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IN SOLID AND STRUCTURAL MECHANICS

Influence of foreign objects on derailment risks in railway switches

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Cover: Foreign object (aluminium spacer) placed between the stock and switch rail in field measurements.

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To Mom & Dad, Sumukh & Prakruthi and Priyanka

Abstract

Railway switches are essential for ensuring efficient train operations, and efforts to improve their safety standards have driven the introduction of so-called switch rail control contact (TKK in Swedish) sensors in Sweden. These sensors monitor the gap between the switch and stock rail, complementing the function of the drives. Such gaps can be a result of undetected foreign objects such as ballast stones or ice, that are stuck between the switch and stock rail. According to statistics from the Swedish Transport Administration (Trafikverket), faults in TKKs due to component failure, snow and foreign object interference, account for a substantial portion of the total faults occurring in switches for a year. This results in increased maintenance and operational costs. Therefore, the aim of the thesis is to evaluate the necessity of these sensors by performing simulations of switch operations and derailment risk to provide input to a technical risk analysis of derailments in switches.

For assessing the derailment risk in scenarios of interfering foreign object, field measurements, finite element (FE) and multibody simulations (MBS) are carried out. Two physical measurement campaigns were performed to obtain the deformation pattern of the switch rail in the presence of a foreign object. These measurements are used to validate the numerical models.

The validated FE model of a switch is employed to perform parametric studies on the influence of foreign object size and position on switching operations. The purpose is to identify in which cases foreign objects can be detected by the drives and when additional switch rail position sensors are needed to ensure that all objects leading to excessive gauge narrowing are detected. Results indicate that TKKs are necessary to detect all cases of gauge narrowing above 15 mm in the current switch design.

The dynamic vehicle–switch interaction with an interfering foreign object is modeled using non-linear flextrack module in MBS software Simpack. The results of the simulations indicate that the risk of derailment is low when the foreign object is modeled with a failure criterion resembling ballast stone crushing. When infinitely strong objects are stuck, the chances of wheel flange climbing are high. Ballast stones seem to not pose a derailment risk if caught between rails as they are crushed by high lateral forces.

Keywords: Railway switch, derailment, finite element method, field measurements, multibody simulations, foreign object modelling, condition monitoring

List of Publications

This thesis includes the following publications

Paper A
S. Bysani, B. Pålsson, E. Kabo, and B. Paulsson, "The influence of trapped foreign objects on railway switch control investigated by simulations and field tests", To be submitted for international publication.

Paper B
S. Bysani, B. Pålsson and E. Kabo, "Multibody simulation of derailment risk in railway switches due to gauge narrowing caused by foreign objects", To be submitted for international publication.

The appended papers were prepared in collaboration with the co-authors. The author of this thesis was responsible for the major progress of the work including taking part in the planning of the papers, developing the methodologies, developing numerical models, data processing, field measurements and writing the papers.

Other publications by the author

S. Bysani and B. Pålsson, "Multibody simulation of derailment risk in railway switches due to switch rail irregularities caused by foreign objects", Proceedings of the 28th Symposium of the International Association of Vehicle System Dynamics, IAVSD, Ottawa, Canada, 2023.

S. Bysani, B. Pålsson, E. Kabo, and B. Paulsson, "Investigating the impact of foreign objects on railway switch control: numerical simulations and field measurements", in J. Pombo, (Editor), Proceedings of the Sixth International Conference on Railway Technology: Research, Development and Maintenance, Civil-Comp Press, Edinburgh, UK, Online volume: CCC 7, Paper 6.14, 2024.

Preface and Acknowledgments

The work presented in this thesis was accomplished between June 2022 and October 2024 at the Division of Dynamics, Department of Mechanics and Maritime Sciences, Chalmers University of Technology. It was performed as part of the activities within the National Centre of Excellence in Railway Mechanics CHARMEC (CHAlmers Railway MEChanics) within the project TS24 – "Technical risk analysis of derailments in railway switches". The project is being funded by Trafikverket (Swedish Transport Administration) under contract number 2021/53614. The project has been supported by CHARMEC's industrial partners. Special thanks to the resources provided by the National Academic Infrastructure for Computing (SNIC) at C3SE partially funded by the Swedish Research Council through grant agreements nos. 2022-06725 and 2018-05973.

I would like to express my heartfelt gratitude to my main supervisor, Docent Björn Pålsson, for his unwavering support, guidance, and boundless enthusiasm for Switches and Crossings. A special thanks to my co-supervisors, Prof. Elena Kabo and Mr. Björn Paulsson. Elena, your meticulous attention to detail in refining my manuscripts has greatly enhanced the quality of my work. Björn, your relentless energy and passion, especially in advocating for the removal of TKKs, has been truly inspiring. I am also sincerely grateful to my examiner, Prof. Anders Ekberg, for steering this project in the right direction and for his insightful guidance.

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Abbreviations

TKK:	Tungkontrollkontakt [Eng:Switch rail control contact]
S&C:	Switches and Crossings
FE:	Finite element
MBS:	Multibody simulations

Contents

Part I

Extended summary

CHAPTER 1

Introduction

1.1 Background

Switches and Crossings (S&Cs) are integral components in the complex railway network. They are essential as they provide flexibility to guide trains to different routes [1], [2]. They are also critical as the parts required for actuation make switches more prone to faults compared to other components in the system [3]. Unreliable switch performance will impact the functioning of the entire rail network [4].

One of the common forms of disruptions for switch operations is when foreign objects, snow or ice get trapped between switch rail and stock rail [5]. These objects prevent the switch from being in control and hence will stop train operations [5], [6]. By being in control it is meant that the drives and any additional sensors report to the signaling system that the switch rail is positioned within tolerances and that traffic can pass.

An example of a ballast stone getting stuck in between the switch and stock rail and preventing the switch from going into control occurred in Hamra, Sweden in 2010, as seen in Figure 1.1a [5]. Traffic was allowed at reduced speed, but the driver failed to spot that a ballast stone had created gap at the tip of the switch rail which lead to wheel flange penetration and a partial derailment, see Figure 1.1b. Hence, foreign objects can cause severe consequences if undetected.

(a) Ballast stone on a sliding chair leading to gap between switch and stock rail

(b) Flange penetration between switch and stock rail due to ballast stone

Figure 1.1: Pictures from an incident which occurred in Hamra, Sweden in 2010 where a ballast stone prevented the completion of the switching operation [5]. Pictures are provided by Trafikverket (Swedish Transport Administration)

1.2 Switch design and operation

A UIC60-760-1:15 right-hand S&C has been used for the analyses in the present thesis and an illustration of it can be seen in Figure 1.2. This switch design is common in Sweden and has 60 kg rails and a constant 760 metre radius curve in the diverging route. Green rails indicate the through route, while blue rails indicate the diverging route. The switch rails are connected together by links at three locations along the length of the switch rail as seen in Figure 1.2. The links not only enhance the bending stiffness of the switch rails by connecting them in parallel, but also ensure that a fixed distance between the rails is maintained. The switch rails are supported by a sleeper-mounted slide chair and rollers, ensuring smooth operation.

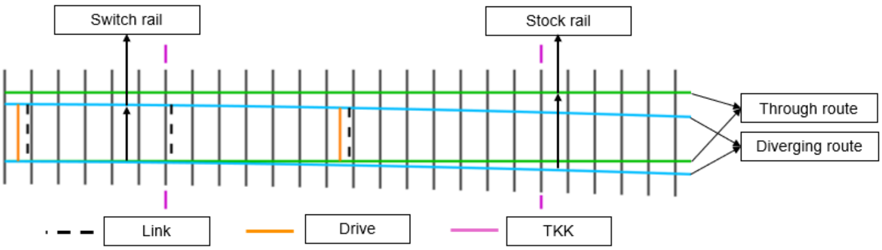


Figure 1.2: Schematic top view of the studied switch panel

Two drives exert a nominal force of up to 6 kN to actuate the switch rails, thus performing the switching operation [7], [8]. The number of links and drives vary depending on the radius of the diverging route and thus the length of the switch panel. To ensure that the switch rails are in the correct positions, the gap between the switch and stock rail is monitored at the drives and at four other locations using so-called TKK sensors as seen in Figure 1.2 and in Figure 1.3. TKK is a Swedish abbreviation for 'switch rail control contact sensors' [6], [9], [10]. Approximately 3500-4000 switches in Sweden are equipped with TKKs. Longer switches are often equipped with four TKKs while shorter ones are equipped with two TKKs, giving in total 12531 TKKs in track [5].

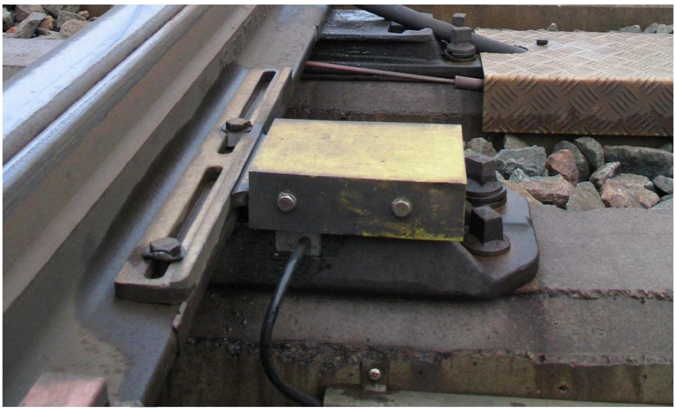


Figure 1.3: TKK sensor in track [11]

Drives and TKKs are connected to the central signalling system. During a switching operation, if any component fails to relay back a positive ‘in control’ signal, it will halt the operation and no train will be allowed to pass through the switch until the issue has been cleared. According to Swedish regulations [8], for a drive to be in control the gap between the switch and stock rail at the drive should be less than the tolerance limit of 3 to 5 mm. During inspections the drive must be in control for a 3 mm gap and not be in control for a 5 mm gap. In this thesis, the upper tolerance limit of 5 mm is considered. Similarly, for the TKK to be in control the gap between the switch and stock rail at the position of the TKK should be less than 10 to 13 mm [8]. During inspections the TKK must be in control for a 10 mm gap and not be in control for a 13 mm gap. The upper tolerance limit of 13 mm is considered in this thesis. According to [12], a rail gauge reduction of 15 mm is considered to be safe, as it could lead to a hard flange contact but should not pose a risk of derailment. Hence the main function of the TKK is to detect cases of gauge narrowing above 15 mm, thereby reducing the risk of any types of derailments. This is ensured by allowing the gauge reduction at the TKK sensors to be 13 mm as will be demonstrated in **Paper A**.

1.3 Aim of research and methodology

To obtain an overview of the reasons for switches not being in control, data from Trafikverket’s log for railway infrastructure faults (ofelia) was analyzed for the full year of 2017. In total there were 8597 faults related to S&Cs. By searching for keywords such as “switch not in control” and “switch not going into position” etc. in the error description, 4853 faults were found. Given that the identification stems from free-text searches the identification accuracy is not perfect, but inspecting samples of the identified issues and the remaining issues, it was concluded that most of the not-in-control cases had been identified. It can thus be noted that a bit more than half of S&C faults are related to not-in-control switches.

Studying the associated reported causes for not in control switches, no root cause was found in 35% of the cases, and the action taken here is typically lubrication, adjustment or just inspection. In 35% of the cases faults were related to component failure, malfunction or wrong setting and following repair or adjustment. Out of these 1711 faults, 201 are associated with TKKs. In

20% of the cases the problem was snow or ice and in 5% of the cases it was a foreign object. 5% are faults that are not easily associated with the other categories, such as damage from maintenance equipment, thunder storms etc.

Studying the snow and ice and foreign object categories together, it was found that in 94% of the cases with these causes, the action taken was clearance, snow clearance or cleaning, confirming that there were actual materials in the way preventing the switch from going in control. For the foreign object category, the type of object is sometimes mentioned, and ballast stones is by far the most common type. There are also instances of wood, animals, tarps etc as well as metal objects such as switch heating elements that have come lose. A breakdown of the fault categories can be seen in Figure 1.4.

As the system does not register if a not-in-control case was caused by the drives or the TKKs, it is not possible to determine how many of the 1188 cases of snow, ice and foreign objects that were triggered by a TKK. It is however reasonable to assume that the TKK contributes to a significant part as it is required to detect interfering objects along large parts of the switch rails as shown in **Paper A**. Together with the faults in the TKK sensors themselves, it is estimated that TKKs contribute to 500 to 1000 not-in-control cases per year. If it can be demonstrated that these types of interruptions do not pose a derailment risk, TKKs could potentially be omitted from the switch control system. This would not only reduce the overall number of control errors in switches, but also lower maintenance and operational costs.

Hence, the objective of this thesis is to better understand the derailment risks associated with trapped foreign objects and thus to what extent the TKK sensors are required to ensure safety. In order to achieve the intended objective, two studies were performed to provide input for technical risk assessment of derailments in railway switches: FE analyses of switch rail deformation (**Paper A**) and MBS analyses to predict dynamic vehicle-switch interaction (**Paper B**).

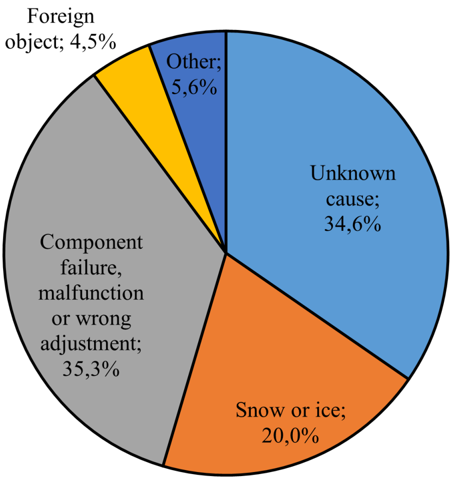


Figure 1.4: Categorization of faults associated with control of switches

These studies have provided the following outcomes:

- A method to evaluate the control condition of the switch panel subjected to a foreign object of varying size placed at different positions along the switch (**Paper A**).
- The influence of foreign objects on switch rail control and the marginal benefit provided by the TKK have been investigated by the means of a FE model and field measurements (**Paper A**).
- A method to estimate the derailment risk in terms of wheel lift associated with foreign object interaction in switches is developed (**Paper B**).
- The derailment risks in railway switches due to foreign object interference for different object types and traffic conditions have been evaluated using multibody simulations (**Paper B**).

The results are based on novel model developments in the form of

- An FE model including both switch rails and investigating the influence of links (**Paper A**).

- An advanced MBS model capable of accounting for the switch rail flexibility and its interaction with the rest of the switch panel (slide chairs, stock rails and drives) in dynamic vehicle–switch simulations (**Paper B**).

In the following, this extended summary will first present common background for the two papers in the form of field measurements and foreign object modeling before presenting the models, methods and main results from the appended papers.

CHAPTER 2

Field measurements

Two field measurements were carried out on UIC60-760-1:15 S&Cs in Vätteryd and Ängelhom, Sweden, in September of 2022 and October of 2023, respectively [3]. The objective of these tests was to obtain measurements of switch rail deformation under interference from foreign objects in order to validate numerical models that are developed in **Paper A** and **Paper B**.

The test setup is as seen in Figure 2.1 and consists of an aluminum spacer placed at the foot of the switch rail. The test methodology consists of taking initial vertical and horizontal gap measurements at five locations along the switch rail without the aluminium spacer. In the next step, the switch is opened up to place the aluminum spacer at the foot of the switch rail and the drives are then actuated to push the switch rail against the stock rail. Final vertical and horizontal gaps between the switch and stock rail, are recorded at five locations along the switch rail. Example test results of the deformed switch rail shape for an object placed at the TKK location between the two drives can be seen in Figure 2.2. More details about the field measurements are given in **Paper A**.

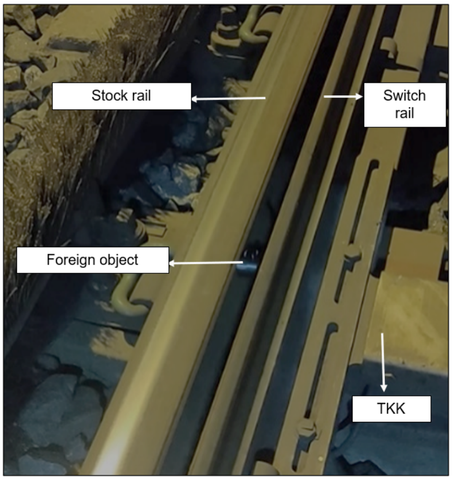


Figure 2.1: Field measurements with foreign object (aluminium spacer) placed between the stock and switch rail

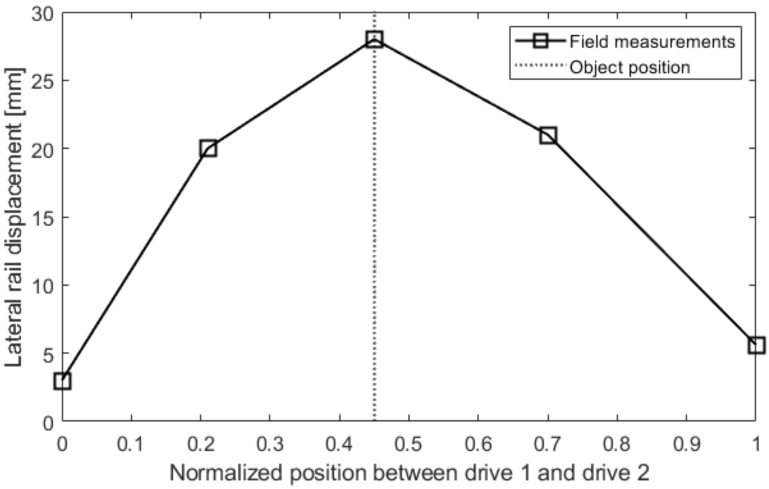


Figure 2.2: Lateral rail displacement measurements from tests, with the aluminum spacer placed at the foot of the switch and longitudinal position of 0.45. Positions along the switch rail are normalized against total distance between the drives.

CHAPTER 3

Foreign object characteristics and modelling

Ballast stones, ice and snow are the most common types of foreign objects that get stuck between the switch and stock rail [5]. In some occasions, metal objects from the train or other sources also find their way into the switch and act as foreign objects [5]. Ballast stones and metal objects are the strongest discrete objects that can get trapped and will therefore be the focus of this thesis as they are the type of objects where the TKK sensor can make the greatest difference. Snow and ice are more likely to build up evenly along the switch and therefore more likely to cause control problems for drives and TKKs simultaneously. Ice falling from passing trains could potentially cause local concentrations of ice where the crushing strength is more difficult to assess and where TKKs might be needed for detection, but this is not investigated in the present thesis.

Ice and ballast stone exhibit the same type of behaviour, as they both get crushed once a certain force is applied [13]. Therefore, the scenario involving ballast stones should be representative of the scenario with single ice objects as the stones are stronger. Tests on the crushing of ballast stones and comparison to FE simulations were performed in [14] and [15]. For crushing tests in [15] Class-I ballast stones of granite with an average size of approximately 35.7

mm were used. Based on the force versus displacement curves in [14] and [15], it was observed that the maximum force a ballast stone could withstand ranged from approximately 35 kN to 45 kN.

In **Paper A**, the foreign object is modeled as rigid to correspond to the stiff cylindrical aluminum spacer used to maintain a prescribed deformation in the field tests.

In **Paper B**, two types of discrete foreign objects with different energy absorption levels are modelled:

- Linear variation: An infinitely strong foreign object is represented as a spring with a lateral stiffness of 40 kN/mm as depicted in Figure 3.1. It is representative of a case where the object does not break under the applied forces.

- Ballast stone case: The foreign object is modelled as breaking at an applied force of 40 kN, see Figure 3.1. This scenario is representative of an actual ballast stone crushing or disintegrating as a result of the applied force.

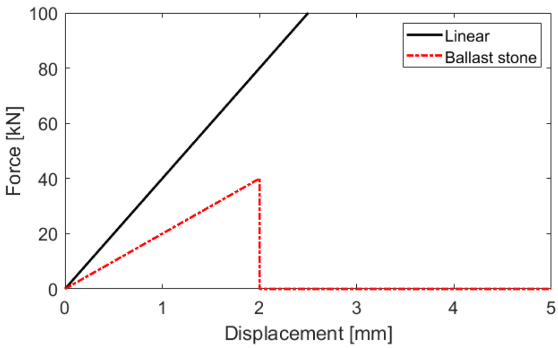


Figure 3.1: Force–displacement relationship for linear and ballast stone object formulations

In simulations, foreign object size is described by their effective object size. It is the local gauge narrowing it induces at the top of the switch rail when placed at the foot of the switch rail. If switch rail rotation is neglected, then the effective object size is equal to the induced gauge narrowing.

CHAPTER 4

Switch control in the presence of foreign object - Paper A

4.1 Model description

To investigate the influence of foreign objects on switch rail control, a numerical model was developed in a commercial FE software ABAQUS [16]. The FE model includes both switch rails, their connecting links and switch rail contact surfaces, see Figure 4.1. Only parts of the stock rail that may be in contact with the switch rail are modelled and are denoted as stock rail support structures.

The links consist of long cylindrical bars connected to the switch rails with pivoting bolt connections. In the model they are simplified into linear springs with stiffness of 1.5 kN/mm to reduce computational resources. The drive forces of 6 kN are applied as point forces acting in the lateral direction at the foot of the switch rail. A trapped foreign object is modelled as a prescribed displacement in the lateral direction at the foot of the switch rail.

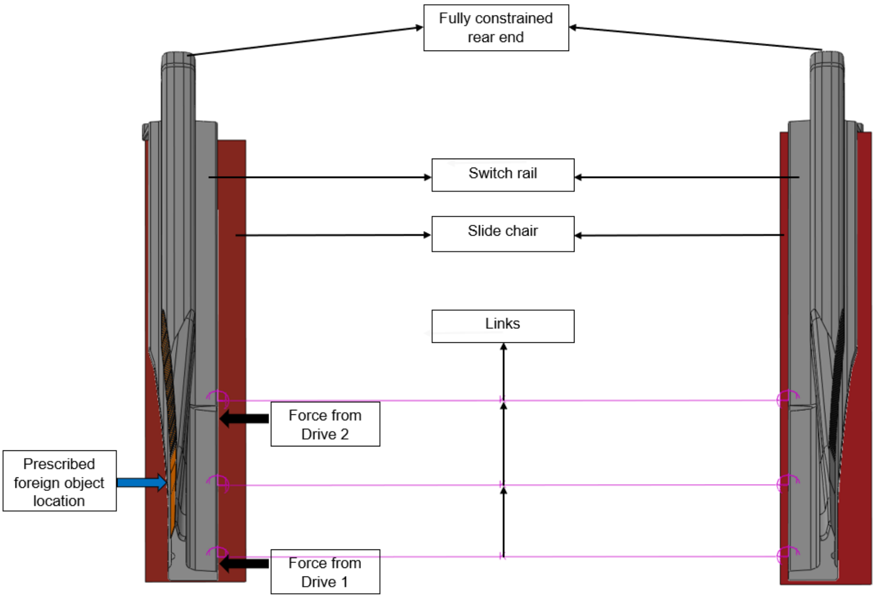
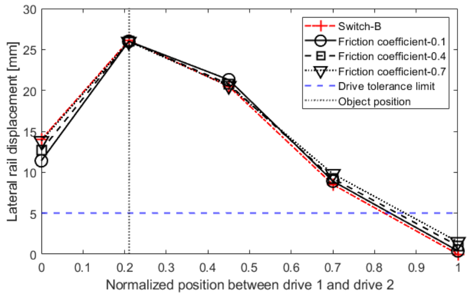


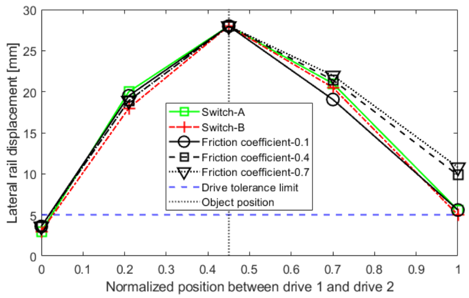
Figure 4.1: FE model of the simulated switch rails with three connecting links.

4.2 Model calibration

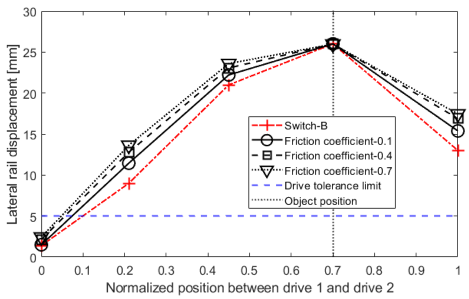
The model is calibrated to field measurements by varying the friction coefficient between switch rails and slide chairs. Simulations were carried out for three friction coefficient values: 0.1, 0.4 and 0.7. Comparisons to switch rail displacements from field measurements are seen in Figure 4.2. The friction coefficient of 0.1 has the lowest Root Mean Square Error (RMSE) value when compared to measurements and is used in the following analysis.



(a) Foreign object position 0.21



(b) Foreign object position 0.45



(c) Foreign object position 0.7

Figure 4.2: Comparison of lateral rail displacements between field measurements (Switch A and B) and results from FE simulations for different friction coefficients between switch rail and slide chairs

4.3 Influence of foreign object size and position on switch control condition

The calibrated FE model is employed to perform a parametric study to investigate the influence of position and size of a foreign object on the switch rail displacement and control. The aim of the investigation is to obtain insights about the marginal benefit of employing the TKK in the switch control system. The methodology followed for the parametric study is elaborated in detail in **Paper A**.

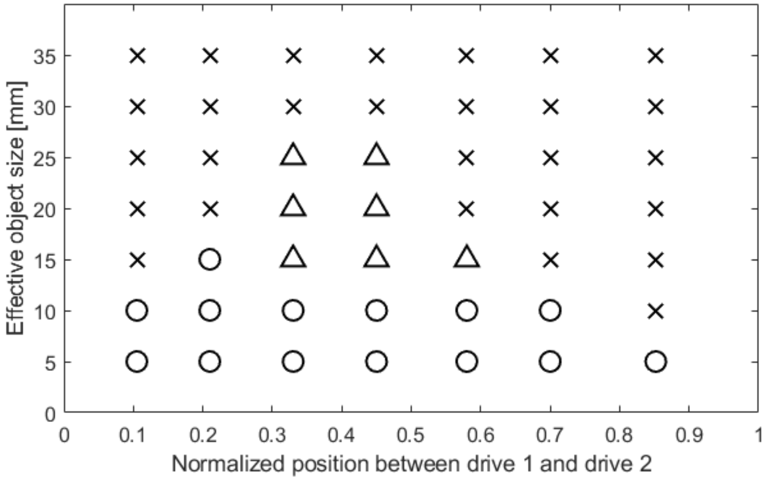


Figure 4.3: A map of switching scenarios w.r.t drive and TKK condition. Effective object size is equivalent to the induced gauge narrowing (see section 3 in **Paper A** for more information). 'O' markers indicate scenarios where the drive and TKKs are in control, 'X' indicate scenarios where the drives are not in control and '△' indicate scenarios where the drives are in control but the front TKK indicates a gap of above 13 mm

Figure 4.3 maps the condition of the drives and TKK for different foreign object scenarios. From the results, it can be seen that in 28 out of 49 loading scenarios, the foreign object doesn't get detected either by the drives or the TKK. In 7 scenarios TKK detects the foreign object while the drives are in control and in the remaining scenarios foreign object gets detected by the drives. Hence, the marginal benefit of the TKK is that it detects cases where the effective object size (gauge narrowing) exceeds 15 mm (refer to section 1.2) and thus constitute a derailment risk if they are strong enough to maintain the gauge narrowing during a train passage. There is one case in the figure where a 15 mm effective object size is not detected by the TKK. The displacement at the TKK in this case is however just a few tenths of a mm away from triggering, so this case would be detected for just a very slight exceedance of 15 mm. For the investigated switch type and drive configuration, the TKKs are therefore necessary to prevent all cases of gauge narrowing significantly above 15 mm.

CHAPTER 5

Derailment risk in switches with trapped foreign object - Paper B

5.1 Model description

Results from **Paper A** showed that if the TKK is omitted there can be cases of gauge narrowing above the accepted safety limit (15 mm). To evaluate the consequence of such cases, multibody simulations of vehicle-switch interactions in the presence of a trapped foreign object are employed. Simulations were carried out in a commercial MBS software Simpack [17]. An overview of the Simpack model including vehicle and track can be seen in Figure 5.1. Simulations of the vehicle passing through the switch in the through route in both directions (facing and trailing) were performed for linear and ballast stone object formulations presented in Section 3. Modelling details are presented in **Paper B**.

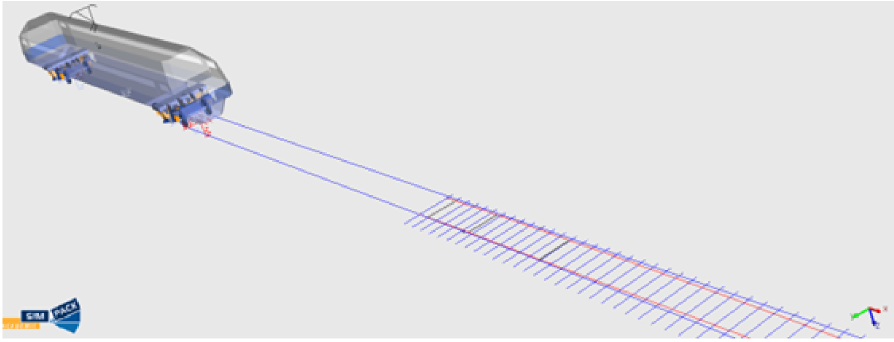


Figure 5.1: MBS model in Simpack, consisting of sleepers, switch and stock rails, and links. Origin of the track model coordinate system is at the start of the S&C.

5.2 Derailment risk evaluation

In the simulations, a wheel lift criterion is utilized to assess the derailment risk. In this case, 6 mm of wheel lift is taken as a limit corresponding to a significant derailment risk [18]. Examining Figure 5.2, it is seen that in the linear object case, the wheel lift is significantly above the safety limit. In the ballast stone case, the lateral forces due to the train passage are large enough to cause failure of the object, resulting in minimal wheel lift. It is shown in Paper B that ballast crushing will happen also for cases featuring variations in wheel–rail friction coefficient, axle load and vehicle speed. Simulations of operations in the trailing move show similar results.

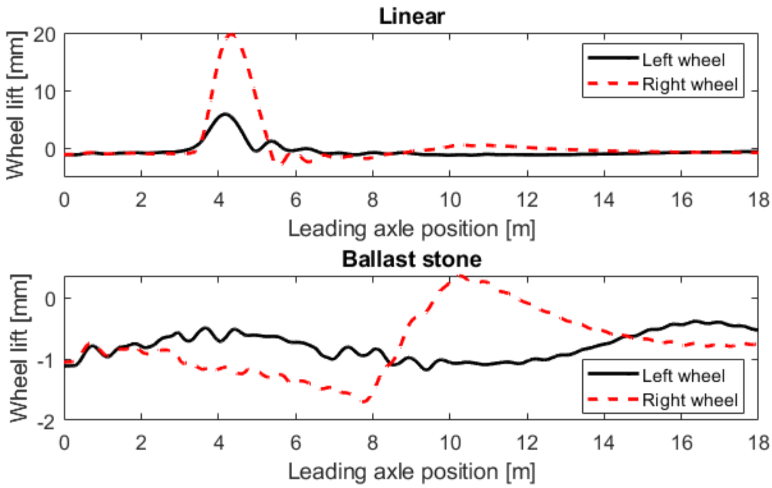


Figure 5.2: Resulting wheel lift relative to ground for left and right leading wheels for linear and ballast stone scenarios. The right wheel is interacting with the switch rail with the ballast stone interference

5.3 Derailment limit in terms of effective foreign object size

The model was applied to study the derailment limit as a function of effective object size to see if objects causing a static gauge narrowing larger than 15 mm could be tolerated [12]. This is investigated by simulating cases for different sizes of linear objects. The resulting maximum wheel lift for these cases can be seen in Figure 5.3. From the results it is observed that wheel lift goes above the safety limit of 6 mm at a gauge narrowing between 15 to 20 mm. Hence the currently accepted gauge narrowing limit of 15 mm is appropriate considering safety margins and the current TKK sensors and tolerances are appropriate if trapped objects with linear deformation characteristics are to be considered.

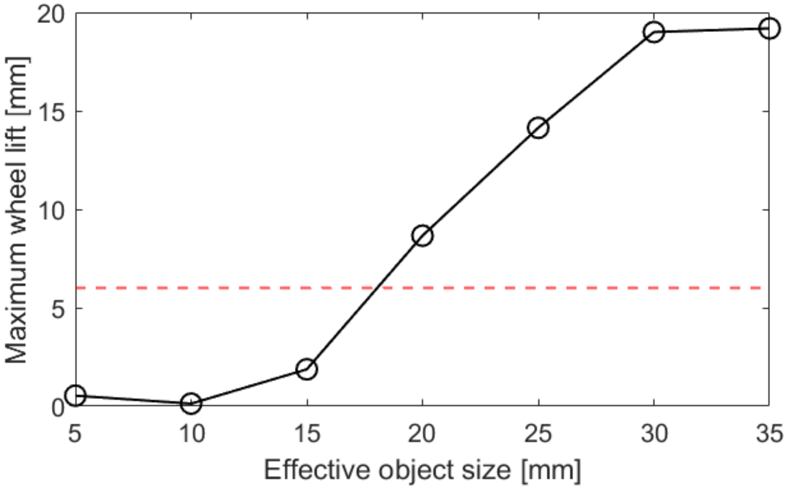


Figure 5.3: Maximum wheel lift variation due to varying effective object size (linear). Red line indicates the 6 mm wheel lift safety limit.

CHAPTER 6

Concluding remarks and future work

Field measurements were conducted on railway switches to investigate the influence of trapped foreign objects on switch operations. The study recorded lateral displacements between the switch and stock rails. Comparisons with results from finite element (FE) simulations showed good agreements. A validated model was used in a parametric study to assess how the position and size of a foreign object affects switch rail control. It was found that TKKs are necessary to detect all cases of gauge narrowing above 15 mm caused by foreign objects.

MBS are used to model vehicle–switch interactions, showing that wheel lift is above the safety limit for linear objects but very low for ballast stone scenarios. In the ballast stone case, lateral forces crush the object before the front wheelset reaches it, keeping the wheel lift within safety limits. Parametric studies reveal that the effective object size without derailment is between 15-20 mm for linear objects, suggesting that 15 mm is appropriate with a safety margin. Therefore, TKKs are necessary in the present system to detect foreign objects that could cause a derailment. In the vast majority of cases however, foreign objects are expected to be crushable and not pose a derailment risk.

The next step in the project will be to evaluate the probability of foreign objects getting stuck in a switch that are not crushable by the oncoming train and could thus result in a derailment. Following this, efforts will be directed towards enhancing current monitoring methods to potentially replace or omit the TKK from switch design. This could for example be achieved by adjusting the number or positioning of drives, or by integrating advanced sensors into the switch system. In addition methods to identify the type and size of trapped foreign object in switches will be explored.

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