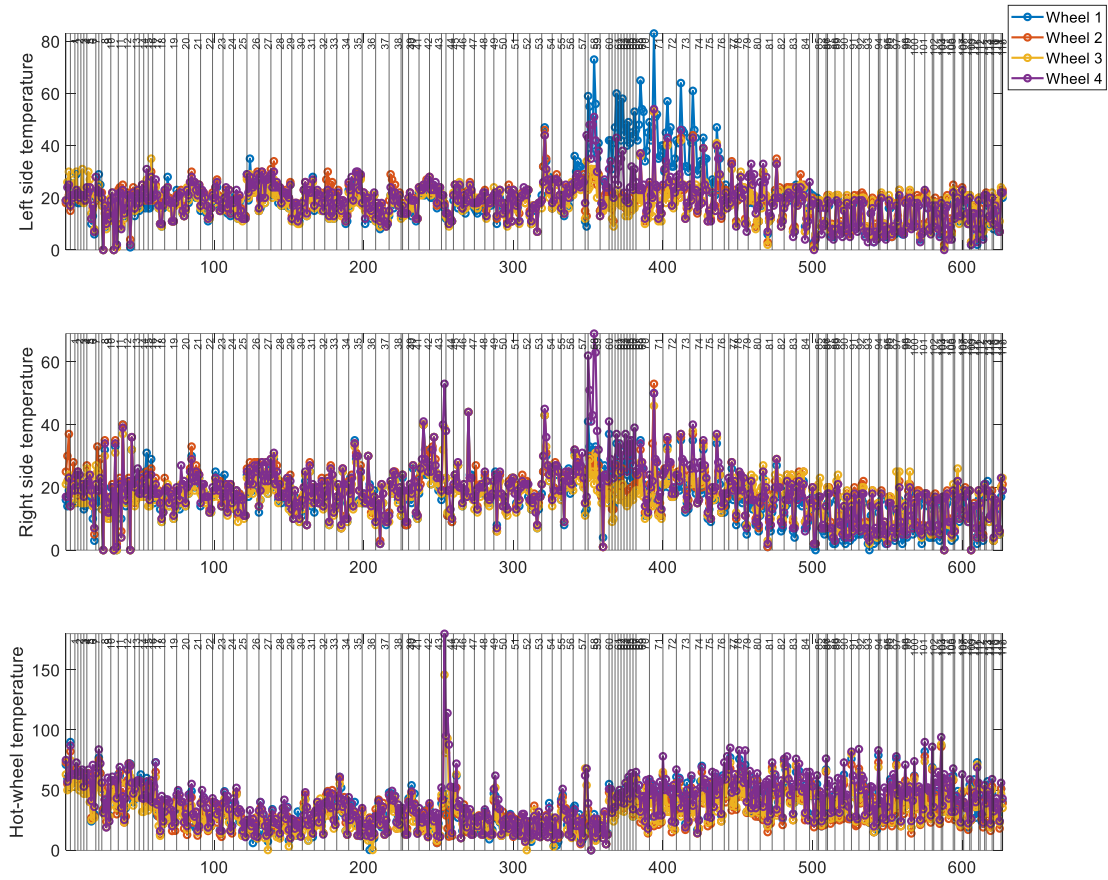


Figure 20. Evolution of bearing and wheel temperatures as function of detector passage

It would be valuable to develop further automatic methods for detecting bearing anomalies. Rather than relying on fixed temperature limits, features that reflect how each bearing temperature evolves relative to the wagon or train average can help reduce environmental influence inherent to Hot-Box detectors. A feature that can be extracted is the K-value, which is calculated by comparing a bearing's temperature with the quantiles of temperatures from bearings on the same side of the train:

$$K_b = \frac{(T_b - Q2_t)}{(Q3_t - Q1_t)}$$

Where T_b is the temperature of the bearing, $Q1_t$, $Q2_t$ and $Q3_t$ are the 1st quantile, median value and 3rd quantile of all the bearing on the same side of the train respectively.

A K-Value above 3 may indicate a Bearing-of-Interest, as shown in Figure 21 where an abnormal rise of the K-Value could highlight a potential issue requiring attention from the operators or maintenance teams (but not necessarily). For instance, Figure 21, the K-value of the right-side increases during 2-3 detector passages. After checking Figure 20, it can be observed that the wheel temperature increased as well, a classic case of wheel

radiation influencing the bearing temperature. Hence the root-cause in this case could be a stuck brake on the wheel. A second anomaly appears on both the left and right side of wheel number 4 after 350 passages. The reason for this anomaly is unknown but quite common when looking at larger datasets. Finally, the anomaly of interest is the one appearing between 350 to 450 passages, where only one side of the wagon's wheel number 1 shows deviations for a long period of time. However, like the previous anomaly, it is almost impossible to understand what root-cause produce this change of behaviour.

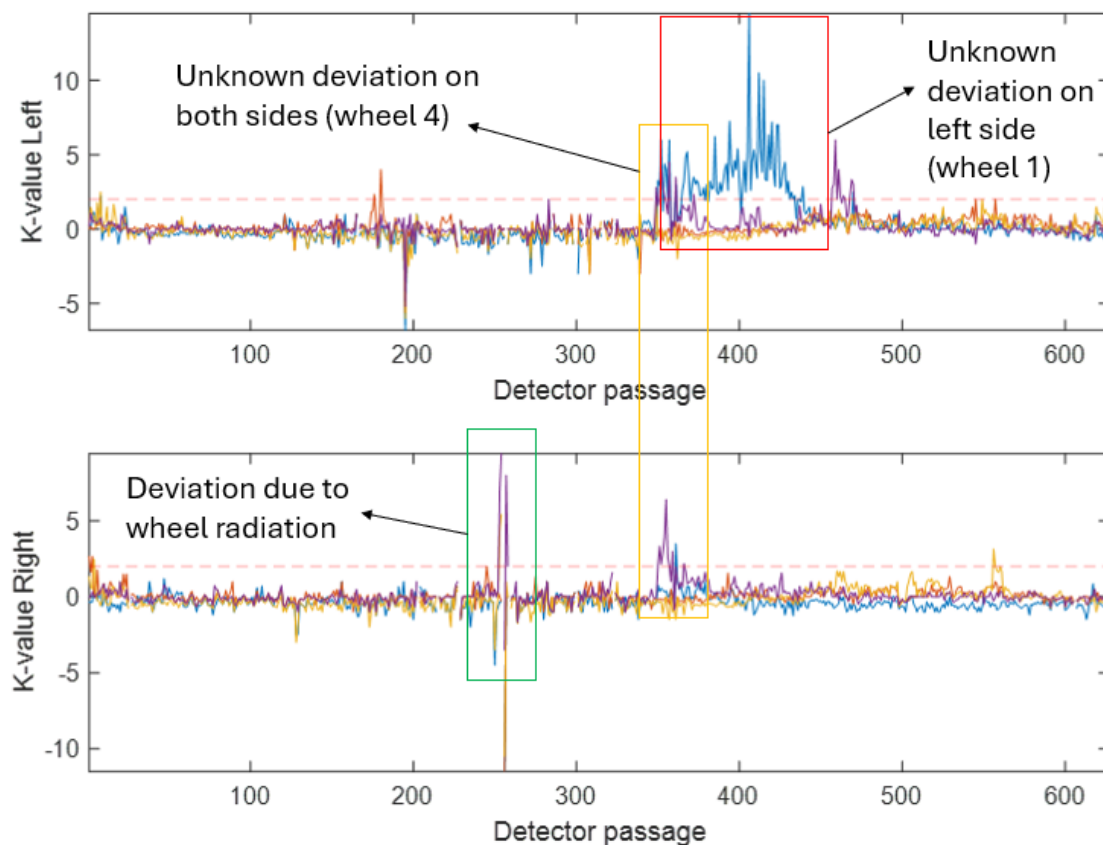


Figure 21. K-Value of the wagon bearing as function of the detector passage

Despite the possible usefulness of K-values, several limitations should be addressed. Low temperature variation during colder days could artificially inflate the K-Values, suggesting a possible need for scaling with temperature range. In addition, since wagons differ in types and load, comparison should be made with similar wagon categories. Finally, K-values alone cannot capture temperature gradients over a travel day, so complementary analysis and additional features are required to distinguish between different anomaly types.

Moreover, K-values do not identify root causes of the occurrence of anomalies (except for the case of wheel radiation on the bearings), making correlation with other detection systems, such as hot-wheel, WILD, or acoustic detectors, important. In the short term, anomalies detected by HB/HW systems could support Intelligent Video Gates through

shared diagnostic information, while in the long term, hot-box detector data could contribute to a bearing life-status index that enables earlier maintenance interventions or adjustments.

6.4.4. Connection to Intelligent Video Gates

While classical wayside monitoring systems (WILD, HB/HW, Bearing Acoustic Monitoring) provide a quantitative and sensor-based condition information, they often operate independently with heterogeneous calibration and data formats. Intelligent Video Gates can complement these systems by providing information on potential failure modes based on high-resolution images.

When lower warning levels are introduced, the IVGs become valuable as a verification step. Subtle degradations detected through rescaled WILD data (like mild wheel-flats, debris on wheel tread, spring and bogies anomalies) may not need immediately workshop intervention, but they can be validated when the wagon passes through an Intelligent Video Gate. This visual confirmation reduces unnecessary alarms and ensures that potentially emerging faults are monitored both in a quantitative way and with visual evidence.

One of the issues of the anomalies with temperature signatures from the hot-box is knowing the root-cause of the deviation from the K-values since the bearing is a closed system. In that context, IVGs could potentially deliver additional and important validation mechanism. Even though it could be tedious to relate the thermal anomalies with all failure modes from automated visual inspection, the K-values could be combined with IVG images to identify and correlate abnormalities. For instance, oil or grease leakage from the axle-box, discoloured bearing house, missing or loose axle-box cover, wheel overheating due to stuck brake-pads or missing brake shoes are example of anomalies that could be observed and merged with wayside data. In that case, the IVGs would work as an automatic labeller and could help develop better model for anomaly detection in a more supervised manner.

Overall, integrating Intelligent Video Gates with classical wayside monitoring systems would enable a multi-modal and cross-checked condition monitoring approach. Harmonized WMS data provides a quantitative check of emerging degradation, while IVGs could give visual confirmation that helps distinguish true mechanical issues from detector issues and artefacts.

However, the current gates in Sweden are not equipped with cameras that focuses on wheelsets or bogie defects, which mean that the integration of the wayside data and IVG in this context need further deployment and specific use-cases that combine both datasets in future studies.

7. Conclusions

The purpose of the tests presented in this deliverable has been to assess the performance, reliability, integration, and interoperability of the Railway Checkpoints in Sweden related to test case “Rolling stock and ILU identification”. Two strategic locations have been decided for the installation of gates, namely the main gateways to and from Sweden i.e. the Port of Gothenburg, Scandinavia's biggest port, and in Malmö in vicinity of the Öresund's bridge, connecting Sweden with the European continent.

The tests were carried out in a comprehensive manner regarding the image analysis for the gate in Gothenburg. The evaluation of the image analysis indicated that Indra's system does not yet fulfil the requirement of correctly extracting 95 % of the wagon numbers (EVN), the ILU codes, and the UN numbers and Hitachi's system does not fulfil the requirement of correctly extracting 95 % of the wagon numbers (EVN). The ability of Hitachi's system to extract ILU codes and UN numbers has not been evaluated, due to lack of data. Although the results of the comparison are satisfactory on certain detection aspects, further work is needed and currently ongoing in improving the algorithms for image analysis as more images are produced from the installed gates.

The gate in Malmö was deployed late March 2026. After that a training period for the gate was launched to train the system to identify all types of EVN, ILU and UN-numbers. At this stage, the system should be considered operational but not yet fully optimized. Iterative improvements are currently being implemented based on the data collected at the installation, focusing on fine-tuning the detection models and system calibration to progressively enhance accuracy and ensure the results meet the highest reliability standards.

RFID readings of wagon numbers are available for both gates but not yet fully matched with the results of the image analysis. This report has also identified paths for exchange and integration of the data retrieved from the checkpoints with Trafikverket's data infrastructure and with classical wayside monitoring systems in Sweden. Wheel Impact Load Detectors (WILDs) provide valuable information for monitoring wheel condition, but their accuracy depends on proper calibration, consistent track geometry, and robust data processing. The study shows that using WILD systems for condition monitoring instead of just automated inspections, together with good detector quality and proper data rescaling, could potentially help identify wheel problems earlier and detect more hidden defects.

The demonstrator definitions and deployment strategies presented in this report will be implemented and evaluated in the next step within *Task 29.2: Demonstration and evaluation of the installed checkpoints*. The demonstrators shall consider the activities listed in the subtasks of task 29.1. Moreover, the definitions will also be an input for WP33, Task 33.5: Showcase of Standardised European Railway Checkpoints.

8. References

- Hildebrandt, F., Deiterding, L., Walker, T., Pelegrin, M., Mendizabal Roche, A., Bueso, M., ... Bryne, B. (2024). *Deliverable 25.1 Report on the basic functional and technical specifications for the realisation of the technical enablers of Seamless Freight, also including the final specification input for FP1*. FP5-TRANS4M-R, Europe's Rail. https://rail-research.europa.eu/wp-content/uploads/2025/03/FP5-TRANS4M-R_D29.1_V3.pdf
- Kordnejad B., Nordmark I., Åkerfeldt M., Bueso M., Mendizábal A., Pelegrin M., Adin I., Losada M., Nielsen J., Klein C., Sengle E., Böhmer L-B., Klass M., Wohlrath R., Vinh-Le T., Neumann T, Salvitti G., Lengu R, Parrilla Ayuso F., de la Iglesia Sánchez R., Díaz Díaz A, Giménez Gómez J., Thiery F., Pum T., Yedema B., Koolstra E., Huergo A., Kjellin M., Tijink M. (2024). *D29.1 Technical definition of the standard IVG for checkpoints and related demonstrators*. FP5-TRANS4M-R, Europe's Rail. https://rail-research.europa.eu/wp-content/uploads/2025/03/FP5-TRANS4M-R_D29.1_V3.pdf
- Kordnejad, B., Åkerfeldt, M., Aronsson, M., Barbi, C. E., Diotallevi, C., Gotelli, G., Garcés Mencía, H., Irala Briones, A., Ivansson, G., Karl, J., Kjellin, M., Merle Carrera, L., Lengu, R., Posseger, E., Treiber, A. (2018), *D4.1 Description of functional and technical requirements and selection of components*, WP4: Intelligent Video Gate, FR8HUB, Shift2Rail. <https://projects.shift2rail.org/download.aspx?id=187175bd-bd44-4927-a5bc-ff43e463c573>
- Kordnejad, B., Åkerfeldt, M., Aronsson, M., Barbi, C. E., Diotallevi, C., Garcés Mencía, H., Gotelli, G., Irala Briones, A., Ivansson, G., Karl, J., Kjellin, M., Lengu, R., Merle Carrera, L., Mitrovic, B., Nordmark, I. (2019), *D4.2 Technical Proof of Concept and Roll-out and Implementation Plan*, WP4: Intelligent Video Gate, FR8HUB, Shift2Rail. <https://projects.shift2rail.org/download.aspx?id=04378f41-67fb-400f-beda-c33a2118fd8e>
- Kordnejad, B., Åkerfeldt, M., Aronsson, M., Gotelli, G., Irala Briones, A., Ivansson, G., Kjellin, M., Lengu, R., Merle Carrera, L., Müllerschön, J., Naranjo, A., Nordmark, I., Römer, H., Wießner, S., Wohlrath, R. (2020), *Deliverable D 3.1, Requirements definition and IVG preliminary installation report*, WP3: Intelligent Video Gate, FR8RAIL III, Shift2Rail
- Kordnejad, B., Åkerfeldt, M., Aronsson, M., Irala Briones, A., Ivansson, G., Kjellin, M., Lengu, R., Merle Carrera, L., Nordmark, I., Olsson, E., Wohlrath, R. (2021), *Deliverable D 3.2, Description of demonstrator – Intelligent Video Gate*, WP3: Intelligent Video Gate, FR8RAIL III, Shift2Rail

Kordnejad, B., Åkerfeldt, M., Aronsson, M., Ivansson, G., Kjellin, M., Lengu, R., Nordmark, I., Rius García, G., Salvitti, G., Vilabella, S., Wohlrath, R. (2022), *Deliverable D 3.3, Demonstration and Evaluation including Best Usage of the Data Capture*, WP3: Intelligent Video Gate, FR8RAIL III, Shift2Rail.

<https://projects.shift2rail.org/download.aspx?id=30189e17-a257-4085-9d12-1a39d656d0fc>

Maglio, M., Lagata, N., Mattsson, K., Nielsen, J.C.O., Vernersson, T. (2025). *Wheel-rail impact loads induced by wheel flats – Simulation model using data from 3D laser-scanned wheel tread defects*. Proceedings of the 29th IAVSD International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD2025), Shanghai (China) August 2025, 10 pp

Maglio, M., Pieringer, A., Nielsen, J.C.O., Vernersson, T. (2021). *Wheel-rail impact loads and axle bending stress simulated for generic distributions and shapes of discrete wheel tread damage*. Journal of Sound and Vibration, doi.org/10.1016/j.jsv.2021.116085

Mattsson, K., Nielsen, J.C.O., Fehrlund, L., Maglio, M., Vernersson, T. (2024). *On wayside detector measurement of wheel-rail impact loads induced by wheel flats – Data analysis, alarm levels and regulations*. In J. Pombo (Editor), Proceedings of the 6th International Conference on Railway Technology: Research, Development and Maintenance, Civil-Comp Press, Edinburgh, UK, Online volume: CCC 7, Paper 7.10, 2024, doi:10.4203/ccc.7.7.10

Trafikverket (2025). *Detektorkartan_2.0_UHtö*,
https://bransch.trafikverket.se/contentassets/aa399d15a6d94be48023a6efc62b1aea/trafikverkets_detektorsystem_uhtto_250908.pdf, 2025-09-08

Trafikverket (2024). *Detektorer. Hantering av larm samt åtgärder efter konstaterade skador* (Detectors. Handling of alarms and measures following ascertained damages, in Swedish). TDOK 2020:0074 v3.0