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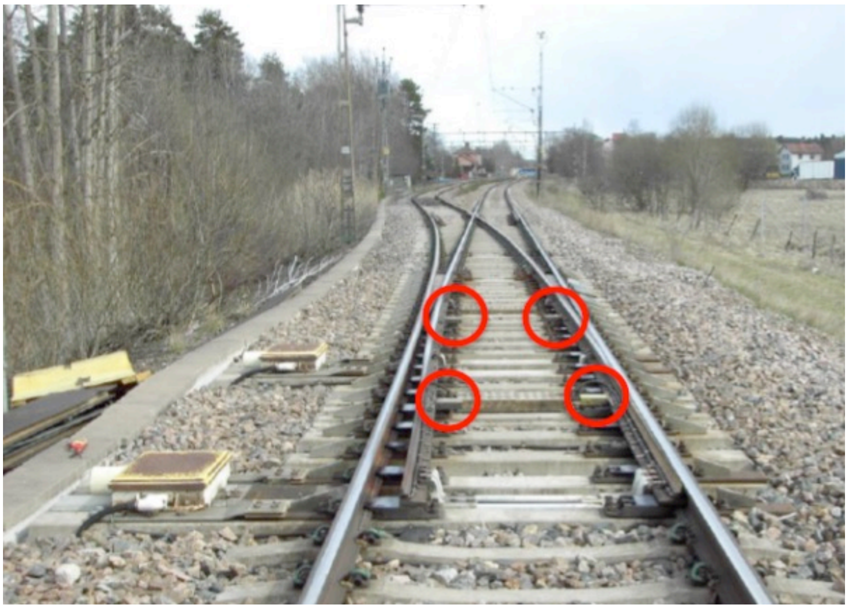

MORE ROBUST SWITCHES THROUGH IMPROVED CONTROL OF THE SWITCH RAIL

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Front:
Railway switch with four switch rail control sensors indicated. Picture courtesy Jan-Erik Meyer, Trafikverket.

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Executive summary

Current switch rail control detectors are among the most traffic disturbing factors in the Swedish rail network. Figures from Trafikverket from 2017 shows that more than 1021 trains were delayed for more than 257 delay hours. The sensor is not an expensive component, but required sensor adjustments when maintaining the switch is time-consuming, costly and cause further traffic disturbance.

The aim of this feasibility study is to evaluate the possibility to enhance the reliability of switch rail control while retaining safety levels. The focus is on the case when foreign objects (e.g., ballast stones) are trapped between the switch rail and the stock rail. This will lead to a rail gauge reduction when the switch rail is closed by the drives. To indicate such a rail gauge reduction that may cause derailments, switch rail control sensors (TKKs) are used in Swedish switches. These control sensors indicate if the switch rail is sufficiently close to the stock rail but are, as mentioned, also major causes of traffic disruptions. It is therefore important to know if, and under which conditions the controls in fact add additional safety. This is the focus of the current feasibility study.

The investigation sets out with a detailed review of previous investigations into the use of switch rail controls and concludes that all Swedish investigations are based on a one-page report (M5745/87) from 1987. From a scientific perspective the conclusions of this report can neither be verified nor falsified, a fact that has been further established by studying all available reports and presentations that may provide insight into how conclusions in M5745/87 were achieved. In particular, the background to current regulations to prevent derailments related to narrow rail gauge are two ORE reports. This study shows that these reports are not applicable for the case of reduced rail gauge in switches.

The study has further studied deformation of ballast stones and loads from vehicles. Preliminary static calculations have been performed and indicate that a derailment cannot be achieved for the studied “worst normal case”. These conclusions must however be further ensured with simulations, and with tests in track. To this end, it has been ensured that simulations of dynamic switch negotiations can be performed. Also, a tentative test plan to validate analyses has been outlined.

Contents

1 Introduction

The nomenclature regarding switch components in the report follows Figure 1.

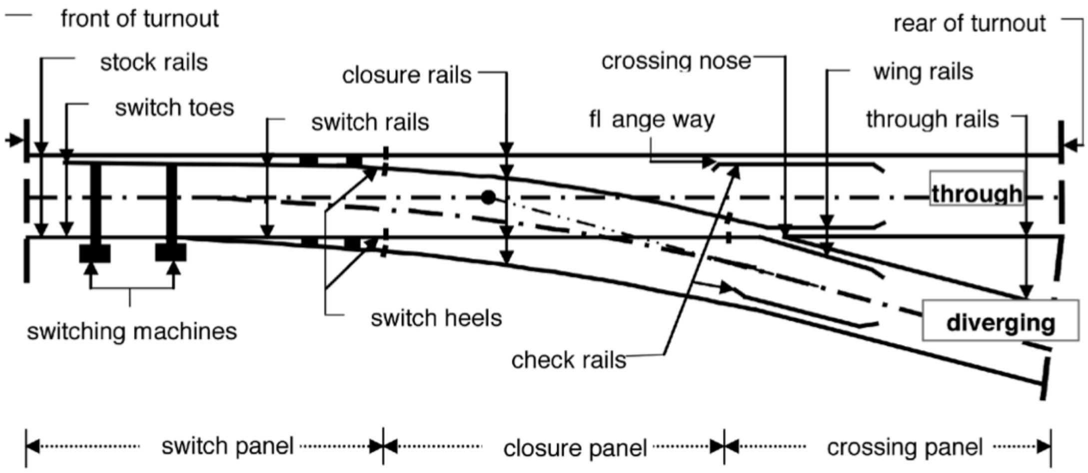

Figure 1 Switch components nomenclature. From [1].

1.1 Aim

The overall aim of the project, and thus this report, are to

- Clarify (as far as possible) backgrounds for previous decisions regarding switch rail controls. (Chapter 3)
- Clarify how the safety level for current systems has been assessed and what supporting scientific and empirical evidence there is. (Chapter 5)
- Clarify how an object caught between the switch rail and stock rail affects the deflection of the switch rail, and how this can be studied further in different degrees of detail. (Chapter 8)
- Clarify how passing vehicles affect the load, how the resulting deflection affects the risk of derailment and how this can be studied further in different degrees of detail. (Chapter 8)
- Summarize the feasibility study with an assessment of the extent to which it is possible to influence switch rail control. This requires concrete proposals on what studies that are required to ultimately reduce switch rail control sensors (in Swedish TungKontrollKontakt, TKK) with maintained or improved safety. (Chapters 11 and 12)

1.2 Methods and models

- Systematic review of previous investigations and follow-ups, as well as of international solutions. (Chapters 3 and 4)
- Traditional literature study with the important complication that much of the documentation is not open (e.g., company reports and ORE reports). Contacts were taken to gain access also to this documentation. (Chapter 5)
- Interview studies. An important aspect is that confidentiality has been required regarding certain aspects. (Chapter 5)

- Investigation of forces and deformations based on information from existing and supplementary numerical simulations, and experimental investigations. (Chapter 8)
- Signalling aspects are investigated by the aid of expertise in the field. (Chapter 9)

1.3 Implementation

- Literature study: Review of reports and investigations on TKKs made since 1987 and reports that form the basis for current regulations. (Chapter 3)
- Interviews and studies on how suppliers and other railway administrations solved the problem. An important conclusion is that TKK is a special Swedish solution. (Chapter 4)
- A first investigation has been made into which forces current and future traffic induce. (Chapter 7)
- Numerical simulations of representative cases with ballast stones trapped between the stock rail and the switch rail have been made. Loads from drives and vehicles are considered. The simulations are intended to show which deformations of the switch rail that can occur when the drives enforce a locked position. (Chapter 8)
- Signalling aspects of modified solutions that abolish TKKs have been assessed in an overview manner. (Chapter 9)
- With the support of performed studies, a first assessment as to if and (to some extent) how it is possible to reduce the number of TKKs and/or introduce modified solutions has been made. (Chapter 11)

This initial feasibility study indicates the potential to reduce or eliminate TKKs. It is also intended to lay the foundation for a next step, which is a more focused and in-depth doctoral project. Such an in-depth study is necessary as, according to current EU regulations, it must be shown that the proposed measure is "at least as safe as today". This requires an in-depth, scientifically based risk analysis. In such a risk analysis, this feasibility study provides more precise input data and better control of what needs to be examined in detail, see Chapter 11.

1.4 References

1. E Kassa and J C O Nielsen, Dynamic interaction between train and railway turnout – full-scale field test and validation of simulation models. *Vehicle System Dynamics*, vol 46, Issue S1&2, 521-534, 2008

2 Brief description of the switch rail control detection sensor

In the late 1980's when SJ started using slimmer and longer [1] switch rails in the new UIC60 switches, there was a concern that the drive could not detect (in the sense that locking is not obtained) if an object large enough to cause risk of derailment got stuck between the stock rail and the switch rail [1]. SJ (and later Banverket) decided to introduce a sensor that would indicate an object which potentially could cause a derailment. This was defined as an object that couls cause a gauge reduction of at least 15 mm [1]. The sensor was introduced and was denoted ”switch rail control contact” (TKK).

The TKK has since then been used and successively improved. Other switch types than the long UIC60 switches have also been equipped with TKKs.

Currently, the most used TKK is the so-called eTKK2 which is an improvement of the previously used mTKK. In this document, only eTKK2 will be dealt with. There are currently 12,531 eTKK2 in the Trafikverkets tracks in different switch types, see Table 1.

Number of TKKs in track	
Type	Number
1:4,8-1:8,1	5
1:9	2624
1:10	2
1:12	255
1:13	280
1:14	651
1:15	6156
1:18,5	2555
Total	12528

Table 1 Number of TKKs in different types of switches in the Swedish railway systems. Figures from Jan-Erik Meyer, Trafikverket.

Longer switches are often equipped with four TKKs and the shorter with two. This means that some 3500–4000 switches are equipped with TKKs.

The various types of TKKs that have existed are well described in [2]. That report also describes when TKKs are required.

A TKK consists of two parts, a magnetic part which is mounted on the switch rail and a contact which is mounted in the sliding plate at the stock rail [2]. Figure 2 shows the magnetic part.

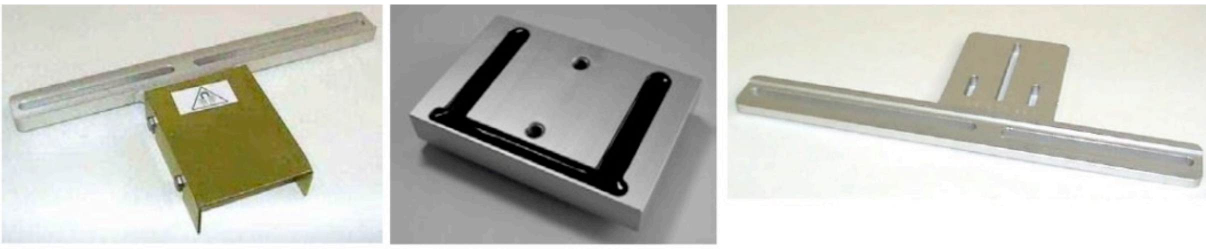

Figure 2 Complete magnetic part (left), magnetic system (middle) and mounting plate (right). From [2]

In the eTKK2, the contact is completely electronic and contains of no moving parts. All components are electronic. The contact consists of sensor, cable and connection plug. See Figure 3.

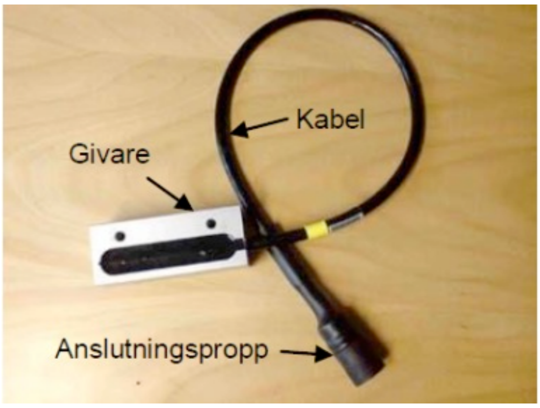

Figure 3 Contact for eTKK2. (Givare = sensor, Kabel = cable and Anslutningspropp = Connection plug). From [2].

In Figure 4 a 1:15 switch with four mounted eTKK2s (in red circles) is shown.

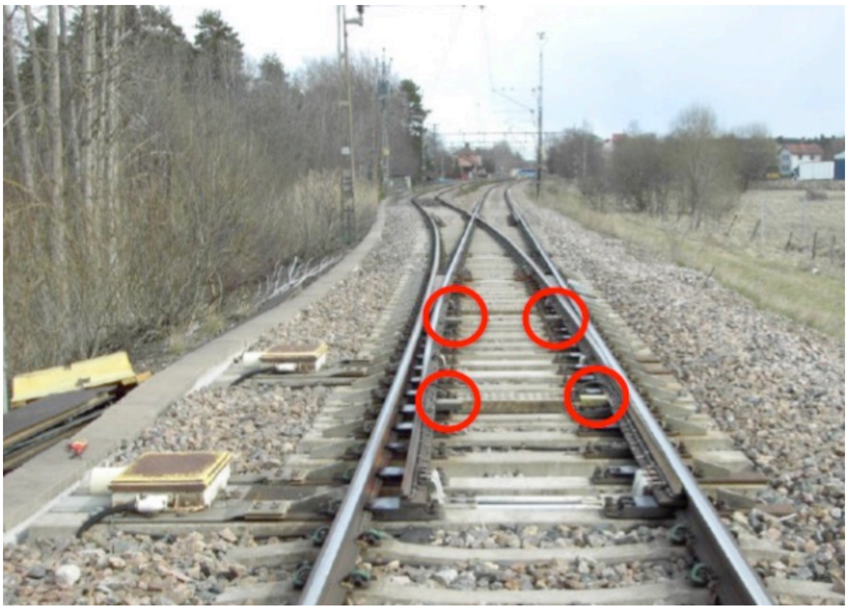

Figure 4 Picture of a switch with four TKKs. Picture courtesy Jan-Erik Meyer, Trafikverket.

The principle of TKK placement is shown in Figure 5.

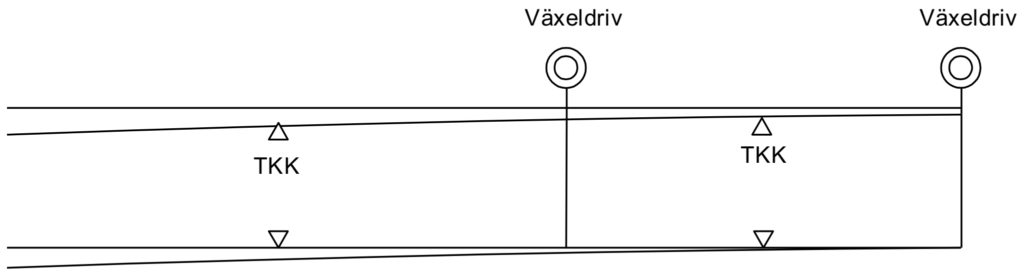

Figure 5 The principle of the placement of four TKKs between and behind the drives ("Växeldriv"). From [2].

2.1 References

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2. J-E Meyer, BVH 1523.016 - Spårväxel Tungkontrollkontakt eTKK2 mTKK, Projektering, montering, justering och underhåll, *Trafikverket* report TDOK 2014:0397, 2014, 28 pp

3 Background to the current practices of switch rail control

This chapter aims to clarify what previous decisions regarding switch rail control are based on. It reviews investigations and follow-ups that have been carried out since 1987. All available documents, which are mainly technical reports, have been studied in the extensive analysis carried out in the project. This chapter summarizes the main findings. Thus, only selected reports are referred to. A complete reference list has also been compiled in the project.

In principle, all investigations refer back to the one-page report M5745/87 [1], however the different subsequent reports make slightly different interpretations of this report. No background documentation to [1] has been found. This is remarkable since the railway in the 1960s to 1990s documented most important research and development work in ORE/ERRI reports.

The key to success in this study was therefore to understand the conclusions in [1] and what support there were for these. To this end, it was important to keep in mind that in 1987 when the report was written, SJ knew that Banverket would be formed the year after. This meant a significant temporary loss of technical competence. Further, a serious switch-related (although not TKK related) train accident occurred in Lerum about two months after [1] was written.

Several of the risk analyses studied were of insufficient quality mainly due to too poor input, which led to (overly) conservative assumptions on input parameters. This led to estimations on the safe side, but with such high uncertainties that it is essentially impossible to make precise conclusions. To be able to make useful risk analyses, significantly more knowledge of the different risk scenarios and the involved parameters is required.

The reports from 2005–2006 are partly based on each other. Conservative assumptions in one report then form the basis for later reports. The main purpose of these investigations was not to question TKK's being or not being, but to develop a more robust TKK solution. That work resulted in eTKK2.

The measurements made in Ålsäng [2] and in eight other places [3] provide good input on how the ability of drives to close when there is an obstacle between the switch rail and the stock rail vary between switches. Similar measurements are proposed in chapter 10 for the "worst normal ballast stone" in a 1:15 switch.

Around 2012–2013, new investigations were made. The main purpose was to illustrate how often events that lead to deviations, incidents or accidents occurred. This was possible since the reporting systems had been enhanced and made more reliable. Simulations were also performed with GENSYS [4] and [5]. However, GENSYS was at that time not suitable to analyse derailments in switches, which was also pointed out in the reports.

British RAIB reports [6] and UIC reports [7] have also been examined to find evidence of derailments due to an obstacle stuck between the switch rail and the stock rail. The reports did however not provide examples of this type of derailment.

A derailment took place in Hamra in 2010 [8] where it was concluded that TKK had indicated an obstacle. A more thorough examination of e-mails, reports, and personal interviews [9] with those involved showed that the first drive had not entered a locked mode. This meant that the wheel flange could penetrate between the switch rail and the stock rail.

Figure 6 The ballast stone that caused the derailment in Hamra 2010. From accident report 2010. Picture courtesy Trafikverket.

The report [10] states that "There are currently no known examples of incidents where the TKK function prevented a derailment". The report also describes an incident in the Södertunnel (Stockholm). It reports that a metal obstacle created a constriction of 25 mm on the switch rail. When commuter train passed through the switch with track gauge 1410 mm flange climbing occurred but did not cause a derailment. Two interesting observations *for this particular case* are then made:

1. A gauge reduction of 25 mm was possible with the drive in control.
2. Even though the constriction is 10 mm larger than the recommended 15 mm, no wheel axle derailed on the commuter train as it passed.

An investigation from 2016 regarding switch 102 in Härad is documented in a report with an associated protocol [11]. It refers directly to M 5745/87 [1] regarding the absolute limit for allowed gauge reduction (15 mm) and says that recent simulations indicate that the mentioned tests are correct with no references. It also includes conservative assumptions. For example, no reduction of the gap on the top of the switch rail due to torsion is considered. An interesting comment for the current switch in Härad 102 is that simulations in [11] show that objects that reduce the track width by 0–22 mm do not cause derailment. Furthermore, it is mentioned that tests have shown that objects over 25 mm are detected by the drive. In other words, only objects with a size in the range 23–25 mm should be of interesting with respect to their ability to cause a derailment while drives are locked.

3.1 References

1. I Bednarcik, UIC60-växlar gångdynamik, *SJ* report M5745/87, 1 pp, 1987

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4 International experience

This chapter aims to review previous investigations carried out by Trafikverket (Banverket) on international perspectives on switch rail control. In addition, it aims to identify how the problem has been solved internationally by contacts with suppliers and railways.

In connection to a bachelor's thesis [5] that dealt with, among other things, TKKs, Chalmers sent out a questionnaire to the members of UIC's Track Expert Group. Few answers were obtained, and the answers received indicated that the respondent did not seem to understand the question. Consequently, that investigation did not identify any railway agency that used a sensor in the same way as is done in Sweden.

4.1 Previous investigations by Trafikverket

Trafikverket (Banverket) has over the years examined international experiences. A summary of this is reported in a memorandum "TKK in an international perspective" dated 2012-10-12 [1]. Here, reference is made to a previous report dated 2006-10-05 [2]. A presentation was also made on 2013-06-13 [3] where Figure 7 was presented.


PM Internationell perspektiv/jämförelse

Hur gör andra förvaltningar när det gäller lägeskontroll av tungan? I rapporten har några förvaltningars lägeskontroll beskrivits. Något gemensamt utformning eller tillvägagångssätt finns inte utan förvaltningar har olika utformningar eller ingen lägeskontroll.

Land/Förvaltare	Tungkontroll
Norge	Teoretiska beräkningar
Finland	Ingen
Schweiz	Ingen
Österrike	Nyligen införd
Belgien	Omläggningsanordningen
SL	Ingen

Figure 7 Overview of international experience of switch rail control. From [3] (in Swedish)

In the memorandum [1] it is stated that there is no basis for answering the question of whether TKK is beneficial for Trafikverket's infrastructure. To answer the question of whether the TKK is needed, references are instead made to experience from other railway administrations with reference to [2],

According to [1] only a few of the other European railways have a sensor control function and location in the way that Trafikverket has.

Some experiences from other railways were also discussed in [1], as summarised below:

JernBaneVerket in Norway (today Bane NOR) has concluded that there is a need to have a total control of the switch rail. They do not however have a component that handles this function.

In Finland, they do not have a special device for detecting the position of the switch rail along its entire length, but on the other hand the drives are quite closely placed. They have, between the gear drives, a passive spring-loaded device that helps with actuation of the switch.

In Switzerland, they have for many years discussed the risk of the switch rail not being controlled along its entire length but have not yet concluded whether it is a risk that needs to be managed. They therefore started an investigation to clarify whether SBB will start using switch rail control.

In Austria switch rail controls (electromechanical switches) are state of the art since many years. With the reinforced switch rail profile it was possible (depending on the switch geometry) to get rid of the controls or to minimize the numbers or to use it just for lock control [7].

In Belgium, no special device is used to detect objects between the switch rail and the stock rail. You rely on the drive to have that control, and do not define specific dimensions.

In Stockholm Lokaltrafik's (SL) network, no special control function is used to detect objects between the switch rail and the stock rails.

4.2 Supply industry experiences

The two dominating suppliers of switches, Vossloh and VAE, have been contacted as part of this investigation.

4.2.1 Vossloh

A teleconference with Vossloh took place in early April 2021 [6]. At the meeting the structure of the feasibility study was presented. Vossloh's international experience with solutions for switch rail detection was discussed. Vossloh did not know of any railway who had a similar specific TKK design as Trafikverket. However, SNCF are using electromechanical controls (Paulvé) in their switches. Vossloh informed about calculations made for Norway about 15 years earlier and informed about work in Austria with a stiffer foot on the switch rail. Vossloh was asked if they knew of any articles, reports, or research in the field. Nothing was known as this issue is mostly handled nationally.

Vossloh was asked whether they knew about accidents or incidents caused by objects being stuck between the switch rail and the stock rail. The answer was that they did not know of reports or accidents in this narrow field.

4.2.2 VAE

On February 2021, a teleconference was held with Heinz Ossberger and Andreas Pogrilz from VAE [7].

At the meeting, it was discussed how ÖBB, DB and SBB solved the issue of switch rail control. No one has a control contact similar to the TKK. On the other hand, there are more drives on the switches, and they are more densely placed. In ÖBB's case, they used an additional control that was introduced due to issues with arced switches in the Alps. Looking at a Hydrostar System the controller is integrated in the locking device.

Railway	Radie	Switch	Date of drawing	Number of drives	Distance between drive 1 and drive 2	Distance between drive 2 and drive 3	Length of switch
ÖBB 1)	760	1:14-1:18,5	2017-12-21	3	4760	4760	22530
ÖBB 2)	760	1:14-1:18,5	2020-11-25	3	4760	4760	22528
SBB	900	1:16-1:19	2002-10-16	3	5200	5200	20790
DB	760	1:14	1995-03-31	3	5430	4815	22354
Bane NOR	760	1:14		3	2963	4240	
Bane NOR	1200	1:18,5		3	4710	5420	

1) normal switch rail	
2) switch rail with increased railfoot	

Table 2 Top four figures taken from drawings. The bottom two from [4[and [8].

4.3 Information from Infrastructure managers

Renewed contacts were taken with some infrastructure managers in 2021 to update the information on their switch rail control practices. The response from Bane NOR was the only response that added significantly new information as presented below.

4.3.1 Bane NOR

To date, Bane NOR has not installed a switch rail control sensor in any switch, even though it is permitted in the technical regulations. The signal department at Bane NOR says that in Norway there are approved control solutions, but so far Bane NOR has only installed a drive unit even though there is the possibility to install a switch rail control sensor in switches with crossing angles ranging from 1:12 to 1:18.4. [8]

Norway has not had any accidents due to objects stuck between the switch rail and the stock rail.

The distances between the switch drives on switches with crossing angles 1:14, 1:18.4 and 1:26.1 are as below with drive distances measured from drive closest to the tip of the switch rail:

- 60E1 1:14 R760, 3 drives: 2,965 m + 4,240 m
- 60E1 1: 18,4 R1200, 3 drives: 4,710 m + 5,420 m
- 60E1 1: 26,1 R2500, 4 drives: 7,220 m + 7,900 m + 7,300 m (without mounted sensors).

4.4 Summary

The strategies to ensure switch rail control employed internationally can be divided into three main approaches

1. Place drives so tight that derailment cannot occur if the drive is locked
    - original strategy
    - there exist only approximate analyses of which distances such placements correspond to
2. Detect any opening that may occur between the drives
    - the TKK strategy and SNCF
3. Employ a laterally stiff switch rail that allows strategy 1 to be fulfilled also with a greater distance between drives
    - new strategy by e.g., ÖBB

Approach 1 requires narrow placement of drives. Approach 2 introduces additional components in the safety system. Approach 3 prevents locking of drives for smaller stones than approach 1.

The Swedish solution with a TKK seem to be unique internationally. In addition, the solution with only two drives on switches with a crossing angle of 1:15 is unique. Using three drives is the common solution.

In Sweden TKKs are also placed behind the last drive which is the inner drive in figure 4 Despite searching internationally, we have not found any corresponding form of solution with a detector behind the last drive.

4.5 References

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5 Safety against derailment in switches due to narrow rail gauge

The purpose of the TKK is to ensure the detection of an object stuck between the switch rail and the stock rail that is large enough to potentially cause a derailment. It should here be noted that if the object is large enough, it will prevent the switch drive from locking. This will be indicated as a fault and train operations will be stopped.

The interesting scenario is therefore an object that is so small that the switch drives will lock, but sufficiently large to potentially cause a derailment. The risk of derailment is in that case caused by the reduction in track gauge. As a wheelset negotiates the narrow section, high lateral forces will occur. These may cause flange climbing or track displacement. Therefore, it is the safety level with respect to these events that must be evaluated.

The flange climbing ratio (Y/Q) where Y is the lateral force and Q is the vertical force is employed in Nadal's a flange climbing criterion, which states that flange climbing will not occur for

$$Y/Q \leq (Y/\,Q)_{\text{lim}} = A \qquad (1)$$

Here A is usually taken in the range 0.8 – 1.2 [4].

The Prud'homme track displacement criterium states that to prevent track shift, the lateral wheel load (S in kN) should be limited to

$$S \leq K \cdot (10 + 2Q_0/3) \qquad (2)$$

where $2Q_0$ (in kN) is the static axle load, K = 0.85 for freight wagons and K = 1.0 for locomotives, motor vehicles and passenger cars.

5.1 Background to current regulations

The current regulations regarding track and switches are mainly based on ORE/ERRI investigations. These are well documented in a large collection of reports. The results of the ORE/ERRI investigations have also often been the basis for UIC leaflets and adapted to national conditions. To answer what level of safety current regulations (that are based these investigations) give, a review of relevant ORE/ERRI reports is therefore required. This work focuses on the ORE investigations B55 and C138, which deal with derailment risks related to flange climbing and track displacement. The literature analysis is complicated by the fact that relevant data are spread over several reports with cross-references cf. Figure 12. A further complication is that development of modern tracks, vehicles and operation have changed the situation. In general, better tracks and carriages have made the current situation safer, while higher speeds, higher axle loads and less time for maintenance may have reduced the level of safety. The analysis of the background knowledge thus needs to be complemented by an analysis of more recent safety data to capture what has happened in the last 30–40 years since the ORE/ERRI reports were drafted.

Finally, it should be noted that national regulations often are adapted. How this was done and what thoughts such an adaption is based on is typically not documented. This means that changes and additions made to the Swedish regulations cannot be fully investigated.

5.2 Development of safety levels

The safety of train traffic has increased significantly over the past 40 years. The development in Figure 8 shows that there has been approximately a halving of fatalities every 10 years between 1970 and 2007. Regarding derailments, there has been a clear reduction also after 2007 [1].

It should be noted that safety enhancing activities in the railway sector often are event driven. This means that the serious accidents in the last 50 years have had a major impact on safety-enhancing improvements.

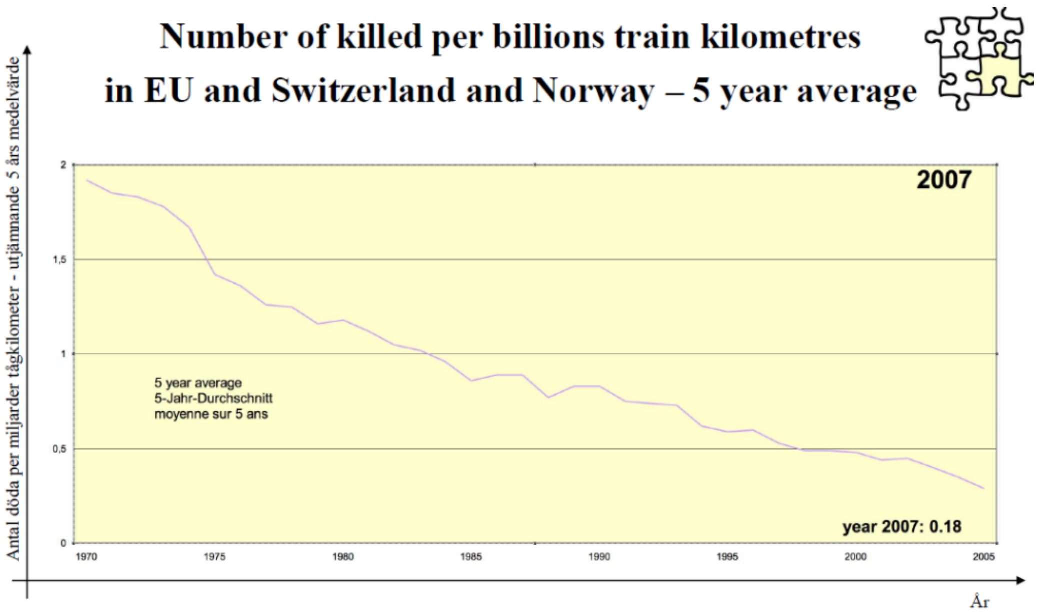


Figure 8 Number of fatalities per billion train kilometres in EU and Switzerland and Norway – 5-year average during 1970 to 2007 (From the UIC Safety database 2008)

5.3 Current regulations, handbooks, and teaching material

The safety level is not given a specific value in recent Eurocodes. EN 14363-2016 [2] refers to two basic studies, namely the B55 and C138 ORE/ERRI reports that were discussed above. In addition, some limit values are stated. See for example Figure 9 where limit values for (Y/Q) are provided.

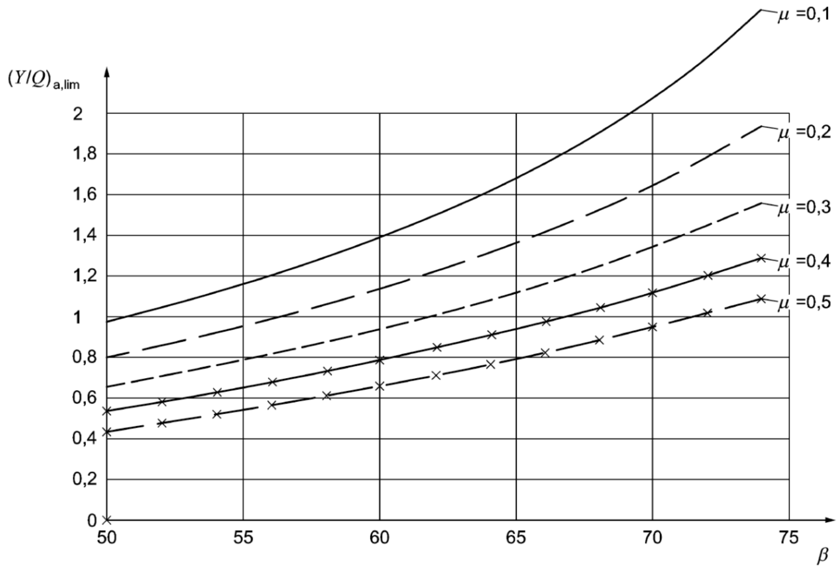


Figure 9 Limit values for (Y/Q) for variation in the flange angle β and the friction coefficient μ. From [2].

To understand the current relevance of the result from C138, one may consult the handbook Modern Railway Track from 2014 [3]. In that handbook, reference is made to ORE 138 Rp8, see Figure 10 and Figure 11.

where f = friction coefficient.

Introducing the formula:

$$f = \tan \emptyset \qquad (4.11)$$

the insertion of (4.8), (4.9) and (4.11) in (4.10) results in the following condition:

$$\frac{Y}{Q} \le \frac{\sin\beta - \tan\emptyset\cos\beta}{\tan\emptyset\sin\beta + \cos\beta} = \tan(\beta - \emptyset) \qquad (4.12)$$

Tests [205] have shown that derailment can occur if the Y/Q ratio over a distance of more than 2 m is greater than 1.2. For this reason the following value is usually retained as the criterion for safety against derailment:

$$\frac{Y}{Q} < 1.2 \qquad (4.13)$$

Often, a maximum wear angle of ½π - β = 32º is

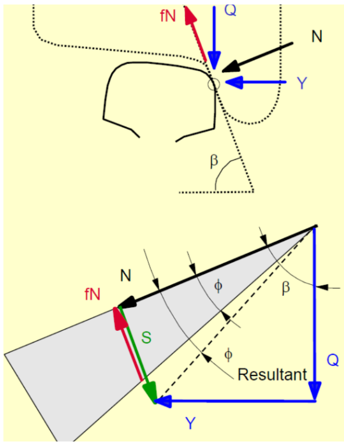


Figure 10 Excerpts from [3]. Reference is made to [205] which is ORE C138 Rp8.

[204] ORE C137 rp12: 'Railway noise: Measurements of the running noise caused by trains on different types of bridges', Utrecht, April 1981.

[205] ORE C138 rp8: 'Permissible maximum values for the Y- and Q-forces and derailment criteria', Utrecht, September 1984.

[206] ORE C152 rp1: 'Introductory study to the problem of assessing track geometry on the basis of vehicle response', Utrecht, 1981.

[207] ORE C152 rp2: 'Preliminary study concerning the application of the mathematical methods for characterizing the vehicle/track interaction', Utrecht, 1983.

Figure 11 Reference to ORE C138 Rp8 in [3].

Even current teaching material on railway technology refers to B55 and indirectly to C138 via the UIC 518. In [4] it is further stated that, in practice, it is extremely rare that flange climbing occurs only due to a high lateral force. Instead, it is almost always in combination with a highly reduced vertical force i.e., significantly less than the nominal value of Q_0. Low values of Q occur when the track is skewed, and the vehicle has a high torsional rigidity. This is not the case when flange climbing is provoked by a reduction of rail gauge in a switch.

The above reasoning shows that:

1. Current regulations related to flange climbing and track displacement have a good level of safety as manifested in the general development towards improved railway safety.
2. Current regulations, manuals and teaching material dealing with track displacement and flange climbing are based on ORE C138 and B55, which in turn are based on Prud'homme's and Nadal's formulas
3. ORE C138 and B55 have also been used to enhance and clarify the requirements in for example in EN 14363-2016 [2].

5.4 ORE C138 [5] Permissible limit values for Y- and Q- forces, and derailment criteria

In this, and the following sections, selected parts from C138 and B55 are discussed to improve the understanding of these.

ORE C138 consists of nine reports and four technical documents. It contains some 1500 to 2000 pages. The work with C138 was conducted during 1973–1986. Extensive studies were performed to define permissible maximum values for Y (lateral) and Q (vertical) forces and related derailment criteria. ORE C138 refers to ORE B55 [6], ORE C53 [7], and ORE D117 [8]. Figure 12 shows an outline of the relation between the different reports. The reports studied in the current investigation are shown in green.

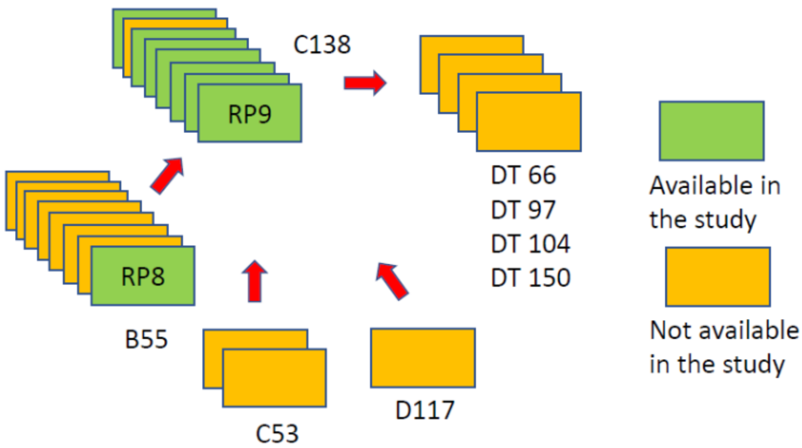


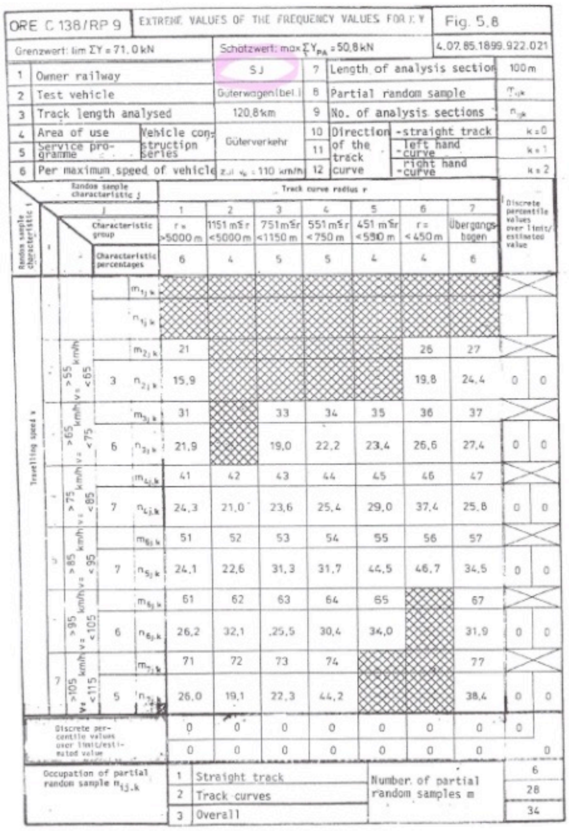
Figure 12 ORE C138 and some other linked documents.

The investigations made by the ORE C138 Specialists Committee compare limit values and derailment criteria in three areas:

1. Limit value of $\sum Y$ (Lateral displacement of track)
   a. RP1 (October 1977)
   b. RP4 (April 1980)

        c. RP5 (September 1980)
        d. RP7 (September 1982)
2. Limit value of Y and Q (Stressing of rails)
    a. RP 2 (October 1978)
    b. RP 6 (September 1980)
3. Derailment criteria Y/Q (Flange climbing)
    a. RP 3 (October 1979)
    b. RP 8 (September 1984)
4. Verification of limit values and derailment criteria
    a. RP 9 (September 1986)
5. Technical documents
    a. DT66, DT97, DT104 and DT150

The Swedish state railways, SJ, participated in the work on ΣY with Tage Andersson who was then head of SJ's laboratory in Hagalund. A thorough review of the ORE/ERRI reports showed that SJ delivered input data from a loaded two-axle freight wagon, but no specific results from Vislanda (as could be related to the M5745/87 report, see chapter 3) could be found. The input data covered an analysed track length of 120.8 km with operations having speeds of up to 110 km/h. Here, 41% of the track has curve radii R>5000 m, and 30% are transition curves, see Figure 13



ORE C 138/RP 9	EXTREME VALUES OF THE FREQUENCY VALUES FOR ΣY	Fig. 5.8
Grenzwert: lim ΣY = 71.0 kN	Schätzwert: max ΣY_{PA} = 50.8 kN	4.07.85.1899.922.021

1	Owner railway	SJ	7	Length of analysis section	100 m
2	Test vehicle	Güterwagen (bel.)	8	Partial random sample	T_{ijk}
3	Track length analysed	120.8 km	9	No. of analysis sections	n_{ijk}
4	Area of use / Vehicle construction series	Güterverkehr	10	Direction of the track curve – straight track	k = 0
5	Service programme		11	– left hand curve	k = 1
6	Per maximum speed of vehicle	z.B. v_F = 110 km/h	12	– right hand curve	k = 2

Travelling speed v	i	Characteristic group		1: r ≥ 5000 m	2: 1151 m ≤ r < 5000 m	3: 751 m ≤ r < 1150 m	4: 551 m ≤ r < 750 m	5: 451 m ≤ r < 550 m	6: r = < 450 m	7: Übergangsbogen	Discrete percentile values over limit/estimated value	
		Characteristic percentages		6	4	5	5	4	4	6		
	1		m_{1jk}									
			n_{1jk}									
>55 km/h v = <65	2		m_{2jk}	21					26	27		
		3	n_{2jk}	15,9					19,8	24,4	0	0
>65 km/h v = <75	3		m_{3jk}	31		33	34	35	36	37		
		6	n_{3jk}	21,9		19,0	22,2	23,4	26,6	27,4	0	0
>75 km/h v = <85	4		m_{4jk}	41	42	43	44	45	46	47		
		7	n_{4jk}	24,3	21,0	23,6	25,4	29,0	37,4	25,8	0	0
>85 km/h v = <95	5		m_{5jk}	51	52	53	54	55	56	57		
		7	n_{5jk}	24,1	22,6	31,3	31,7	44,5	46,7	34,5	0	0
>95 km/h v = <105	6		m_{6jk}	61	62	63	64	65		67		
		6	n_{6jk}	26,2	32,1	25,5	30,4	34,0		31,9	0	0
>105 km/h v = <115	7		m_{7jk}	71	72	73	74			77		
		5	n_{7jk}	26,0	19,1	22,3	44,2			38,4	0	0
Discrete percentile values over limit/estimated value				0	0	0	0	0	0	0	0	
				0	0	0	0	0	0	0		0

Occupation of partial random sample $n_{ij.k}$			Number of partial random samples m	
	1	Straight track		6
	2	Track curves		28
	3	Overall		34

Figure 13 Input data from SJ for RP9 in C138. From [5].

5.4.1 Limit value of ∑Y (Lateral displacement of track) in RP1, RP4, RP5 and RP7

C138 report 1 (Rp1) is entitled "Effect of the spacing of consecutive axles on the maximum permissible value of $\Sigma Y = S$ from the standpoint of track displacement. First part: Tests with a two-axled wagon."

The report describes the following:

1. The research program
2. Test installations used
3. The two-axle vehicle
4. General conditions for performing the static tests, which are performed at low speed with the two-axle wagon
5. The result of these tests

The length of the track section with lateral track displacement is 8 or 9 sleepers, corresponding to some 5 meters. The maximum track displacement tested is 15 mm.

The tests also reported the consolidation of the ballast.

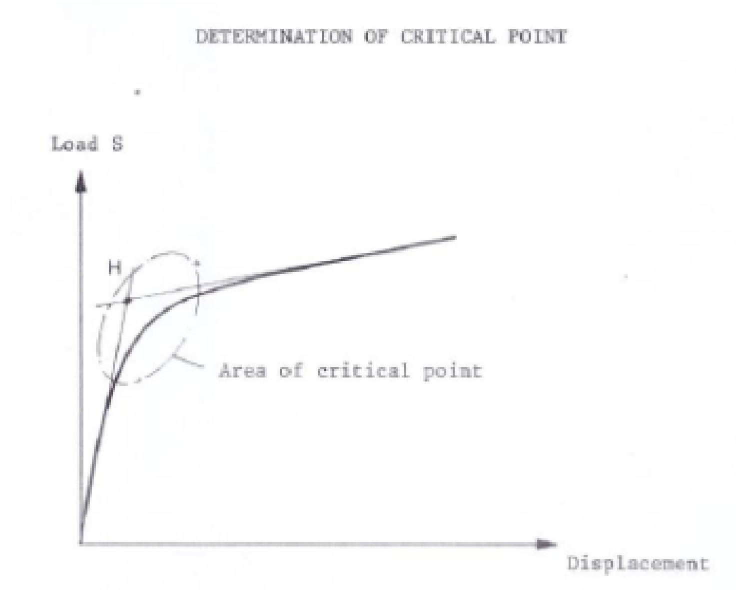


Figure 14 Load displacement curve to find the area of critical point H regarding track shift. From [5].

RP4 is a second part of RP1 but features tests of freight wagons with bogies.

RP 5 investigates the effect of speed on permissible maximum loads from a track displacement perspective. The report is divided into two parts, namely driving tests in tracks and simulated operations in a test rig. Obtained result showed that the influence on sleepers and reactions related to the maximum permissible total transversal force for the track do not vary significantly with the speed. These conclusions relate to test rig results.

RP7 is the concluding report for ΣY. It also deals with the maximum permissible value S_{lim} of the total transversal force $S = \Sigma Y$ from the point of view of track displacement. It concerns the influence of oscillatory variations of the axle load on the $S_{\lim}$ value. The study of this influence was carried out according to a program which included a series of tests with a wagon that had variable axle load traveling at low speed on an experimental track. Conditions were kept as similar as possible to those of the tests featuring a constant axle load as described in RP1. The results of the tests with variable axle load were interpreted through comparisons with constant load experiments.

The report further provides a description of the research program and a brief reminder of the main points of RP1. Information on the particularities of the installation and the wagon in the case of variable load tests. The conditions under which the tests were carried out, and results obtained. An analysis of results and comparison with those of tests at constant load is provided.

With some reservations regarding the application of low-speed test results, the commonly used relationship $S_{\lim} = K\,(10 + P_0 / 3)$ [kN], where P_0 is the nominal axle load and K a characteristic coefficient of the track, is found to be valid if the dynamic load variations do not exceed the level corresponding to generally accepted vertical running qualities. For larger load variations, the $S_{\lim}$ value must be reduced. An additional reduction of the K coefficient to 0.9 appears to be suitable. (Regarding current views see the introduction of chapter 5.)

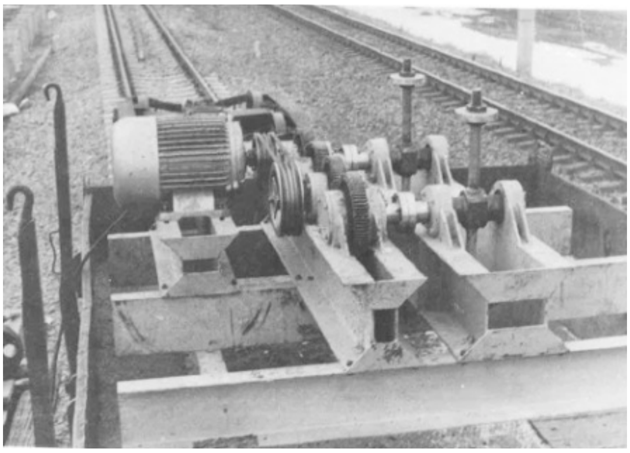


Figure 15 View of the vibrator used in tests. From [5].

For all the experimental cases, employing instantaneous values of the axle load in the formula $S_{\lim} = K\,(10 + P_0 / 3)$ [kN] was considered to be on the safe side.

The work on ΣY limits has as its main purpose to prevent lateral track shift. **The results are hardly relevant for local track displacements that occur in a switch rail if a ballast stone is stuck between the switch rail and the stock rail.**

5.4.2 Limit value of Y and Q (Stressing of rails) in RP2 and RP6

These reports deal with "Limit values for Y and Q (stresses in the rails)".

In RP6, calculation methods from RP2 and DT 104 are used. The effects of vertical and horizontal rigidity of the track, sleeper distance, wheelbase and rail profile are presented using isobar plots. Calculation results are compared with measurements.

Figure 17 show the FE mesh in the numerical model, and an example of parametric influence presented in isobar plots.

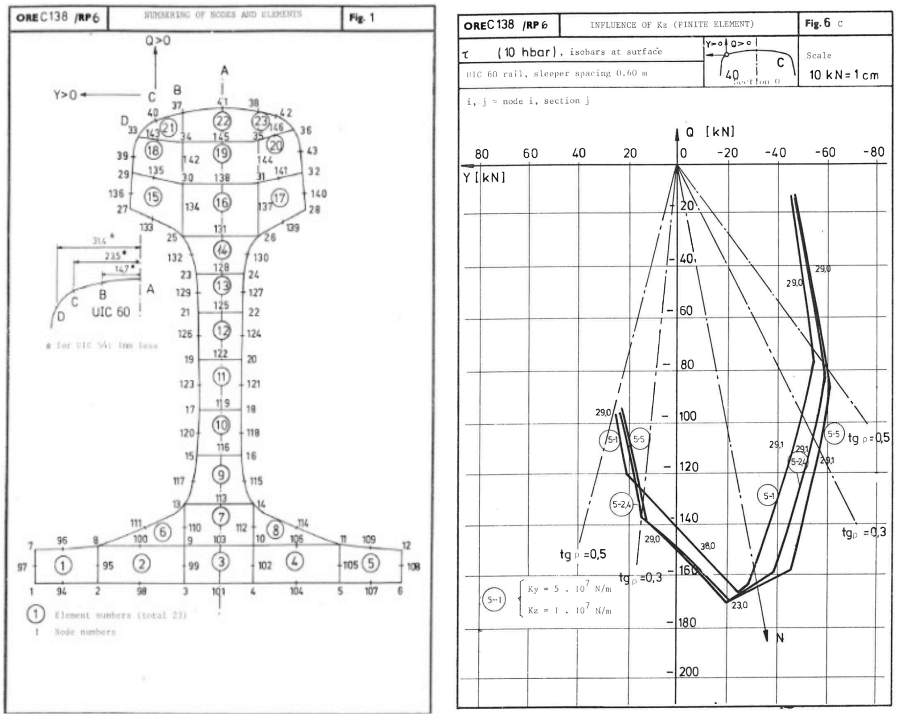


Figure 16 Examples on FE-mesh and isobar for UIC60 and 60 cm sleeper spacing. From [5].

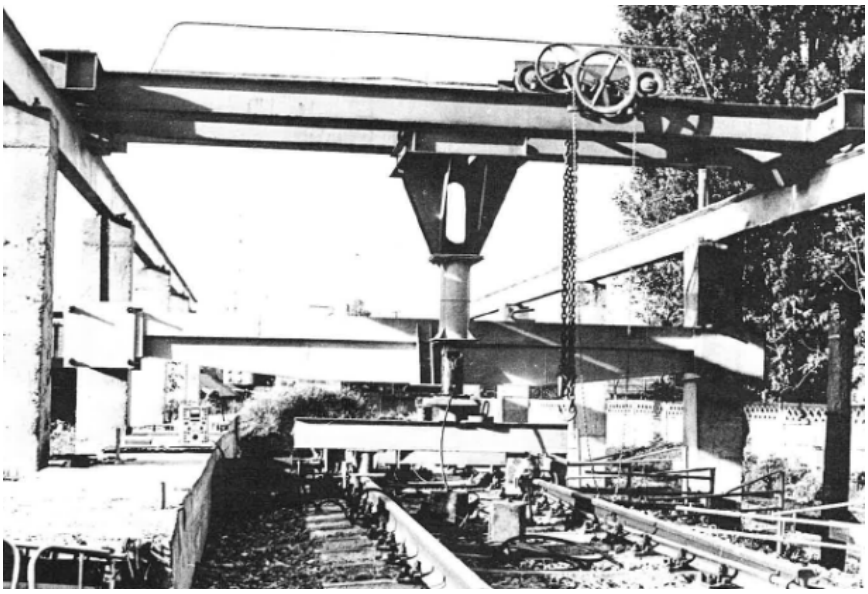


Figure 17 General view of the test rig used. From [5].

5.4.3 Derailment criteria Y/Q (Flange climbing) in RP3 and RP8

The task for RP3 was formulated as “Limiting Y/Q ratios in respect of derailment safety”. It describes tests carried out in Derby in 1978. It was a new series of derailment tests where test conditions were more stringent and allowed for statistical analyses of the result. The report provides analyses of a case where a two-axled vehicle was forced to derail.

In Rp8 the statistical analysis of tests to establish a $(Y/Q)_a$ derailment criterion were carried out.

BR, CFR, DB, SBB and SNCF participated in these tests (SJ did not participate). It can be noted that

1. The tests were divided into "special conditions" and "conditions similar to normal traffic".
2. All tests were performed at low speeds ($v \leq 40$ km/h).
3. A total of ten different parameters were measured, calculated, and recorded, along with additional details regarding the test ratio.
4. The purpose of the statistical analysis was to develop reasonable values for $(Y/Q)_a$ from the measured values where $(Y/Q)_a$ is for the first axle and the worst Y.
5. Only dry track tests were used. This corresponds to conditions of higher friction.

The important conclusions from Rp8 are:

1. Using a geometric criterion, climbing was considered as the front wheel lifting a distance of d_{za} = 6 mm. A clear difference was obtained between sample distribution of the target value $(Y/Q)_a$ for non-derailment and derailment samples. Differences in the $(Y/Q)_a$ level between non-derailment and derailment could be detected immediately before wheel climbing.
2. Changes in test parameters such as speed, angle of attack, vertical wheel forces, radii and twist have no clearly distinguishable influence on the target value $(Y/Q)_a$ as they overlap. This means that it was only possible to have an idea of general trends. Under quasi-static conditions, a derailment seems to be a chance occurrence which cannot be predicted in advance in any one specific case.
3. Comparison between two DB sample distributions for "non-derailment" led to a sufficient distribution. The limit value derived is roughly $(Y/Q)_a \sim 0.8$ due to the fact that different extreme test conditions can interact. For example, extreme track geometry, large angle of attack, unfavourable friction and differences in wheel load may decrease the limit value. In the conclusions of the report it was stated that ”The above figures are a pessimistic estimate”.
4. All results in the report must be considered as a presentation of the results of the specific tests performed. “It is thus not possible to determine a generally applicable limit value $(Y/Q)_a$ with these tests as a basis.”
5. When defining a limit value for $(Y/Q)_a$ (with possible differences for quasi-static and dynamic cases), it is advisable to also take into account that the analysis concerning (Y/Q) takes place in traffic on different railways and for various vehicles.
6. The conclusions ends with a comparison with B55 concerning the value $\lim(Y/Q)_a$ = 1.2 used by the B55 Specialists Committee.

The investigation of C138 and B55 indicate that they have chosen a "low" level of safety in combination with saying that the values for flange climbing are conservative.

This means that the decrease in probability of derailment due to flange climbing that a TKK can provide is likely small since high lateral forces are already presumed in the analyses.

5.5 ORE B55 Prevention of derailment of goods wagons on distorted tracks

This chapter is a brief summary of B55 Rp8. Several text parts taken directly from Rp8.

During the years 1959–1983 (24 years), extensive studies on prevention of derailment of freight wagons on skewed tracks were performed in working group B55.

B55 was started since there were derailments of freight wagons despite compliance with current regulations. The task of the committee was to develop rules that included both vehicles and tracks. These would at the same time ensure safety against derailments, and handle twisting of tracks. This complex problem would also be explained in a simple and comprehensible standard. The basis for the work was extensive testing.

B55 consists of eight reports [6]. The work was attended by 12 experts from five countries and a representative from ORE. DB (leader) and SNCF dominated with more than half of the participants. B55 RP8 is the final report (170 pages) that summarizes the investigation.

The problem of “prevention of derailment of goods wagons on track twist” was considered in detail. The bulk of the work consisted of the “ORE B55 calculating and test procedure” for the design of wagons to be newly constructed and for the testing of vehicles about to enter service.

Fundamental theories and statistical investigations were included only where it was deemed necessary for better understanding of the various parts.

The recommendations included rules on track layout, for example track cant, as a function of track radius and track twist.

Starting with the characteristic features of twist derailments, the theory of prevention of derailment when negotiating track twists was expanded. Wheel-load and guiding forces were related to given track and vehicle conditions. This, in essence, makes up the B55 approach. It was possible to simplify the procedure to cover all significant factors by using equivalent starting conditions, together with numerically known input data when keeping within the limiting values. The statistical safety of the model thus developed completes the theoretical basis of the ORE B55 system.

To achieve a balance between conditions necessary for track and vehicle, a start was made from the track twist under given track conditions. A similar relationship has been derived for track cant using investigations into various types of running gear and vehicles complying with these conditions.

By restricting the track twist, it was possible to use greater track cant to avoid severe speed restrictions in tight curves. The twist specified for the testing of vehicles was a balanced, statistically safe, specified value for the design and maintenance of vehicles.

The account of the relationship between guiding forces and wheel-load forms a major part of the report. ORE B55 supplies a generally valid estimate of the quasi-static behaviour in the curve for certain types of running gear. The theory of reduction in the wheel-load demonstrates the factors influencing safety against derailment.

The ORE B55 calculation and test procedure contains recommendations for designing new vehicles (or testing vehicles about to enter service) regarding their safety against derailment. The main task is to determine the required torsional characteristics. The procedures were developed with mainly goods wagons in mind. The theoretical relationship may however in principle be applied to all types of vehicles. A pre-condition is however knowledge of the break-point equations of using the suspension and torsional elements as well as the laws governing the running-gear, and vehicle-specific factors.

Tables, figures and flow-charts describe the ORE B55 calculating and testing procedure. The most important relations governing the basic track and vehicle parameters may also be deduced from the figures. The results of measurements and analyses carried out on various railways concerning guiding forces, wheel-load, as well as torsional stiffness for several types of goods wagons, complete the report. The appendices contain descriptions of special features of the ORE B55 calculation and test procedure.

B55 contains "Probability levels" indicating that a probability-based approach has been used. See Figure 18.

Explanations to Table on page 23

The preceding relations are not valid for all the base lengths. As far as the individual Administrations are concerned, the following restrictions must be allowed for:

(*) SNCF Group 3: The relations are only valid for bases ⩾ 5.40 m. For shorter bases, the twists calculated for the 3 probability levels approach 10 . 2a, which corresponds to a relative twist of about $10^{o}/oo$.

(+) DB Group 1 and 2: The relations are only valid for base length ⩾ 3.60 m. For the base length 2a = 1.80 m, the twists calculated are:

Probability level	Group 1		Group 2	
	Straight track and curves	All lay-outs	Straight track and curves	All lay-outs
10^{-6}	15.0 mm	15.0 mm	15.0 mm	14.0 mm
$5 . 10^{-5}$	13.0 mm	13.0 mm	13.0 mm	13.0 mm
10^{-5}	12.1 mm	12.0 mm	12.0 mm	12.0 mm

(**) NS Group 1: The relations are only valid for base lengths ⩾ 3.60 m. For the base length 2a = 1.80, the twists calculated are:

Probability level	Straight track and curves	All lay-outs
10^{-6}	16.0 mm	16.0 mm
$5 . 10^{-5}$	14.0 mm	14.0 mm
10^{-5}	13.0 mm	13.0 mm

(++) ÖBB Group 2: The relations are only valid for bases ⩾ 3.60 m. For the base length 2a = 1.80, twists calculated are:

Probability level	Group 1	
	Straight track and curves	All lay-outs
10^{-6}	17.0 mm	19.0 mm
$5 . 10^{-5}$	15.0 mm	16.0 mm
10^{-5}	14.0 mm	15.0 mm

Figure 18 An example of B65 probability levels. From [6].

5.6 Summary of safety levels

5.6.1 Confidence coefficient for assessment criterion *Y/Q* according to C138 and B55

In establishing the confidence coefficient P_A = 95% for statistical evaluation in ORE Reports C138/Rp8 and B55/Rp8, it was assumed that quasistatic derailments were involved. In such cases ($v \leq 40$ km/h) the damage to be expected from derailments would be minor and, therefore, the selected confidence coefficient of P_A = 95% was deemed adequate.

This is interesting as it is probably from C138 that the commonly used speed limit 40 km/h under potentially hazardous conditions has been retrieved. Also note the clear coordination with B55.

5.6.2 Confidence coefficient for assessment criterion $\sum Y$ according to C138

The limit value $\sum Y$ can also be used for higher speeds. Since derailments at high speeds can cause greater material damage, and danger to life and limb, a higher confidence coefficient was required. A confidence coefficient of P_A = 99.7% was adopted by C138 for this application.

Although no probability calculation was carried out on the degree of safety evidenced by the formula 0.85 (10 + P_0/3), according to Prud'homme, it is stated that this limit value provides a result of approximately 3 standard deviations below the mean track resistance value for deconsolidated track.

It should be noted that exceeding the limit value is not a hazard unless it occurs at a point where there is localised weakness of the track. The confidence coefficient P_A = 99.7% therefore ensures a very high degree of overall safety.

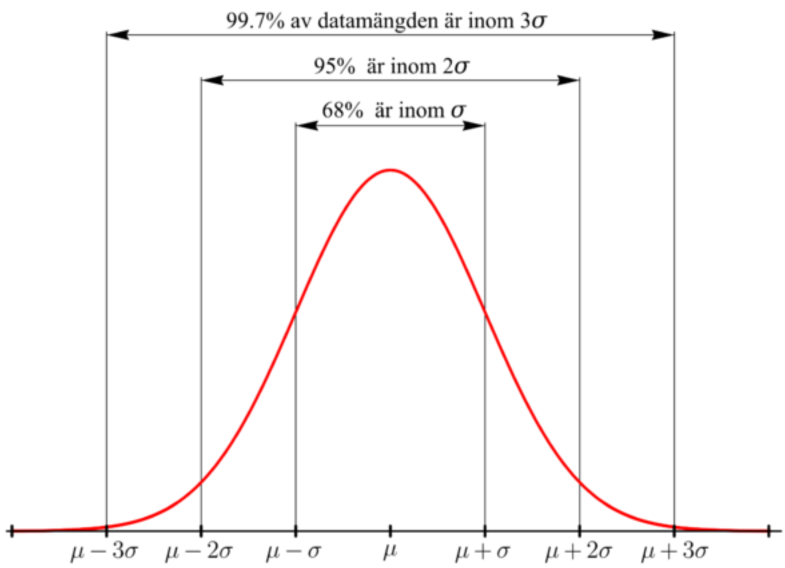


Figure 19 Normal distribution with indications of one, two and three standard deviations (σ). (By Svjo - CC BY-SA 4.0).

In B55 a normal distribution is used, see Figure 19. Values within one standard deviation (σ) from the mean (μ) constitute 68.27% of the data set; two standard deviations constitute 95.45% of the data set and values within three standard deviations comprise 99.73% of the data set. In statistics, this is referred to as the 68-95-99.7 rule.

5.6.3 Summary of assessment of flange climbing criterion Y/Q (a summary from Rp9);

The following limits were confirmed for safety against derailment;

1. Y/Q = 1.2 (P_A = 84%) distribution limited at one end
2. Y/Q = 0.8 (P_A = 95%) distribution limited at both ends.

The tests carried out under quasi-static conditions (v ≤ 40 km/h) in special (laboratory) and near-operating conditions resulted in a limit value lim(Y/Q) = 0.8 with a reliability probability of PA = 95% and with limitation of the distribution at both ends. It was further considered that the effect of the train speed on the derailment criterion Y/Q is negligible.

From this it must be concluded that the cumulative derailment-promoting arrangements for determining a limit value for Y/Q were very severe when compared with normal operating conditions and consequently resulted in the low limiting value of 0.8. This could be verified for track curve radius values of r>300 m but could not be confirmed for r ≤ 300 m.

Investigations to determine how far Y/Q could be increased were not carried out but long service experience with values approaching 1 never resulted in derailments.

It is stated that adhering to a limit value Y/Q = 0.8 in any case provides a high degree of safety against derailment. The level of this safety factor is stated to be the decision and responsibility of the railway involved. The limit value Y/Q = 0.8 is intended solely for assessing the Y/Q values obtained from measuring runs in normal operating conditions. The limit value lim(Y/Q) = 1.2 for vehicles, as used in the ORE B 55/Rp8 calculation and testing method, ensures a safe operating condition.

Therefore it is concluded that no change needs to be made to the model and no alteration should be made to the input value of $\lim(Y/Q)_a$ = 1.2 as design value for the calculation of the torsional stiffness of vehicles or for the conventional test on a special track described in B55/Rp8.

5.6.4 Recommendation (taken from C138 Rp7, 8 and 9)

C138 established the following limits for the approval of vehicles for use in international traffic.

1. offset criterion $\Sigma Y = 0.85\ (10 + 2Q_0 / 3)$.
2. criterion for permissible bending stresses in the rail, on the basis of the permissible stresses defined by the railways.
3. criterion for derailment due to flange climbing $Y/Q \leq 0.8$.
4. calculation of permissible torsional rigidity and testing on special track (ORE B55 Rp8) $Y/Q \leq 1.2$.

It has been shown that due to the different measurement methods, measurement registrations and text analyses adopted by the railways, there are differences in the analysis results obtained. The C138 Committee therefore recommended that a standardized method of analysis should be used for future international analysis work. The method described in the annexes to the committee's final report C138 Rp9 is an example of such a method.

The railways are urged

1. to take the necessary measures to adapt the results of the report to their own circumstances.
2. to ensure systematic collection and analysis of data to guarantee the mathematical relationships on a broader basis or to extend the limited validity intervals to the long term.

Further research was recommended in the event of unexplained railway incidents, the probable cause of which is a fault in the wheel / rail system.

Since the focus of both C138 and B55 is on plain track, they are not directly applicable for switches and crossings, and therefore not for the investigation of TKKs. The consequence of this is that there is currently no confirmed safety level for the case of reduced track gauge in a switch.

5.7 References

1. UIC Safety Database report 2019
2. SS-EN14363-2016 Railway applications – Testing and Simulation for the acceptance of running characteristics of railway vehicles – Running Behaviour and stationary tests
3. C Esveld, Modern Railway Track, MRT-Productions, 2014
4. E Andersson o M Berg, KTH, Järnvägssystem och spårfordon, KTH, 2001
5. ORE, Permissible limit values for Y- and Q-forces and derailment criteria, Report C138,1977-1986
6. ORE, Prevention of derailment of goods wagons on distorted track, Report B55 , 1959-1983
7. ORE, Behaviour of the metal of rails and wheels in the contact zone, Report C53, 1959-1976
8. ORE, Optimal adaption of the conventional track to future traffic, Report D117, 1968-1983

6 Ballast properties

Our assessment is that the worst common object that can get caught between the switch rail and the stock rail is a ballast stone for two reasons:

1. It takes a greater force to crush a ballast stone than an ice cube
2. Loose metal objects of a "suitable dimension" are extremely rare.

An analysis of the risks of derailment due to a ballast rock that causes a reduction in rail gauge is strongly dependent on the properties of the stone. Here it is mainly the size, shape, brittleness and hardness of the ballast stones that are important. In addition to this, a study has been proposed to identify how a ballast stone deforms when subjected to forces from the drives, and a lateral force representing a passing wheel. See further Chapter 10.

In this feasibility study, the idea is to identify a reasonable worst stone. The topic is then to be analysed further in the subsequent doctoral work.

When the switch rail goes into position, there is a gap between the stock rail and the switch rail where the TKK is located today. According to the supplier, this gap is 6 mm for a 1:15 switch. A trapped ballast stone will be deformed by the force from the drive, which is set to be 6.5 kN/drive [1]. The deformation of the ballast stone due to the force from the drive has been assumed to be 5 mm based on [1] and internal reasonable experience assessments. Some additional support is provided by a picture from the trapped stone related to the derailment in Hamra 2010 see Figure 6.

Further support for the crushing deformation of ballast stones is given by work reported in a master's thesis [1]. Here, several experiments were performed where stones were placed on a plate and then subjected to crushing loads, see Figure 20. The measured deformation showed so-called load drops i.e., when the crystalline structure is rapidly broken down. See Figure 21.

Based on the analysis of ballast stone sizes and shapes, the worst normal ballast stone is assumed to have a width of 40 mm when trapped between switch and stock rails. This gives a displacement of roughly 30[1] mm between the switch rail and the stock rail at the position of the stone.

[1] Ballast stone width 40 mm, minus gap 6 mm, minus ballast deformation 5 mm.

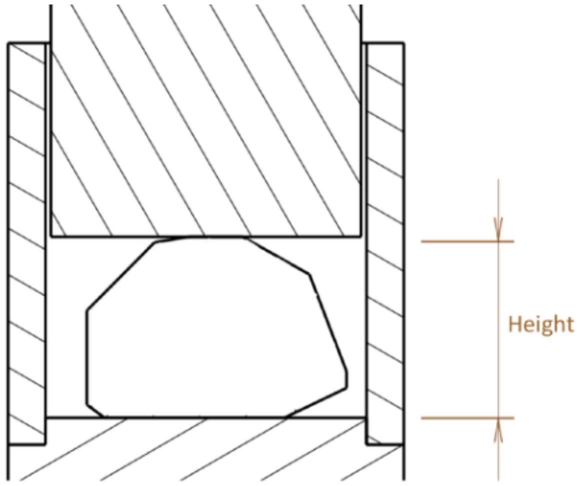


Figure 20 Cross section of the hydraulic press test set up. From [1].

In the ballast crush tests, 15 stones were tested. Figure 21 shows the results of these, and also the predicted deformation behaviour for idealized stone geometries (cube, oval, cylinder, real-cubic and real-round) for reference.

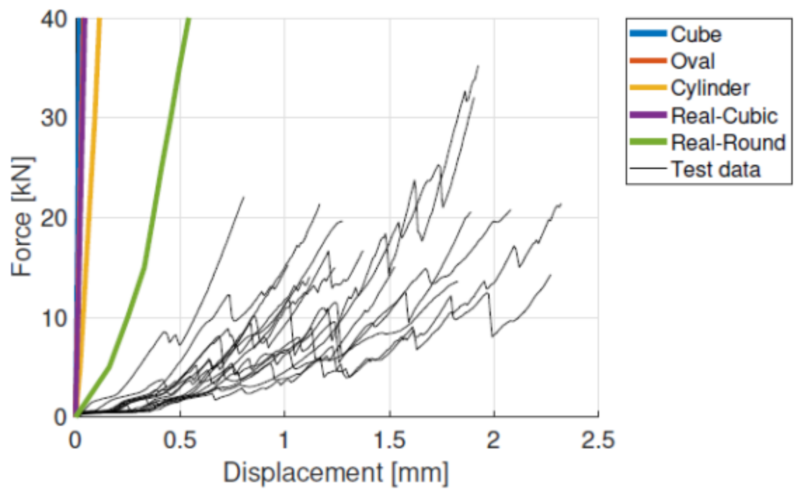


Figure 21 Displacement predicted by FE analyses and evaluated from test data. From [1].

Since the deformation of the ballast stone is an important parameter in terms of derailment, a full-scale test of ballast deformation behaviour in a switch has been proposed in Chapter 10. In addition to the forces from the switch drives, the stone will be further deformed by the horizontal wheel load (*Y* in Figure 10). This force is significantly greater than the force from the drive and is also repeated for each wheel axle that passes. It is therefore not unreasonable to assume that the ballast stone is crushed after a train passage. A simpler test to verify this is presented in Chapter 10.

6.1 References

1. R Hafström, Loading and crushing of trapped ballast stones, Chalmers University of Technology, Master's thesis 2020:61, 2020

7 Forces from switch drives and vehicles

7.1 Forces from switch drives

The deflection device that handles the movement of the switch rail is in everyday speech and in the latest Eurocodes referred to as a drive. The drive imposes the (pushing or pulling) force on the switch rail using bars. This induces a movement between the two extreme positions that are secured by a locking device. The force is partially adjustable and can vary between 4.0 and 6.5 kN. In Sweden, 6.5 kN is commonly used.

Figure 22 Two types of drives: To the left a traditional design with open bar installation, and to the right a modern design with built-in bars of the type Easyswitch. Picture courtesy A Alqvist, Vossloh.

In the analyses of international experiences, it was difficult to find out which drive forces that are applied, but indications are that the force is normally in the range 4 to 6.5 kN.

The only administration from whom we received detailed information was Bane NOR [1]. They apply a lower force to the second drive. This may be a solution that should be considered since a lower force more easily indicates if an object is stuck between the switch rail and the stock rail. However, the high force should be maintained in the drive at the tip of the switch rail to ensure that it closes and prevents derailments such as the Hamra incident, see chapter 3.

In verification tests (see chapter 10), the force has been set 6.5 kN on drive 1. On drive 2, loads of 4.0, 5.25 and 6.5 kN are proposed to be tested. This is done to evaluate how sensitive the drives are with respect to locking at varying force magnitudes.

7.2 Forces from vehicles

Since the 1990s, Sweden has consciously worked to enable more train operators. This has meant that today Transportstyrelsen have issued 86 valid permits [2]. Of these, 15–20 are for passenger traffic and 25–30 for freight traffic. The remaining are, for example, museum traffic and freight traffic on networks that are not managed by the state.

A review of the leading axle of the vehicles in question shows that the axle load is normally 16–21 tonnes. The smallest axle load (11.3 tonnes) was found for an Y1, see Figure 23

Figure 23 An Y1 passenger train. By Markus Tellerup, CC BY-SA 2.5.

Table 3 shows axle loads and axle distances for trains operated by SJ.

Littra	Axelload first axle [Kg]	Axelload second axle [Kg]	Distance between the axles [mm]
Rc6	19500	19500	2700
X2	18798	18819	2900
X2	16800	16800	2900
X2U	18406	18434	2900
X40	min 18 466 – max 21	min 18 466 – max 21	2500
X40	min 17 953 – max 20	min 17 953 – max 20	2500
X55	18500	18500	2700
X55	18500	18500	2700

Table 3 Axle loads on trains operated by SJ. By P Söderström SJ.

The derailment in Hamra in 2010 involved an X31 train (not an SJ train). It had an axle load of 13 tonnes, which is an unusually low axle load.

Figure 24 The derailed X31 at Hamra 2010. From the accident investigation, Picture courtesy Trafikverket.

The most dangerous derailment case has been judged to be when a vehicle with a low axle load enters from the tip of the switch rail and goes into a deviating track. The transition to the deviating track induces a high horizontal force when the vehicle is shifted sideways. This force is aggravated by a narrow rail gauge.

7.3 References:

1. Bane Nor, ERTMS-Programmet, Utredning og risikoanalyse deteksjon av sporviddereduksjon, 2021.
2. Transportstyrelsen website, https://transportstyrelsen.se

8 Preliminary calculations

Note that the calculations described in section 8.1 feature static loads. The aim is to get an estimation of the switch rail deformation due to loads from drives and horizontal wheel loads when a vehicle negotiates a switch with a reduced rail gauge. Static calculations are also necessary to obtain calculation results that are verifiable in full-scale tests, as described in Chapter 10.

Section 8.2 explores the potential for simulations featuring dynamic switch negotiations.

8.1 Static loads from drives and influence of a lateral load on the switch rail

When a train enters a switch where a ballast stone is trapped between the stock rail and the switch rail, the narrowing in track gauge will give rise to lateral forces. These tend to bend and twist the switch rail so that the opening closes. They also impose high forces on the stone between the switch rail and the stock rail.

The purpose of these preparatory static calculations has been to show how the switch rail is deformed by forces from the drive and vehicle when an object is stuck between the switch rail and the stock rail at the same time as the drive has entered a locked position.

Two load cases have then been considered. The first is the deformations that occur due to the forces of the drives that lock the switch rail – note that if the drives are not locked, there will be no green light from the signalling system, which means that train is not allowed to pass. **Consequently, if the trapped stone is too large, the switch will not go into position and lock, and no train should be allowed to pass.**

The second force is a horizontal load of 10kN on the upper part of the switch rail in the middle of the drive while the switch rail is locked and deformed by the object. This force should represent a lateral force from a wheel negotiating the switch although the magnitude may not be representative, as discussed below.

8.1.1 Load case 1

Each drive loads the switch rail with 6 kN. At the same time as there is an obtrusive object that causes a deformation of 30 mm at its location, see Figure 25.

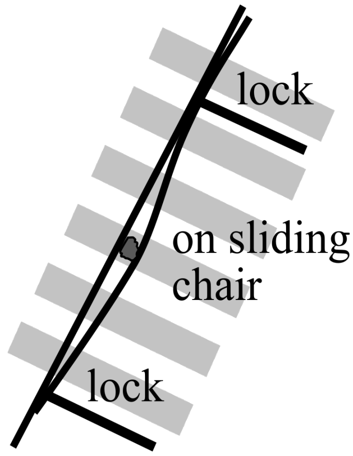


Figure 25 Sketch of the locked drives and the trapped ballast stone.

The cross-section deformation where the object is located is indicated in Figure 26. Here δ = 30 mm is the horizontal deformation that occurs at the moment when the switch rail just reaches the object. When the bottom of the switch rail is obstructed by the stone, a twisting of the switch rail occurs. This causes a reduction Δ_d of the gap at the rail head.

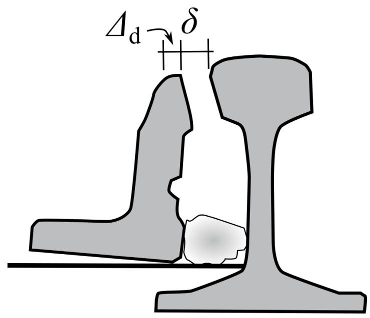


Figure 26 Cross-sectional deformation due to loads from the drives.

8.1.2 Load case 2

The drives are now locked (the switch rail rests against the stock rail at the drive) with an object that causes a deformation of 30 mm at the switch rail foot. Then we apply another load of 10 kN at a position 15 mm below the tip of the switch rail directed towards the stock rail. This will cause further deformation, Δ_W, at the rail head, see Figure 27.

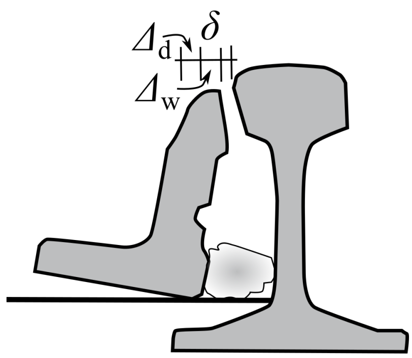


Figure 27 Cross-sectional deformation due to loads from drives and a wheel.

The reason why 10 kN has been chosen is that it should be possible to verify the behaviour – it corresponds to a load magnitude that easier can be applied in field testing and results in an elastic deformation. The force–deformation behaviour is however not fully linear since gaps at the drives, wear, friction etc have an impact. These effects have at this stage been considered small or giving additional deformation, which provides estimations on the safe side. Note however that the wheel load experienced in practice will not be a linear function of the gap between the switch rail and stock rail.

8.1.3 Numerical simulations

The simulations were performed by Björn Lundin at SCANSCOT with the support from Björn Paulsson [2]. The calculations were made in Abaqus with the following boundary conditions.

1. The switch rail on each sleeper rests on plates with no friction
2. The switch rail is considered clamped where it is welded against the switch.

Steel is modelled as linear elastic with a density of 7000 kg/m^3, and an elasticity modulus of 210 GPa.

In addition, there are some mechanical gaps. A switch rail just over 20 m long is affected by the ambient temperature. For a rail, it is considered to be between -20 ° C and + 55 ° C in southern Sweden. This means that the toe of the switch rail moves about 10–15 mm in relation to the drive closest to the switch toe through temperature expansion. However, for the current simulations, the temperature variation during a train passage are of interest. These are so small that they can be neglected. In addition, there are displacements and geometry changes caused by traffic and wear. These are considered to result in larger displacements. See Figure 28 and [3].

The horizontally movement of the switch rail is induced by two drives that are modelled as two prescribed displacements, see Figure 29. Geometrical gaps in the driving and locking devices are significant, see Figure 28 that shows attachment of the front drive to the switch rail. As seen, these are not completely rigidly attached. According to [1] they allow for further deformations. These corresponds to a more flexible switch rail construction, which would easier close the gap at a trapped object (larger Δ_d and Δ_w in Figure 27). In addition, they may require the drive to close for slightly larger stones. In total, it is however believed that it is a conservative assumption not to consider gaps in the current analyses.

Figure 29 and Figure 30 describe load cases 1 and 2 (as outlined above) more in detail.

Figure 28 A 1:15 switch with a zoom-in of the connection between the drive and the switch rail. (B Paulsson)

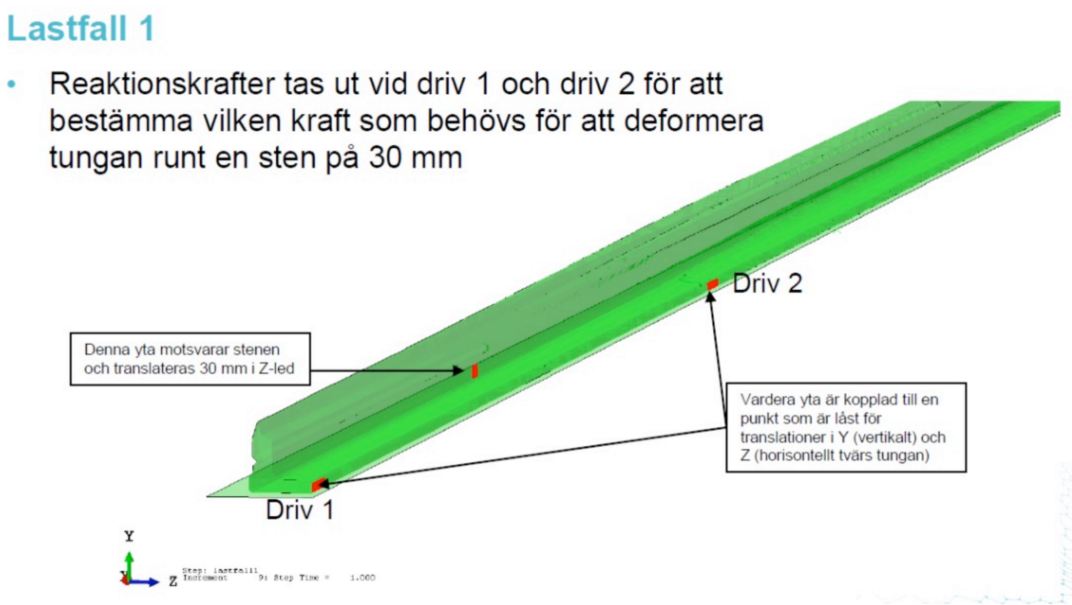


Figure 29 Description of boundary conditions

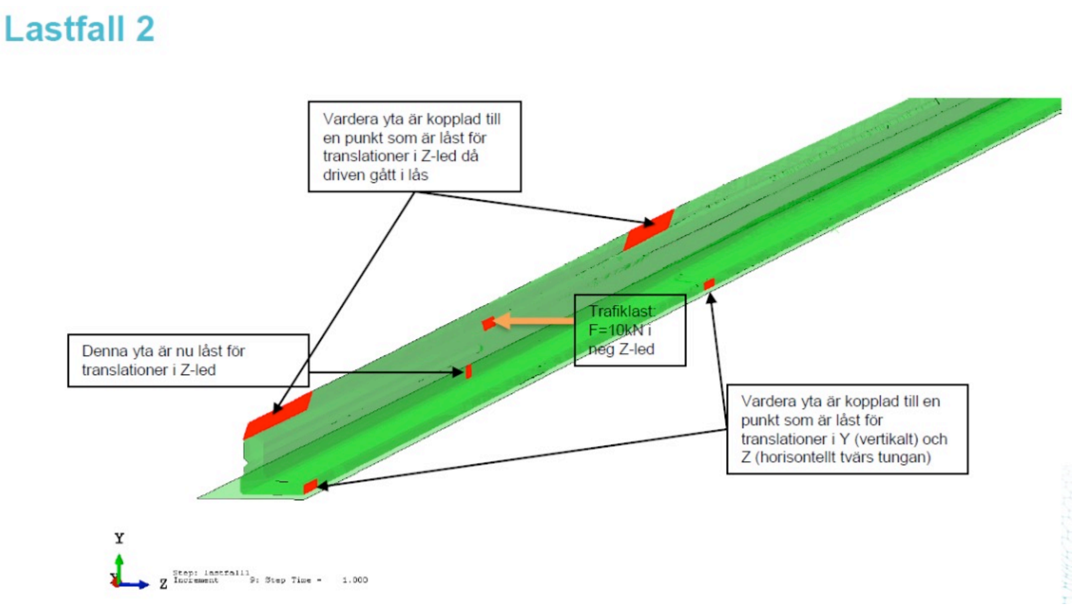


Figure 30 Description of how boundary conditions are modelled.

Resultat

- Lastfall 1 (sten på 30 mm kilas fast mellan tunga och stödräl)

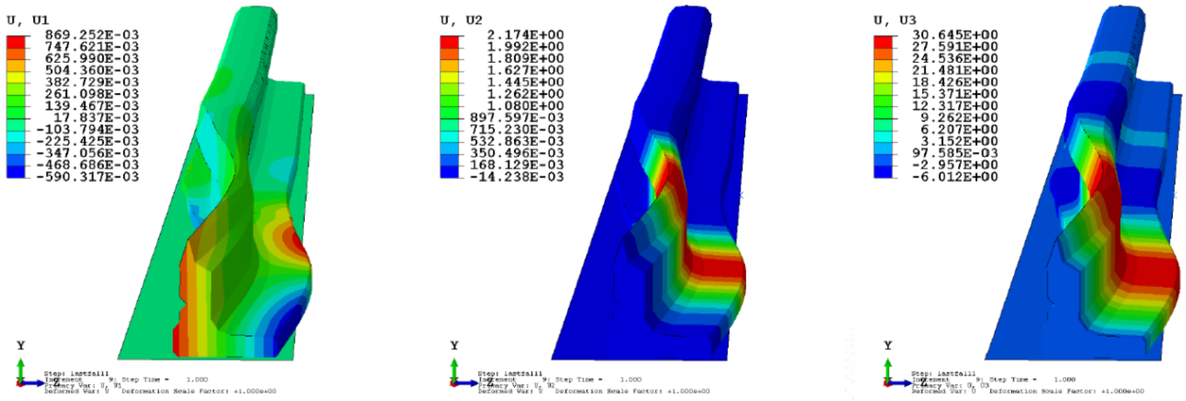


Figure 31 Deformation of a locked switch rail due to a prescribed 30 mm horizontal deformation of the rail foot.

As seen in Figure 31, the simulations capture the horizontal deformation of 30 mm at the foot at the position of the obstacle when a 30 mm stone is trapped between rail foot and support rail. The corresponding vertical lift is 2.17 mm

Resultat

- Lastfall 2 (trafiklast på 10kN verkar horisontellt på tungan medan stenen fortfarande är fastkilad)

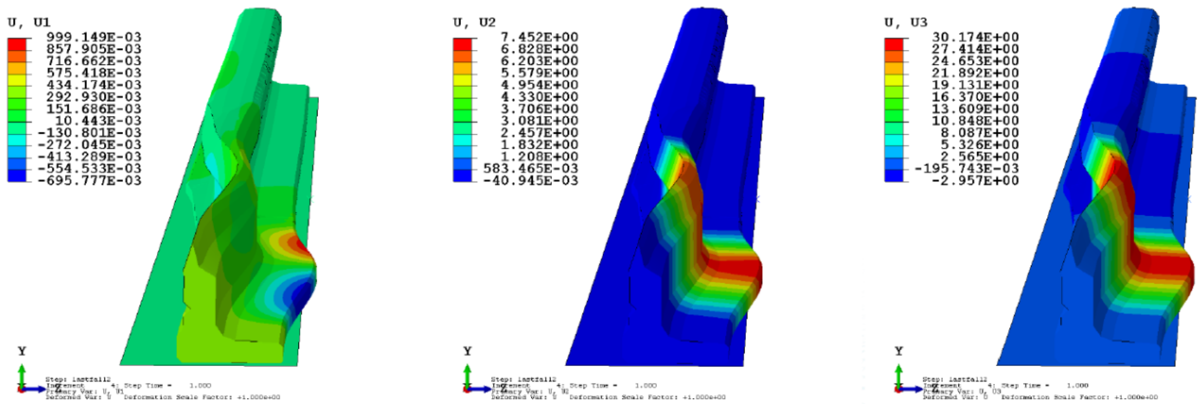


Figure 32 Deformation of a locked switch rail with a 30 mm rail foot deformation due to an applied horizontal wheel load acting on the switch rail head.

The results for load case 2 show a sustained horizontal displacement of 30 mm in the foot (U3 in Figure 32). The vertical lift of the edge of the foot due to the static horizontal load of 10 kN is 7.45 mm (U2 in Figure 32). If the vertical lift of the foot is known, the horizontal movement at the top of the switch rail can be estimated as the ratio of the height of the switch rail (134 mm) divided by its foot length (105 mm) based on the presumption of a rigid cross-section and that the outer corner of the web/foot-connection is fixed during the rotation.

In M5745/87 (see chapter 3), it is stated that 15 mm is the upper limit for the gauge reduction, which should absolutely not be exceeded. If we in this feasibility study adopt this as an hypothesis, we can reformulate the derailment criterion as defining what horizontal force from the wheel that is required to achieve this.

In an undeformed configuration the flange angle is β=75° see Figure 10 and [1]. When the horizontal force has deformed the tip of the switch rail by 15 mm, the angle β has been reduced by about 6° [1]. This reduces the allowed (U2 in Figure 32) value of Y/Q slightly see Figure 9.

$$\delta - \Delta_d - \Delta_W \leq 15 \text{ mm} \tag{3}$$

δ = 30 mm and Δ_d = 2.17·134/105 = 2.77 mm.

In order for the rail gauge to decrease to below 15 mm, it must be ensured that $\Delta_W \geq$ 12.23 mm. As discussed above, a horizontal force of 10 kN resulted in a vertical lift of the tip of the rail foot by 7.45 mm. Due to rotation (with presumptions detailed above), the corresponding horizontal deformation of the switch rail head is then 7.45·134/105 = 7.45·1.28 = 9.54. The contribution from the force is 9.54–2.77 = 6.77 mm. To obtain $\Delta_W \geq$ 12.23 mm, the required force can then be estimated as

$$F \geq 10 \cdot 12.23/6.77 = 18 \text{ kN} \tag{4}$$

Note that we have presumed linearity between force and deformation, and that the cross-section is rigid and rotates around a fix outer corner between foot and web.

Another effect that is not considered is that the wheel force will further deform the ballast stone, see Figure 21. This in turn will give rise to further reduction of δ. How large this deformation will be, should be further investigated in field tests.

According to the SS-EN14363-2016 (see also Figure 9), Y/Q has to be above 0.8–1.2 for flange climbing to take place. This corresponds to an axle load of less than 1.2·2·18.1 = 44 kN, i.e. some 5 tonnes. This is not fulfilled for any of the vehicles described in chapter 5.

8.2 Simulations of dynamic switch negotiations using Simpack

The section is written by Björn Pålsson, Chalmers.

The feasibility study has also investigated whether the commercial multi-body dynamics code Simpack can be used for to further investigate risks for derailments. It has been evaluated whether the software can be used to study the dynamic vehicle–switch interaction when the switch rail support is disturbed by a foreign object according to the set-up in load cases 1 and 2 in the previous section. The assessment is that Simpack has the functionality to perform these investigations from its 2022 release. In addition to the functionalities available in the program, CHARMEC has a model of a turnout structure in Simpack's flextrack format that can be used as a basis for further investigations. The model uses beam elements to model rails and sleepers, and it accounts for the varying rail properties where needed, as in the switch rails.

To conclude, Simpack has the functionality required to model and simulate relevant TKK cases from the next release and there are base models to start from.

8.3 References:

1. Vossloh, Drawing 1-79117 of a 1:15 switch rail, 2013-10-24
2. Scanscot by Technia, Personal communications and modelling support to Björn Paulsson, 2021
3. R Hafström, Loading and crushing of trapped ballast stones, Chalmers University of Technology, Master’s thesis 2020:61, 2020

9 Switch rail control from a signalling perspective

The chapter is written by Per-Erik Ingels, Trafikverket

The signalling system should, among other things, ensure that conditions for driving railway vehicles across a certain track section at a certain speed are safe, and that this information is communicated to the vehicle and the driver. These checks include control of all switches along the track section.

For some switch types, the signalling system only controls the position sensors in the switch drives (control of position). In other switch types, the track width in the switch unit is also controlled in one or several positions using sensors (switch rail control sensors – TKK) placed at relevant positions of the switch unit (track gauge control).

Which checks that need to be made for a specific type of switch in order for a railway vehicle to be allowed to be driven at different speeds through the switch, depends on the switch construction and is decided by the switch engineers.

The Swedish signaling system's method for checking rail gauge is by establishing one or more electrical contacts via position sensors/circuit breaker located in the switch drive and by switch rail detection sensors (TKK).

Two important principles in the design of these electrical control circuits are reliability and fail-safe. To enhance reliability, the circuit for position control (control of position in the switch drive) and rail gauge control, have now been divided into two separate circuits. This limits effects of faults in rail gauge control. Previously, it was common that the two controls were merged for one switch. In that case, a fault in rail gauge control resulted in a fault for the entire switch. In a switch that was intended to provide flank protection, this protection could then not be provided, and the signalling system indicated stop. By separating the control circuits, it was instead possible to check the rail gauge separately after each switch transition, whereas the drive positions can be controlled continuously.

Even though the control circuits for drive position control and rail gauge control are designed for enhanced reliability, there is always a risk that faults develop in the control circuits. In addition, the fact that demands on traffic safety, and fail-safe designs are prioritized above reliability demands will influence the reliability of the control circuits.

The best way to maintain both high safety and high reliability is to construct track switches in a manner that minimizes the demands for technical controls in the signalling system.

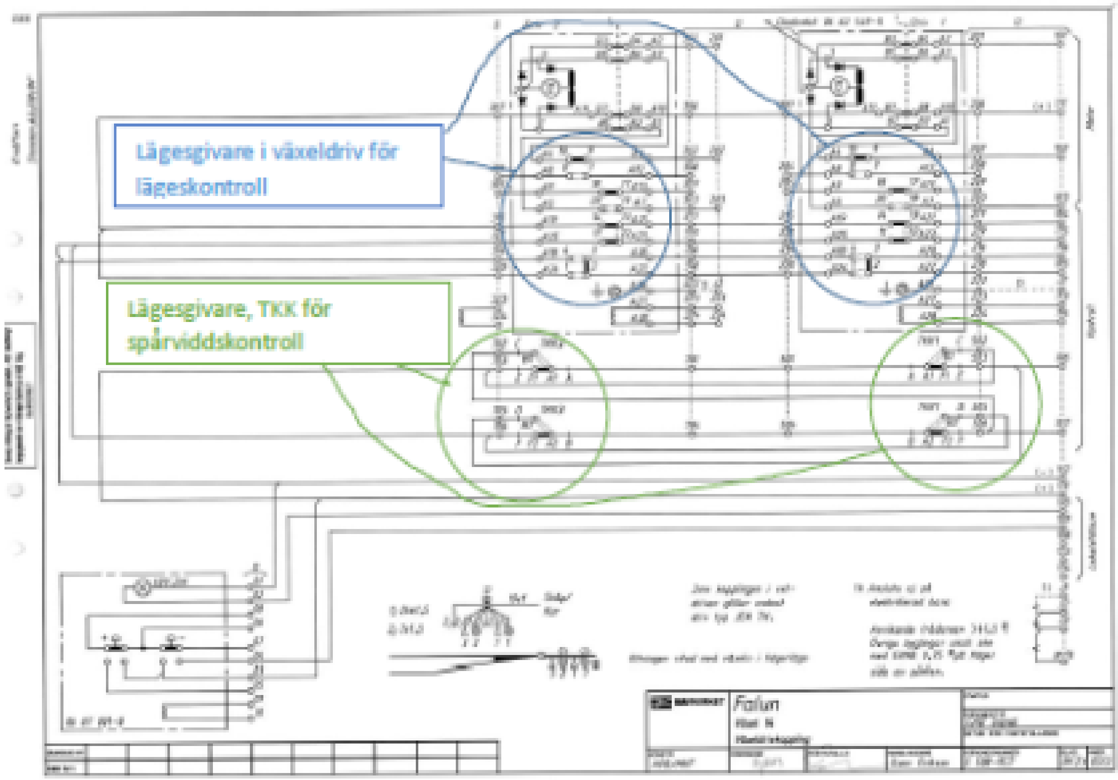


Figure 33 The drawing shows in blue the control of position ("Lägesgivare i växeldriv") and in green rail gauge control ("Lägesgivare TKK för spårviddskontroll"). Drawing from Trafikverket.

10 Suggestions for field tests to verify preliminary analyses

A description of limited tests to verify and calibrate the preliminary calculations has been outlined. These tests can also be a way to obtain an early reduction of the number of switch rail control sensors, by showing that some of these do not have a safety-enhancing function. Due to Covid-19 and the limited time for the pre-study, it has so-far not been possible to carry out these tests.

The idea is to clarify how an object trapped between switch rail and stock rail affects the deflection of the switch rail, and how this can be further studied in different degrees of detail. The work includes in the first set tests to verify results from calculations, and to verify the assumed ballast characteristics. More specifically, the tests are expected to provide results that can be used to verify/revise:

1. Calculated deformation of the switch rail when exposed to forces from the drives with a fitting piece of varying width placed between the foot of the switch rail and the stock rail.
2. Deformation/fracture in ballast stones placed between the foot of the switch rail and the stock rail. This test is repeated to see how the ballast stone is further deformed when loaded several times.
3. For which size of a fitting piece locking of the drives occur when the fitting piece is placed on different sliding plates in the vicinity of the TKK.
4. Which horizontal deformation of the upper edge of the switch rail that occurs when a horizontal force of 10 kN is applied to the upper part of the switch rail.

A preliminary plan has been prepared and communicated to Trafikverket.

11 Recommendations

The most important recommendation of the pre-study was to continue with a PhD project to finally be able to quantify safety levels, and hopefully be able to reduce the number of switch rail controls. This has now been achieved, and the work will start 2022.

It is also recommended to continue the open discussions with Transportstyrelsen. This has been achieved and Transportstyrelsen has been informed at two occasions about the progress of the project. At the same time, Transportstyrelsen has presented its view on how a detailed risk analysis according to common safety methods for risk analysis (CSM-RA) should be made.

The feasibility study and previous studies have shown the difficulty of obtaining detailed information on how other countries solve the control of the switch rail. Therefore, the information from the suppliers has been valuable since they have a more comprehensive view of the issue. To continue an open information exchange with the leading suppliers would therefore be valuable.

In parallel with the PhD study, it is recommended to start a project which, based on the new knowledge gained in this study should aim to reduce switch rail controls that do not enhance safety. A first step should be to define an action plan based on inspections of a few different types of switches in track.

12 Concluding remarks

The report sets out with an introduction to switch rail control. It then reviews previous investigations on the use of switch rail controls and concludes that all Swedish investigations are based on a one-page report (M5745/87) from 1987. From a scientific perspective the conclusions of this report can neither be verified nor falsified. This has been further established by studying all available reports and presentations that may provide insight into how the conclusions of M5745/87 were achieved.

Current regulations regarding track displacement and flange climbing contribute to the railway's positive safety development. These regulations are based on the ORE/ERRI reports C138 and B55. However, these investigations do not give a clear indication of safety levels related to reduced rail gauge in switches.

Degradation and fracture of ballast stones trapped between switch rail and stock rail has been investigated to some extent in a MSc project. Also loads from vehicles have been investigated to some extent. Both areas should be studied further in the subsequent PhD project.

Preliminary static calculations indicate that a derailment cannot be achieved for the studied "worst normal case". These preliminary calculations need to be complimented by simulations of dynamic train negotiations. The simulations should further be verified towards tests in track since there are several influencing parameters that are difficult to evaluate only by calculations.

It has been investigated and ensured that simulations of dynamic switch negotiations can be made using the commercial code Simpack. During the feasibility study bugs in Simpack have been identified. These bugs are fixed in a recent release.