Innovations Deserving Exploratory Analysis Programs

IDEA

Safety IDEA Program

Reducing Wheel Climb at Switch Points to Reduce Derailments

Final Report for
Safety IDEA Project 23

Prepared by:
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April, 2014

TRANSPORTATION RESEARCH BOARD
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Final Report:

IDEA Project S-23

Prepared for

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Transportation Research Board

National Research Council

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Joseph Smak: Senior Director of Track maintenance and Compliance, Amtrak

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Executive Summary

Wheel climb derailments in switches remain a major derailment category for both freight and passenger rail operations in the US. Wheel climb derailments occur at both high and low speeds in both facing and trailing moves through the switches. While some causes are relatively straightforward, such as over speed entering or leaving the switch, or a broken point, most wheel climb derailments are a combination of a worn switch point (to include profile and angle of the switch point) and a worn wheel. A number of European railroads have adopted switch maintenance practices that focus on wheel climb in the switch point area, several of which have the potential to improve current US rail maintenance practices.

This report includes the results of a survey and detailed engineering analysis of international maintenance practices aimed at reducing the risk of wheel climb at switch points and describes the potential application of these practices for US freight and passenger railways. As part of this activity, the study team examined international standards and practices from several major international rail systems and compared them to AREMA, FRA and individual US railroad switch point inspection practices. They then analyzed several of these practices from the perspective of the dynamic load environment of US railroads to include expected lateral (L), vertical (V) and L/V force levels and the associated potential for wheel climb in the switch point areas.

The specific problems addressed by these practices and corresponding measurement gauges include:

- Improper flange contact between the wheel flange and the switch point (switch rail[1]) which could lead to wheel climb
- Excessive or unusual wear of the switch point (switch rail) and of the stock rail. This includes the condition where the stock rail head wear is greater than the wear on the switch point
- Excessive switch point damage to include chipping and wear
- Improper switch point (switch rail) profile to include switch rails with sharp gauge corner profiles
- Excessively worn gauge face of the switch point or stock rail with corresponding sharp gauge face wear angle which could lead to wheel climb.

The researchers, working with the Expert Review Panel and Norfolk Southern research staff developed a series of hand held measurement gauges to address these problem areas, based on European practice, and then modified to reflect US conditions and practices. These gauges were then taken out into the field, for evaluation on a series of

[1] In Europe, the switch point is often referred to as the switch rail.

switches in various conditions, by a team of rail experts (the Study Team)[2]. Those gauges that were considered to be ineffective were dropped from consideration. A series of three such field evaluations were performed in a yard provided by Norfolk Southern.

The specific focus of the evaluations and gauges was on switch point conditions not currently fully addressed by FRA, AREMA or known railroad practices, but which have been shown to contribute to wheel climb derailments in switches.

The Study Team determined that several gauges were of real value in defining poor switch conditions that could potentially result in a wheel climb derailment. These include gauges that looked at several problems commonly seen in US switch points, such as improper flange contact between the wheel flange and the switch point, excessive switch point damage, and excessively worn gauge face of the switch point or stock rail with corresponding sharp profile angle.

Specifically, the following gauges were recommended by the Study Team for further development and field evaluation, and potential adoption by US railways and transit systems to control wheel climb derailments:

- The chipped point (CP2) gauge which addresses chipped or damaged switch points, as modified based on US wheel and switch designs
- The TGAAR1B gauge which is the US version of the UK Network Rail TGP8 gauge, using an AAR 1B new wheel profile
- The gauge face angle (GFA) gauge with a 32 degree gauge face angle.

In addition, the Study Team judged the third generation severe profile (SP) gauge to be useful and it appears to work well in the field, giving an indication of potential for wheel climb for a severely worn wheel. However, it still requires additional development work for use as a go/no go inspection tool.

[2] The team of rail experts included the Expert Review Panel supplemented by Norfolk Southern research staff personnel and the researchers.

Introduction

Wheel climb derailments in switches remains a major derailment category for both freight and passenger rail operations in the US. Wheel climb derailments occur at both high and low speeds, and in both facing and trailing directions. While some causes are relatively straightforward, such as over speed entering or leaving the switch, or a broken point, most wheel climb derailments are a combination of a poor or degraded switch point (to include profile and angle of the switch point) and a worn or degraded wheel profile [3]. A number of European railroads have adopted switch maintenance practices that focus on wheel climb in the switch point area, several of which have the potential to make switch inspection and maintenance in the US more effective.

Examination of the FRA safety data base shows that track caused derailments are a major derailment cause in the US and that switch point derailments are among the largest categories of track caused derailments, representing approximately 10% of all track caused derailments in 2013 (1).

A large number of these derailments are related to worn switch points; particularly switch points that exhibit large gauge face angles or poor wheel rail contact (2,3) For example, this was the case with the May 2006 derailment of an Amtrak train on Metro North Rail Road where the cause was found to be a worn switch point. Several injuries were reported during that derailment. Numerous other examples for both passenger and freight train derailments exist (1, 2, and 3).

Noting that approximately 50 to 60 derailments per year are associated with worn or broken switch points (1), (the number would be much higher if non-FRA reportable derailments were included) and further noting that these types of derailments are often not a simple single cause derailment, the potential benefits of the development of improved maintenance and safety practices to reduce the risk of these derailments is very high.

Stage 1

Task 1. Literature search.

The initial task performed was a comprehensive literature search focusing on international practices to address the risk of wheel climb at the switch point area of the turnout. Note there is a variation in terminology between American and European practice: American terminology refers to the “turnout” to include the switch points, stock rails, closure rails and frog; while European terminology often uses the term “switch” for

[3] Other factors that may influence wheel climb are truck condition, vehicle performance, high angle of attack or other factors that may result in an increased L/V ratio.

the full turnout. Furthermore, European terminology often refers to the switch point as the switch rail or switch blade, also referred to as the lame d'aiguille (French) or weichenzunge (German).

A review of key European literature and standards show several major innovative approaches to switch inspection from a derailment prevention point of view. These will be discussed herein.

Network Rail (UK)

British Railway standards[4] associated with the identification of derailment risk at switches focus on identification of derailment hazards, particularly at the switch point (4). Network Rail hazards include the following conditions:

- Improper flange contact between the wheel flange and the switch rail[5]
- Excessive or unusual wear of the switch rail (point) and of the stock rail
- Excessive switch rail damage
- Improper switch rail profile.

Several conditions, also referred to as Derailment Hazards, are checked according to Network Rail Standard NR/L2/TRK/0053, "Inspection and Repair to Reduce the Risk of Derailment at Switches." These include:

- Improper contact between the wheel and the switch rail. The check is to ensure there is no contact made between the switch rail and the bottom of the wheel flange. This check is performed using a specially designed track gauge known as the TGP8 Gauge, which is based on the British P8 wheel profile and intended to ensure that the flange cannot climb the switch rail onto the stock rail, causing a derailment.
- Derailment Hazard 3 is a condition of stock rail headwear associated with a less worn switch rail, checked using Network Rail Gauge 1.
- Derailment Hazard 4 is a condition of switch rail damage which is checked using Gauge 2, to identify an unsafe damaged switch rail.
- Derailment Hazard 5 is a condition of a switch rail with a sharp gauge corner profile, checked with the Network Rail Switch Radius Gauge.

Thus, four Gauges are used:

- TGP8 wheel profile gauge
  - Checks if any contact is made below the 60° line
- Switch Wear Gauge 1
  - Checks vertical wear on stock rail relative to switch blade height
- Switch Wear Gauge 2
  - Checks switch blade is not damaged near switch point
- Switch Radius Gauge

[4] Network Rail is the infrastructure owner and maintainer in the UK and includes virtually all of the lines associated with the previous British rail system.

[5] When Network Rail standards are referenced; the term switch rail will be used instead of switch point since that is the commonly used British term. Elsewhere the term Switch Point will be used.

– Checks that there is not a sharp corner in hardened steel.

In carrying out the inspection process, the inspector first checks for improper wheel contact on the switch rail; specifically to ensure there is no contact made between the bottom of the wheel flange and the switch rail, such that the flange could climb the switch rail onto the stock rail, causing a derailment. This check is made using the "Track Gauge with P8 Wheel Profile", or TGP8 Gauge, to ensure that there is no flange/switch rail contact below the 60° line on the gauge. The TGP8 gauge is applied along the length of the switch rail, up to 2000 mm [78"] past the switch point, depending on the switch design. A diagram of this check is shown in Figure 1 and the Gauge itself in Figure 2.

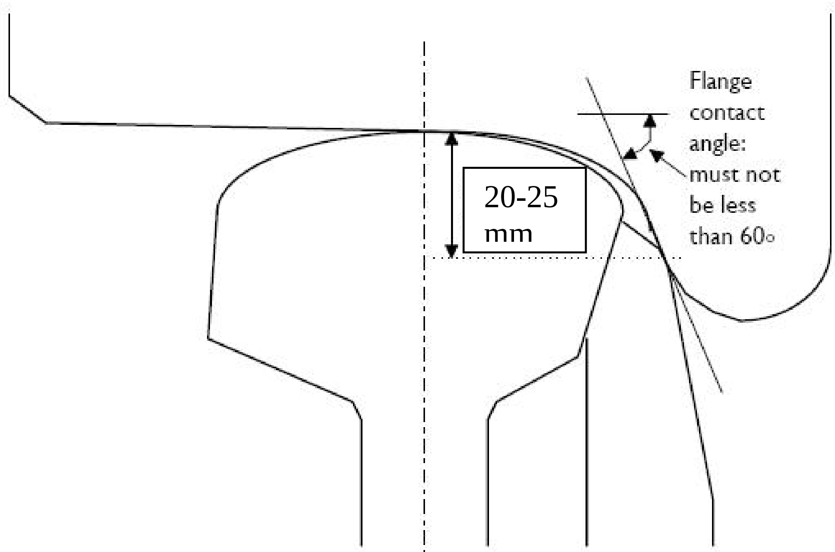


Figure 1 TGP8 Gauge to Check Flange Contact Angle

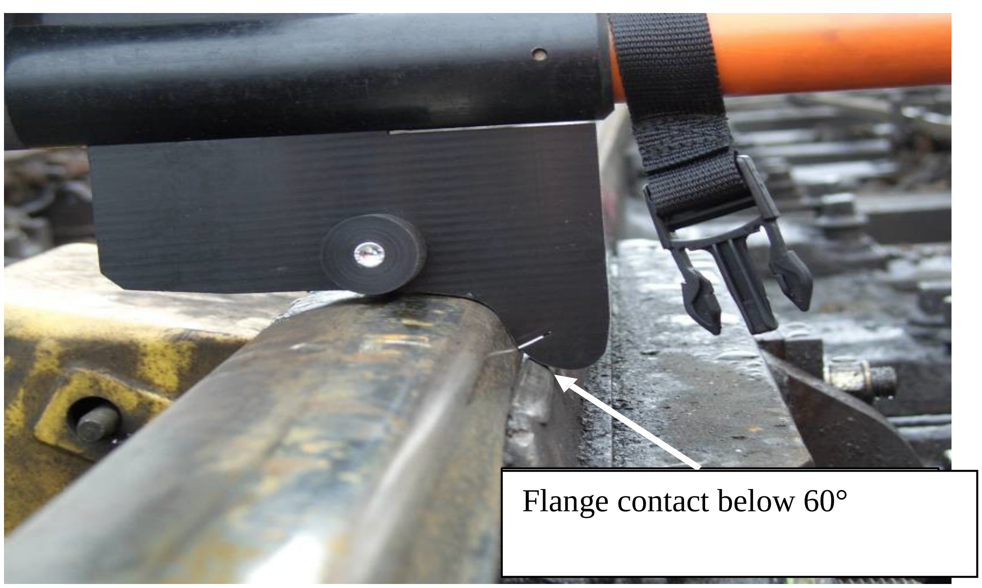


Figure 2: TGP8 Gauge showing switch point contact below the 60° mark – unsafe.

Figures 3 presents a digital representations of the wheel profile and the switch point as taken using automated switch inspection technology (5,6), and shows improper wheel flange contact, with contact occurring below the 60° mark.

Figure 3: Flange contact below 60° mark

The next inspection standards are based on two Network Rail Gauges (both mounted on a track level or equivalent rod[6]) that were based on earlier UIC gauges. The two gauges, shown in Figures 4A, B and C, are as follows:

- **Gauge 1.** Identifies the relationship between the running surface of the stock rail and the top surface of the switch rail at a specified position back from the switch tip. This is used to inspect for stock rail headwear associated with a less worn switch rail (Derailment Hazard 3).
- **Gauge 2.** Identifies whether the depth of any damage or chipping of the switch rail running surface is safe (Derailment Hazard 4)

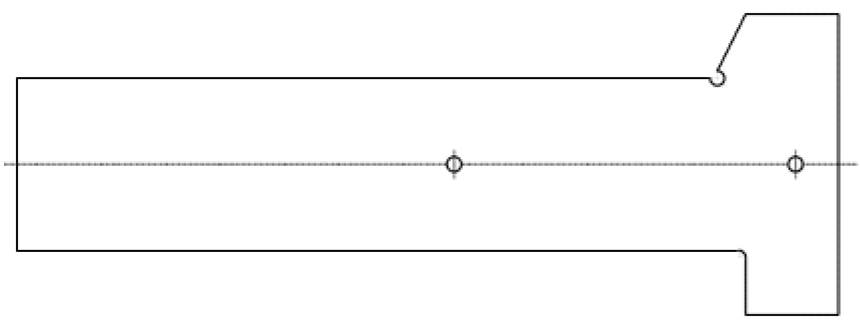


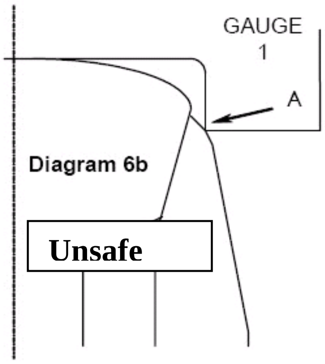
Figure 4A: Gauge 1 (bottom) and Gauge 2 (top)

[6] To reference the adjacent rail in order to provide an accurate measurement.

Figure 4B: Switch Gauge 1 used to inspect for stock rail headwear associated with a less worn switch rail.

Figure 4C: Switch Gauge 2 used to inspect for switch rail damage.

As noted, Derailment Hazard 3 is a condition of stock rail headwear associated with a less worn switch rail, which is checked using Gauge 1. A diagram of this condition and the associated Gauge 1 is shown in Figure 5.



Gauge foul of switch rail – **Unsafe**

Figure 5: Stock Rail Headwear Associated with a Less Worn Switch Rail

Thus Switch Wear Gauge 1 is used to check that the switch rail (switch point) is not sitting too high relative to the stock rail, at a specific location 40 mm past the switch point. Thus, for chamfered and undercut switches:

- If the corner 'A' of gauge 1 passes over the top of the switch rail the clearance criterion will have been met
- If corner 'A' of gauge 1 will not pass over the top of the switch rail the switch fails the inspection and remedial work is necessary.

Switch Wear Gauge 1 is applied as shown in Figure 6 for a rail profile that fails the Gauge 1 condition of not allowing any contact between the switch rail and the bottom of Gauge 1. Note, in these images, the original rail sections are traced in red, the measured rail profile is traced in yellow, and Gauge 1 is traced in blue.

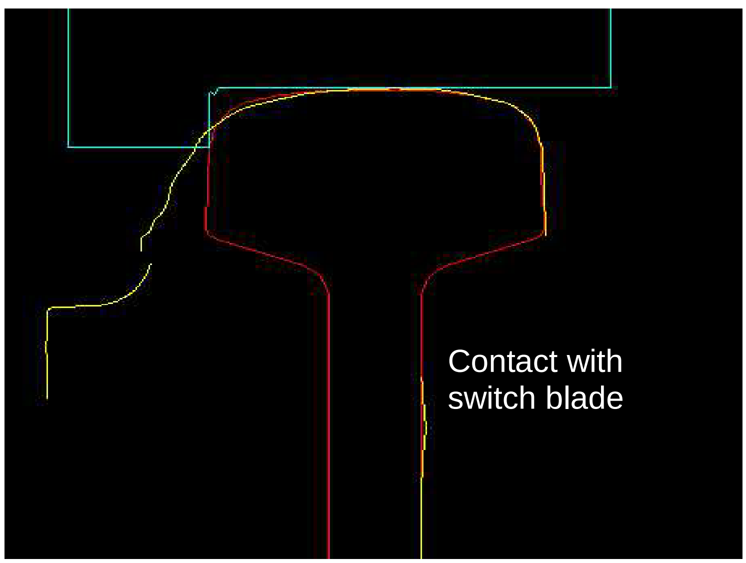


Figure 6 Application of Switch Gauge 1 for Relative Switch Rail Height; Fails Condition

Derailment Hazard 4 is a condition of switch rail damage, which is checked using Gauge 2 to identify an unsafe damaged switch rail. A diagram of this condition is shown in Figure 7. If corner 'A' of gauge 2 passes over the top of the damage at any position, without contacting the switch rail, then the switch rail fails the inspection.

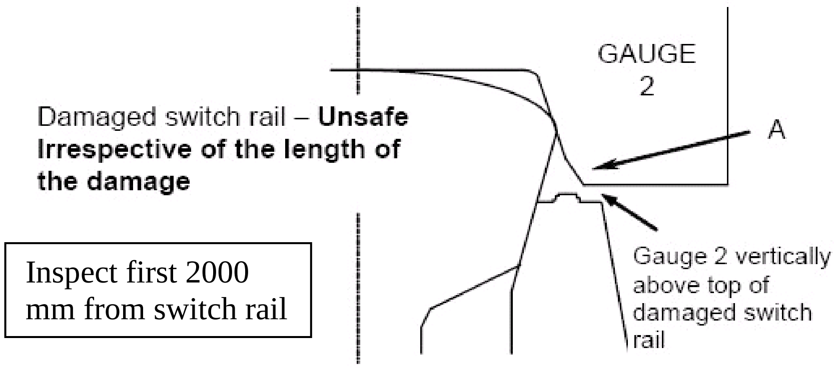


Figure 7 Derailment Hazard 4: Switch Rail Damage

Thus, as noted above, Switch Wear Gauge 2 is used to check that there is no damage to the top surface of the switch rail, and in particular there is no damage associated with the top surface being broken off. The region where Gauge 2 is applied is within 2000 mm of the switch point.

Switch Wear Gauge 2 is applied to switch rail in Figure 8. This profile fails the Gauge 2 condition because the bottom corner of Gauge 2 is both above and inside the top surface of the switch rail. In this image, the original rail section is traced in red, the measured rail profile is traced in yellow, and Gauge 2 is traced in green.

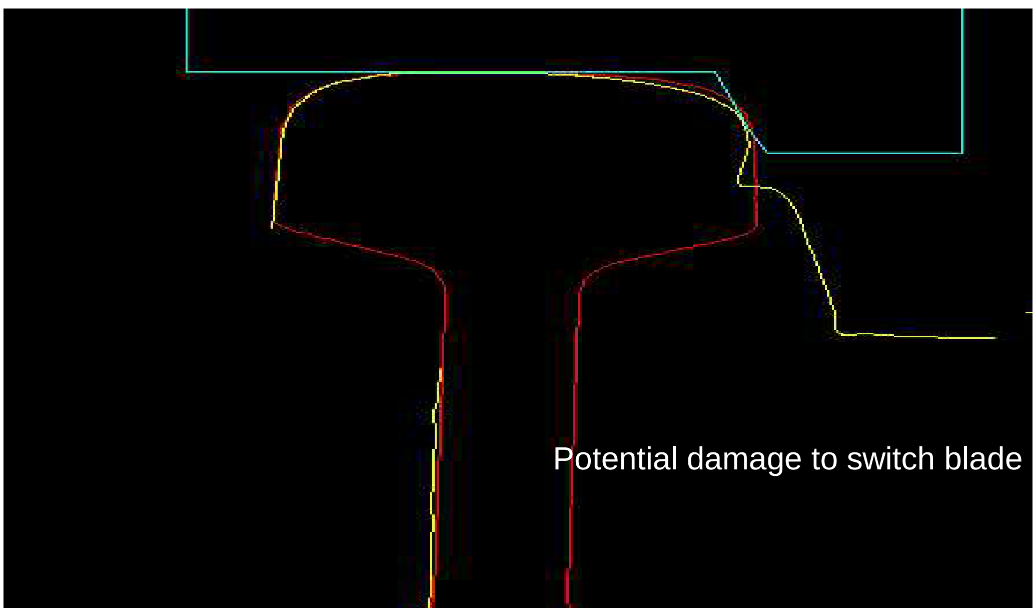


Figure 8: Switch rail with damage that fails Gauge 2 inspection

Derailment Hazard 5 is a condition of a switch rail with a sharp gauge corner profile, which is checked with the Switch Radius Gauge. A diagram of this condition and the associated Switch Radius Gauge is shown in 9.

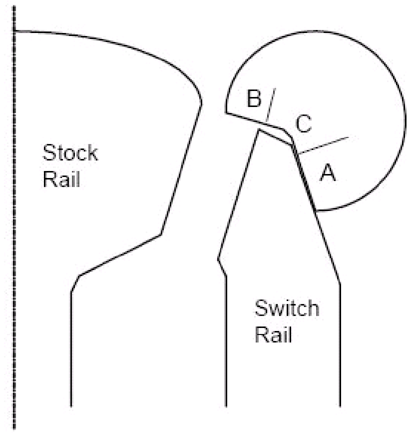


Figure 9: Derailment Hazard 5: Switch Rail with a Sharp Gauge Corner Profile

The condition is unsafe if a pronounced edge or sharp radius on switch rail at C precludes contact with gauge at B (or at A, if the gauge is rocked). Thus the Switch Radius Gauge is used to check that the top of the switch rail is not too sharp in switch rails made of hardened (e.g. relatively brittle) steel to prevent breaking off the top of the switch rail by stress concentrations. For non-hardened steel, a sharp switch rail surface would likely deform by plastic flow instead of breaking out, therefore it is not as critical of a condition. The region where the Radius Gauge is applied is within 2000 mm of the switch point. Figure 10 shows a rail profile that fails the Radius Gauge condition because the upper and lower edges of the gauge do not contact the switch rail.

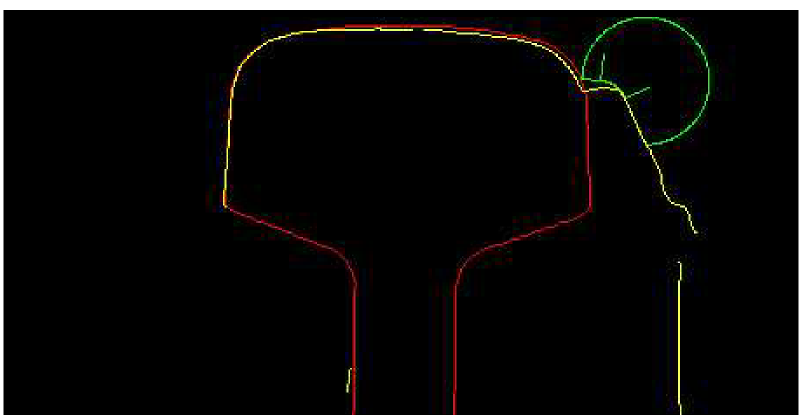


Figure 10: Derailment Hazard 5: Not Acceptable Condition

Another Condition that can result in a wheel climb derailment is a worn switch rail gauge face, as shown in Figure 11. If the gauge face is worn to a flatter angle, such as shown in Figure 11, wheel climb and associated wheel climb derailments can occur.

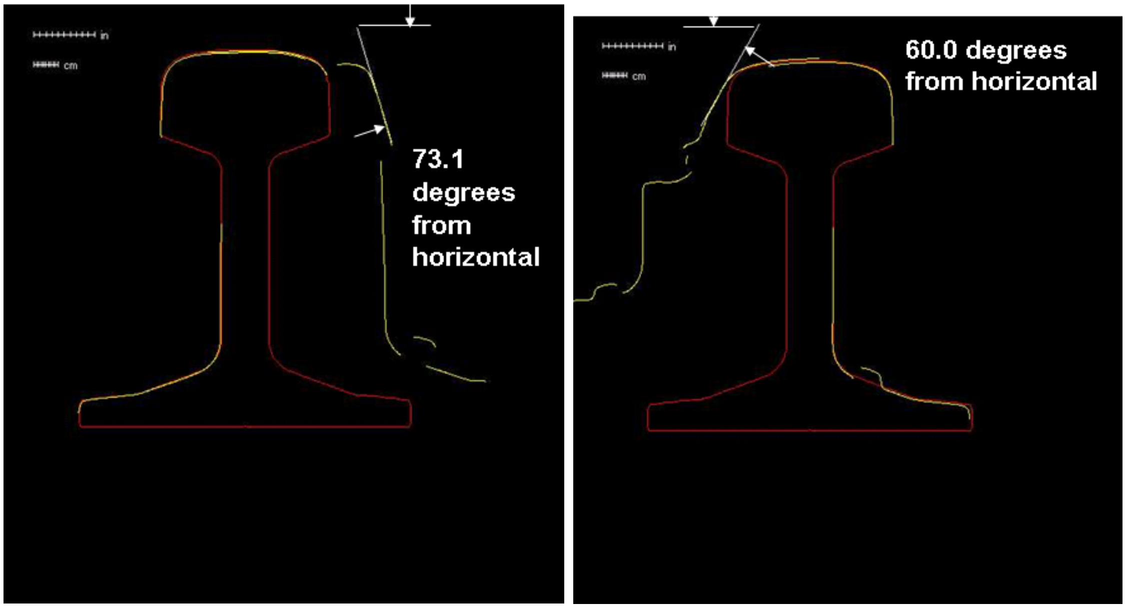
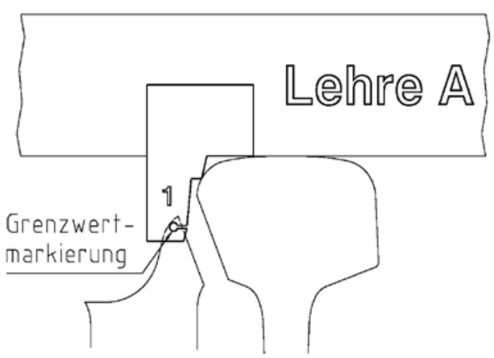


Figure 11: Examples of Gauge Face Angle Measurement

Swiss Federal Railway (SBB)

In a manner analogous to that used by Network Rail, the SBB (Swiss Federal Railway) also uses specialized manual switch gauges that can be carried by the inspector and used for measuring the condition of the switch points (switch rail or weichenzunge).

SBB Gauge A (Lehre A) is used to measure the relative height of the switch point (switch rail)[7] and the stock rail in the area of the switch point. Figure 12A shows a severe wear condition where Gauge A does not properly fit against the closed switch point, but rather there is contact between the gauge and the point (the point lies within the outline of the gauge). In this case, the switch point is in a derailment hazard or "red" derailment condition and corrective action is required.



[7] The term switch point will be used here-in instead of switch rail with regard to SBB and other standards

Figure 12A: Unsafe ("red") switch point condition

Figure 12B shows a different unsafe condition where the switch point is lower than 2 mm below the limit mark. In this case, the switch point is in a derailment hazard or "red" derailment condition and corrective action is required.

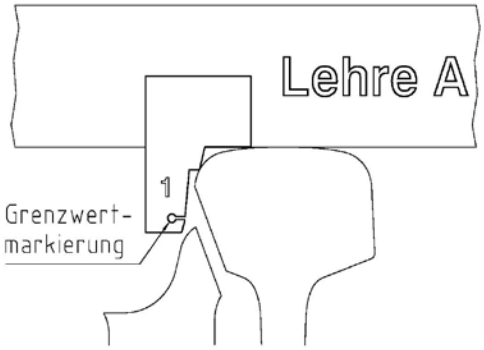


Figure 12B: Unsafe ("red") switch point condition

Gauge A is also used to measure the location of the point of contact between the switch point and stock rail as illustrated in Figure 13. This makes use of the distance feeler illustrated as number 5 in Figure 13.

Figure 13 shows how Gauge A is used to measure the location of the point/stock rail contact. Note the Limit mark on Gauge 1 [Grenzwertmarkierung] and the distance feeler [Abstandfaster]. If Gauge A can properly fit and clear the distance feeler located at the contact point of the switch point and stock rail and the switch point is higher than 2 mm below the limit mark, then the switch point is in acceptable ("green") condition.

In Figure 13, Gauge A does not properly fit and clear the distance feeler located at the contact point of the switch point and stock rail even though the switch point is higher than 2 mm below the limit mark. In this case the switch point is considered unsafe and in "red" condition, requiring corrective action.

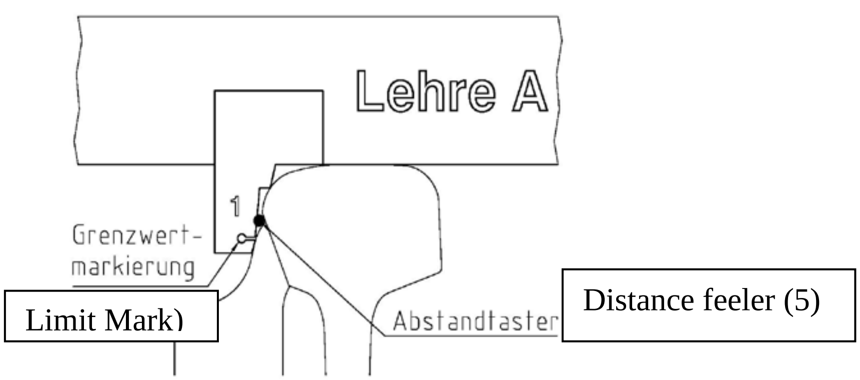


Figure 13: Unsafe ("red") switch point condition

Gauge B is used to look at the magnitude of any chips, breaks, or surface defects on the switch point along the length of the switch point. This is illustrated in Figure 14, which shows how Gauge B is applied to the closed switch point. The depth of the defect, 2T, and the length of the defect, 2L, is measured as shown in Figure 14. If the defect is less than 2T in depth and less than 2L in length then the switch point is in acceptable ("green") condition. No action is required.

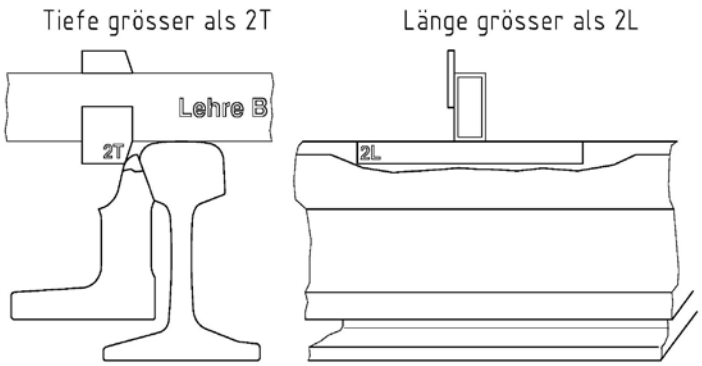


Figure 14: Unsafe ("red") switch point condition (Depth greater than 2T, length greater than 2L)

Gauge C is used to look at the magnitude of the wear angle in the switch point along the length of the switch point. This is illustrated in Figure 15. It is noted in the Swiss standards that the slope angle of the switch point is an important criterion for derailment safety. This includes after grinding or reprofiling the switch point, where a conscientious effort must be made to control the slope of the switch point. This is consistent with Network Rail standards noted earlier. If the angle of the switch point is shallower than the gauge C angle (5) for a length of 300 mm (12 inches) or greater, as shown in Figure 15, then the switch point is in unsafe ("red") condition and corrective action is required.

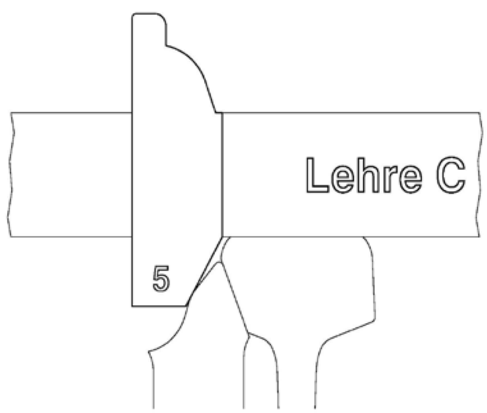


Figure 15: Unsafe ("red") switch point condition (angle less than Gauge C (5) for length of 300 mm).

Scope of Literature Search

It should be noted that the original project scope included German, French and other railway standards. As part of the literature search activity, these railways were contacted, and in the case of the German Federal Railways (DB), had initially responded that they would supply their standards (initial indications were that the Austrian Federal Railway OBB would also supply their standards). However, when the formal request for standards was made, the standards were not provided, in spite of repeated requests and contact follow up. After discussion with SBB, the researchers felt that there was strong similarity between the various German speaking rail systems and that the Swiss Standards would be representative of the DB and OBB as well. Although it is unfortunate that the French (SNCF) standards could not be obtained, after reviewing British, French and German publications on track inspection and maintenance, the judgment of the research team was that by having the British and Swiss standards, a significant portion of the major European inspection standards were included in the survey.

Task 2: Analysis of Selected Parameters

The focus of this task was on identifying types of inspections in current use overseas, and determining which of these may be best adapted for use in the US. In addition, as part of Task 2, a set of four gauges, the same as or similar to the Network Rail gauges, were manufactured by Norfolk Southern and tested at a NS yard on October 23, 2013.

The gauges that were manufactured and used were:

- Network Rail Switch Gauge 1 used to monitor stock rail head wear (see Figures 4B)
- Network Rail Switch Gauge 2 used to monitor chipping of switch rail (see Figures 4C)
- A modified TPG8 based on a new AAR 1B wheel profile (see Figure 16, bottom gauge)
- A modified TPG8 based on a severe worn US wheel profile (see Figure 16, top gauge-upside down position)
- Network Rail Switch Radius Gauge used to monitor sharp tip radius on switch point (nicknamed “Pac Man” because of is shape – see Figure 9)

Figure 16: AAR 1B Wheel Profile Gauge as manufactured in the US by Norfolk Southern (bottom, on switch point) with severely worn US profile gauge in top position.

Switch Point Damage, Chipping and Wear

Switch point condition is normally defined in current US standards. Some US railway and transit standards take their lead from FRA Track Safety Standard 213.135 (h) which states that "unusually chipped or worn switch points shall be repaired or replaced." No specific dimensions are provided, either in the basic standard or in the FRA Compliance manual, which provides guidance as to the interpretation of the FRA standards by FRA track inspectors. However, many railways and transit systems do have more specific standards. These standards can take the form of defining depth (height) from the top of the switch point and corresponding length of the damage or, more commonly, depth (height) from the top of the stock rail with corresponding width and/or length.

An example of the first is found in paragraph 8-3.c the US Department of Defense Unified Facilities Criteria Track Standards (8) which states that "If the switch point is chipped, broken, or worn more than 0.5 inch down and 6 inches back from the point, maintenance standards require the switch point to be restored or replaced. " An example of the latter is Amtrak's standards (9) which state that:

- Unusually chipped or worn switch points with an unprotected flat surface 5/16" or more in width at a depth of ¾" below top of stock rail and switch point must be removed and replaced immediately. May contribute to wheel climb derailments.
- Replace switch rails and matching stock rails when worn or chipped so that the top of the switch point is more than 7/8" below plane across top of stock rail.

Likewise, the Federal Transit Administration (FTA) Compilation of Industry Best Practices for Track Inspection and Maintenance (10) states that "immediate protection and corrective action are necessary when a switch point is found to have an unprotected flat surface of 5/16” or more in width and a depth of ¾” or more below the top of the stock rail. It further recommends speed restrictions as shown in Table 1.

Depth of Chip	Speed	Condition
Up to 3/16”	Maximum authorized speed	Green
Greater than 3/16” to 3/8”	30 mph	Yellow
Greater than 3/8” to 3/4”	15 mph	Red
Greater than 3/4”	Supervise all operations, repair immediately	Black

Table 1: Chipped Point Depth Limits

These appear to be similar or somewhat larger than the British and Swiss standards for chipping noted in Task 1. The Network Rail parameter is 0.65” which is approximately 21/32”. The Network Rail parameter for length is 200 mm (8”) for a single defect. The Swiss (SBB) standard is for a depth 2L = 16.5 mm = 0.65” or approximately 21/32” and a length 2T = 180 mm = 7”. It should be noted that while both Network Rail and SBB define a specific gauge for measurement of chipping and wear, none of the US standards make use of a similar gauge.

Wheel flange Contact on Chipped Switch Point

The study team evaluated the NS manufactured Network Rail Gauge 2 for chipped switch points (Figure 17) on October 23, 2013. While the go/no go gauge itself appeared to be both useful and practical, it appeared that the gauge was condemning switch points that were, in the opinion of several experienced railroad and transit maintenance officers on the Expert Review Panel, still functional and not ready to be removed from track. This suggested that the height of the gauge may not be appropriate for US conditions.

Figure 17: Chipped point as measured by Gauge 2

In order to analyze the allowable size of a chip for US applications, and the corresponding height of this go/no go gauge, a series of analyses were performed using the standard AAR 1B wheel profiles (both Narrow and Wide flange).

The first set of analyses was based on the location of the gauge point of the wheel (where the radius reverses on the wheel flange); where there is the greatest potential for wheel climb.

For the AAR 1B Narrow flange wheel, the analysis determined that the distance from top of stock rail to the point of potential wheel climb is 0.69” at the gauge line. If the distance is taken from the tape line of the wheel, add 0.009 to get 0.70”.

For the AAR 1B Wide flange wheel the analysis determined that the distance from the top of the stock rail to the point of potential wheel climb is 0.71” at the gauge line. If the distance is taken from the tape line of the wheel, add 0.009 to get 0.72”.

Thus, based on these analyses, it appears that a more suitable gauge height, corresponding to the distance between the top of the stock rail and the damaged switch point, is 0.70.” Based on this, Gauge 2 was redesigned to reflect this new height.

Analysis of the Network Rail (NR) Gauge 2 flange angle, which should correspond to the wheel flange angle, showed that the NR Gauge 2 angle was 30º relative to vertical (60º relative to horizontal), which is not considered to be representative of US wheel profiles which have between 15º and 20º flange angles relative to vertical (70º to 75º relative to horizontal). As a result, the redesigned Gauge 2 was given an angle of 20º relative to vertical.

Wheel Profile and Contact with Switch Point

A key area that international standards address and US standards do not is the area of improper wheel contact on the switch rail that could result in the flange climbing. As noted in the Task 1 section, Network Rail checks this using the TGP8 Gauge, which ensures that there is no flange/switch rail contact below the 60° line on the gauge. A diagram of this check is shown in Figure 1 on page 8.

The Network Rail TGP8 gauge is based on a British P8 worn wheel profile and is designed to ensure that there is no improper wheel flange-switch rail contact, as designated by the 60° line or mark on the gauge (3C). The inspector uses this gauge to ensure that there is no wheel flange contact on the switch rail below the 60° line for the first 2000 mm past the switch point. This type of wheel-rail contact for several types of US wheel profiles is illustrated for conventional rail in Figure 18.

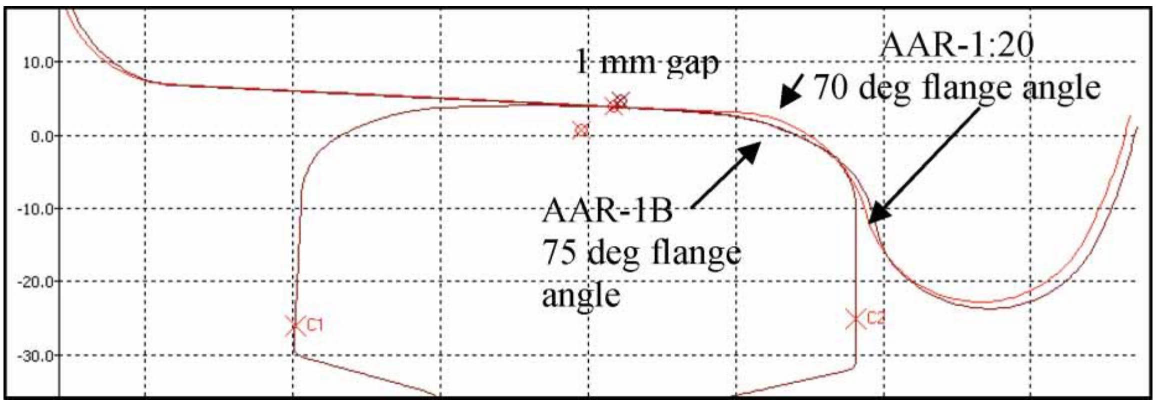


Figure18: AAR 1B vs. 1:20 wheel profile contact with new rail

It should be noted that this TGP8 gauge serves as a caution, rather than as a go/ no go gauge, such that if contact is made below the 60º mark, further investigation of the condition of the switch point must be made.

In order to assess the potential for such a gauge in the US, Norfolk Southern manufactured several profile gauges to include:

- Modified TGP8 gauge with AAR 1B wheel profile (bottom profile Figure 19)
- Modified TPG8 based on a severely worn US AAR 1B wheel profile (top profile Figure 19).

The NS-manufactured wheel profile gauges were evaluated in a NS yard on October 23, 2013 by the Study Team. Based on the evaluations in the field, the US version of the Network Rail gauge, using an AAR 1B new wheel profile and switch point contact below the 60° mark appears to identify an undesirable condition (Figure 19). Thus, the Study Team judged the gauge to be a helpful aid to inspection. The severely worn profile represents a condition in which derailments have, in fact, occurred (there was evidence of wheel climb at one of the measured switches considered during this field evaluation) and was of real interest to the Study Team. However, analysis of the mechanisms of wheel climb suggested that the 60º check, by itself, may not be the most effective indicator of potential wheel climb for this severely worn profile. Thus, the Study Team recommended that the US severely worn profile gauge be further evaluated to see if a more effective measurement gauge or approach can be developed based on this profile.

Figure 19: Modified Wheel Profile Gauges during evalution

Gauge Face Wear Angle

Gauge face wear angle standards have been used to control wheel climb derailments in both Europe and the US (11). That is because dynamic wheel climb derailments occur in the curved portion of the turnouts, usually at the switch point area, where high levels of lateral wheel rail forces are developed. One survey of turnout related derailments in transit systems found approximately 40 % of all track caused derailments were turnout related and that wheel climb at switch points is a major subcategory (11, 12).

Among those factors that have been reported to contribute to this class of wheel climb derailments is the angle of the gauge face of the rail, usually the outside or high rail of the curve. A sharp angle is often found on rails subject to gauge face wear, i.e. outside or high rails, where this gauge face wear can result in the development of a significant angle (ϕ) between the gauge face and the vertical. As this angle increases, the potential for a wheel to climb the gauge face of the rail increases.

The occurrence of dynamic wheel climb is also associated with high levels of lateral loads and correspondingly high L/V ratios (ratio of Lateral wheel/rail force to Vertical wheel/rail force). Wheel climb will occur when the net "upward" component of the lateral (L) and vertical (V) wheel/rail forces, parallel to the rail gauge face, is greater than the resistance to that force due to the normal force component N and the corresponding coefficient of friction (13). Since the potential for wheel climb is directly related to the L/V ratio, those combinations of L/V ratio, gauge face wear angle (ϕ), and coefficient of friction which introduce an unacceptable level of risk for wheel climb can be defined (11, 12, 13). Figure 20 present such a sensitivity analysis, which shows the calculated L/V ratios associated with wheel climb as a function of different gauge face angles and coefficients of friction.

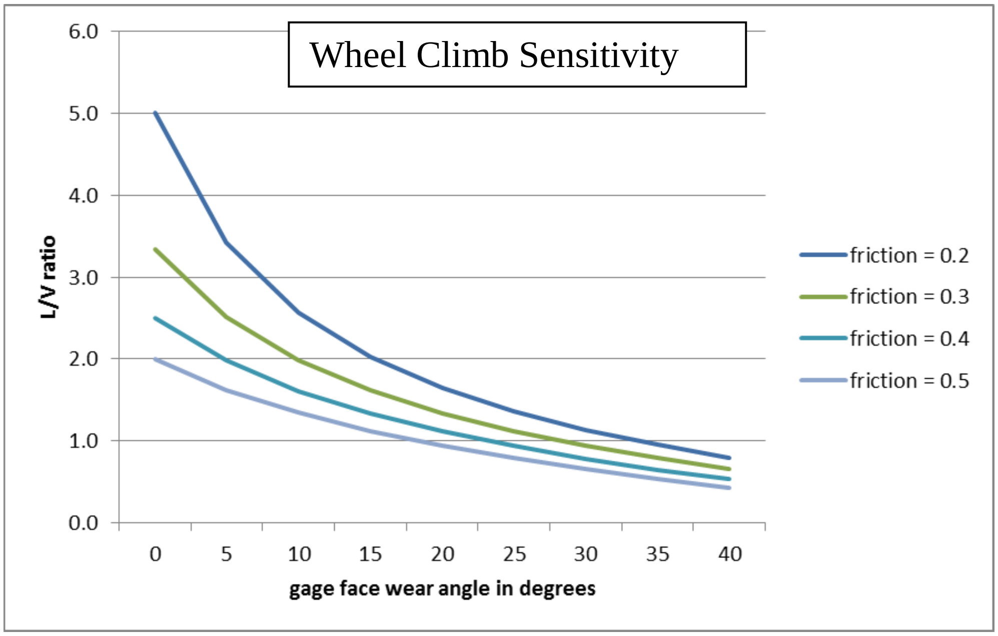


Figure 20: L/V Ratio vs. Gauge Face Wear Angle for different coefficients of friction

To illustrate this behavior, for a well lubricated condition, with a coefficient of friction of 0.2 and a gauge face wear angle of 28 degrees, the level of L/V required for wheel climb is 1.20, a very high level rarely seen in service. However, for a very dry condition, corresponding to a coefficient of friction of 0.5, the same amount of gauge face wear angle results in an L/V level required for wheel climb of 0.70. This is a level that has been measured in the field on a regular basis, and is, in fact, below the traditional Nadal wheel climb threshold of 0.8.

Likewise, increasing the allowable gauge face angle, i.e. allowing a flatter "slope" at the gauge face, while holding coefficient of friction constant, will result in a reduction in the L/V ratio required for wheel climb and consequently increasing the potential derailment risk. Thus, for a coefficient of friction of 0.4, a gauge face angle of 18 degrees requires an L/V ratio of 1.20 for wheel climb, an extremely high level which is difficult to reach, while a gauge face angle of 32 degrees requires an L/V ratio of 0.7. As noted above, this is a value that has been measured in the field for a range of vehicle types and operating conditions.

The risk of wheel climb can thus be reduced by setting a maximum limit to the gauge face wear angle, forcing the wheel climb requirements to a level of loading (L/V ratio) that will not be encountered in the field. Alternately, if the maximum L/V ratio that occurs on track is known (through field measurements, tests, analytical modeling, etc.), together with an appropriate coefficient of friction, then it is possible to calculate the maximum allowable gauge face angle above which wheel climb may occur. This would thus be the limit for maximum allowable gauge face wear angle.

One such example is the case of the Port Authority Transit Corporation (PATCO), where maximum measured lateral load values (L) were available from field tests (12). Using the worst case measured L/V levels, L/V ratio for this equipment were found to be always less than 0.84 for unguarded curves (no guard rail)[8]. Defining a light to moderate level of lubrication (0.4) resulted in a gauge face wear angle limit of 28º.

Other tests on transit and railway systems have measured L/V ratios of the order of 0.8 to as much as 2.0 (under very controlled circumstances). These include such measured L/V test values as:

- Tests on SEPTA which generated L/V values of the order of 0.6 to 0.65 with maximum values of the order of 0.8 (14)
- Transit Cooperative Research Program (TCRP) reported tests on passenger cars at the Transportation Technology Center (TTCI) with a reported maximum L/V ratio of 2.00. Additional L/V values of 1.32, 1.79 and 1.85 were reported(15)
- Tests on Atchison Topeka and Santa Fe (ATSF) double stack operations in high degree of curvature territory which generated maximum L/V ratios of 0.77 (16)
- Test on Burlington Northern Santa Fe (BNSF) and Amtrak in the Pacific Northwest which generated maximum L/V values of 0.87 (17)

Depending on the coefficient of friction, these L/V ratios translate into rail wear angle limits as follows:

L/V	**Coefficient of Friction**		
	0.3	**0.4**	**0.5**
0.7	38.3	33.2	28.4
0.8	34.6	29.5	24.8
1.0	28.3	23.2	18.4
1.2	23.1	18.0	13.2

Noting that the majority of the measured maximum L/V ratio values are of the order of 0.8 or less, suggests wear limits of the order of 25° to 33°. This is consistent with the maintenance values adapted by several US properties, including Amtrak, BART (San Francisco), PAT (Pittsburgh) and SEPTA (Philadelphia) who have defined gauge face wear limit values (usually as maintenance limits) between 26° and 32°, based on the anticipated (or measured) levels of loading, and standards for lubrication.

[8] L/V ratio went as high as 1.14 for guarded curves, however, the guarded rail is designed to prevent wheel climb.

While most freight systems in North America have not adopted gauge face wear standards, their European counterparts have. In Europe, where this parameter is frequently used, standards likewise range from 26º to 32º.

Thus, for example, British Rail uses a gauge face wear angle standard of 26º (18). As noted in the reference, this limit is imposed to avoid derailments, i.e. to prevent the class of wheel climb derailments already noted above. Other European and international railways likewise use a gauge face wear angle limit or, alternatively, use a more restrictive limit to measure gauge face wear, in lieu of the angle limit, in order to restrict wear and prevent excessive gauge face wear angle values. Thus, for example, on the Netherlands Railways, the limit for lateral (gauge face) wear is 8 mm (.32 inches) without any gauge face angle limit, or it is extended to 12 mm (0.5 inches) if a gauge face angle limit of 32° is imposed (13). Likewise Indian Railways define limits of lateral wear and angle of wear to avoid the "risk of wheel mounting the rail caused derailments" (19).

For measurement of this gauge face wear angle, while several rail systems have developed hand gauges which can be used to measure gauge face wear angle, either as a direct measurement or as a go/no go gauge, current rail profile measurement technology now allows for the measurement of the complete rail section. This approach uses laser based rail profile systems such as ORIAN and LaserRail as well as the more focused turnout oriented inspection system mounted on the Automated Switch Inspection Vehicle (ASIV) (5, 6). With this profile, the actual wear angle is calculated and compared to the defined standard (be it a safety or maintenance standard).

Initial Assessment

Based on Task 1 and Task 2 and the field assessment on October 23, 2013, the Expert Review Panel made the following assessments:

- Switch point profile gauge (aka Pac Man): This gauge was judged to be inconclusive. The difference between compliance and non-compliance was determined to be very small, and it was not clear where non-compliance represented a dangerous condition.
- Gauge No. 1: This gauge addressed stock rail head wear and was judged to be inconclusive. Based on field observations, a switch point that was too high relative to the stock rail is not necessarily a dangerous condition.
- Gauge No. 2: This gauge addressed chipped or damaged switch points. The Expert Review Panel agreed that this gauge is useful, but requires modification based on US wheel and switch designs. The Expert Review Panel recommended a modified version with a vertical dimension (height) of 0.70” (compared to 0.65”) and a gauge-face angle of 70° (compared to 60°).
- TGAAR1B Gauge: This is the North American version of the Network Rail TGP8 gauge, using an AAR 1B new wheel profile. Switch point contact below the 60° mark appears to be an undesirable condition, and thus the Expert Review panel judged the gauge to be a helpful aid to inspection.

- NS worn wheel gauge: Whereas the TGAAR1B used a new wheel profile, this gauge used a wheel with a near-vertical flange and a plastic-flow bead at the tip – exactly the sort of wheel that climbs on a marginal (or worse) switch point. While the concept was good, the Expert Review Panel determined that the 60 degree mark on this gauge did not quite serve as the proper indicator; i.e. the execution was lacking. The gauge duplicated the part of the wheel at the bottom (6 o'clock) position, with the tip of the flange 1-1/2" below the rail running surface. This is not the part of the wheel that climbs a point - it is a different point on the flange circumference, one closer to the top of the point that does the climbing.
- All gauges should be mounted on a track level or equivalent rod in order to reference the adjacent rail to provide an accurate measurement.

Stage 2

Evaluation of Stage 1 Results

The researchers, together with the Expert Review Panel, reviewed the results and initial assessment from Stage 1. Based on this review, the following actions were taken:

Gauge No. 2 for measurement of chipped or damaged switch points was modified to reflect US switch point designs, conditions, and practices. The modification resulted in a change in several key dimensions to include a vertical dimension (height) of 0.70" (as compared to the original 0.65") and a gauge-face angle of 70° (as compared to the original 60°). NS manufactured the modified gauge, as shown in Figure 21, which was used in the follow-on field evaluation.

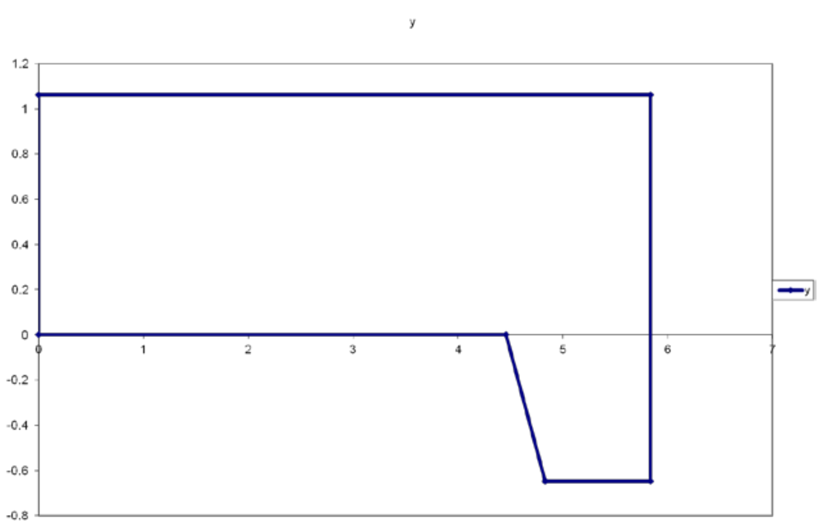


Figure 21: Revised Network Gauge no. 2 – vertical dimension of paddle extended from 0.65" to 0.70", and gauge face angle changed from 60° to 70°

The wheel climb gauge based on the AAR 1B profile, the TGAAR1B Gauge, which is the North American version of the Network Rail TGP8 gauge, was to be further evaluated in the follow up field test(s). As noted in the initial assessment, switch point contact below the 60° mark appears to be an undesirable condition, and thus the gauge was judged to be a helpful aid to inspection, but the Expert Review Panel recommended further evaluation.

A moderately worn profile wheel climb gauge based on a moderately worn AAR 1B profile was also developed by NS using the profile shown in Figure 22. This is similar to the TGAAR1B Gauge, which used a new AAR 1B profile, but used the worn profile shown in Figure 22 instead. As noted in the initial assessment, switch point contact below the 60° mark appears to be an undesirable condition

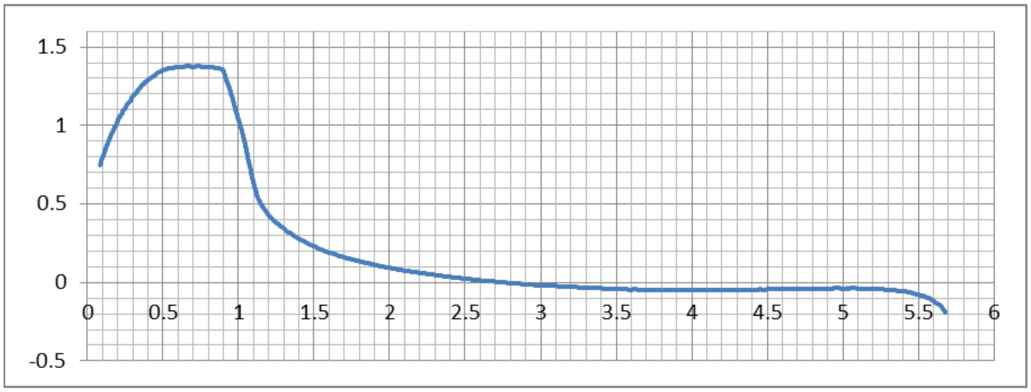


Figure 22: Moderately worn AAR 1B profile used for TG wheel climb gauge

The extremely worn NS worn wheel gauge required further modification. A new gauge, referred to as the "half-moon gauge" was developed by NS from a wheel segment with the moderately worn wheel profile as shown in Figure 23.


Figure 23: "Half Moon" gauge with Moderately Worn Wheel Segment

These gauges were modified and a follow up field test was performed on January 28, 2014.

Field Evaluation of January 28, 2014

As was found in the field evaluation of October 2013, Gauge 1 was judged to be inconclusive and not a subject for further evaluation.

The study team judged that the modified Gauge 2 (Figure 21) with the height and angle changes to reflect US practice and designs was very useful and recommended that it be adopted by US rail systems.

The AAR1B new wheel profile and the moderately worn AAR 1B profile (Figure 22) were both judged to be very useful for determining conditions of switch points. The Expert Review Panel members agreed that if the wheel-switch point contact is below the 60º mark, then there is definitely a problem. (See Figure 3 on page 9)

The research team and Expert Review Panel also reviewed the severely worn AAR1B worn wheel profile but found that it did not give a good indication of potential wheel climb. "The half moon" worn wheel gauge produced by NS (Figure 23) was intended to replace this severely worn wheel gauge. This new gauge is a 3 dimensional inspection tool which is supposed to duplicate the wheel movement on the switch point. The gauge is applied by moving it back and forth along the switch point. However, review in the field indicated that it was not showing the wheel climb threshold as accurately as required for an effective gauge. That is because the point that the inspector needs to see (where the wheel starts to climb) is hidden behind the gauge. In addition, the gauge does not properly duplicate the angle of attack of the wheel to the rail which is the worst case scenario. As a result this gauge was not considered effective in its current shape, and again a modified version was developed for further field testing.

Follow Up Assessment

Based on the field assessment on January 28, 2014, the following additional assessments were made by the Expert Review Panel:

- Gauge No. 2: The modified version of this gauge addressed chipped or damaged switch points for US switches and would be useful and valuable.
- TGAAR1B Gauge with moderately worn profile: This is the US version of the Network Rail TGP8 gauge, using a moderately worn AAR 1B wheel profile. Again, switch point contact below the 60° mark appears to be an undesirable condition, and thus the gauge would be a helpful aid to inspection.
- 3-D TGAAR1B Gauge with moderately worn profile (half- moon gauge): This uses a full 3-D wheel segment of a moderately worn AAR 1B wheel profile and would not be a helpful aid to inspection. A third attempt to redesign this gauge was made by NS.

Redesigned Severe Profile Gauge

Based on the results of the previous field tests with the severely worn profile gauges (TGAAR1B Severe and ‘Half Moon” Gauges), the NS team developed a revised gauge that simulates contact of a worn (vertical) wheel flange. This gauge, referred to here as Severe Profile Gauge (SP Gauge), was based on the 3-D TGAAR1B Gauge which had been machined out of an actual freight car wheel. The SP Gauge has an angled gauge face with the measuring section adjustable vertically, which duplicates worn wheel/switch point contact, no matter what the height of the switch point is relative to the stock rail.

Initial development looked at three different gauge face angles; 85°, 80° and 75° relative to horizontal. Field tests on NS indicated that the 85° gauge face was too steep, and resulted in virtually every switch point failing. The 80° gauge face angle was also too steep, but not by much (the gauge face angle of a new switch point for NS standard plan is 78°). To address this, NS added a small square notch to the bottom corner of the 80° gauge (see Figure 24), to make the 80° gauge face angle gauge a little less likely to fail a switch point. A "pass" edge and a "fail" edge were marked on the notch. However, this gauge was hard to see (the notch is very small), and too lenient (allows acceptance of a potentially failing point). The gauge with a 75° gauge face angle performed best and resulted in fewer good points failing. While this gauge is still a little strict, the corner contacts good switch points, though not by much. However, with operator discretion, the Expert Review Panel judged this gauge to be useful and it was evaluated during the March 26, 2014 field test.

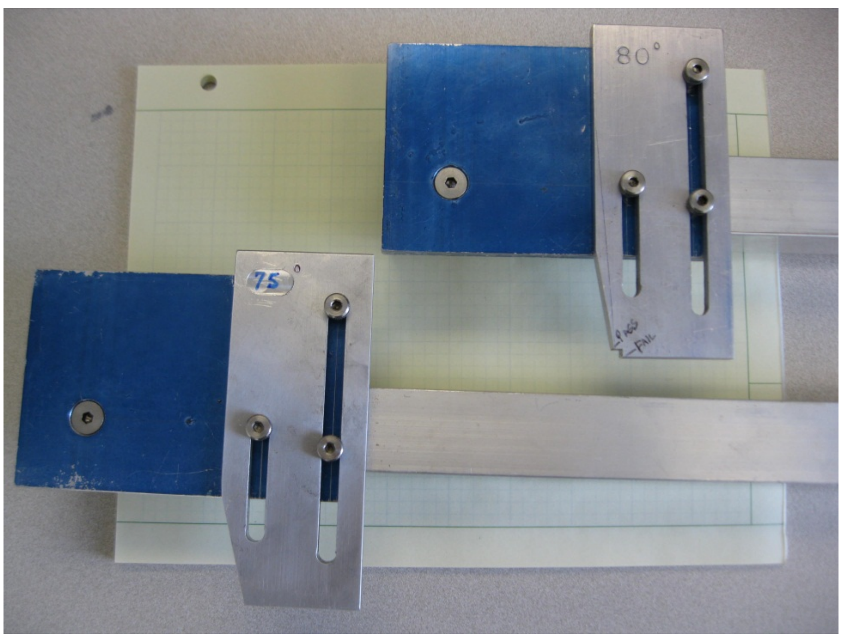


Figure 24: Adjustable 80° notched gauge (top) and 75° gauge (bottom)

Field Evaluation of March 26, 2014

A final field evaluation was performed on March 26, 2014. A series of 5 switch points of several different design configurations and conditions were examined using the two versions of the SP gauge (Figure 24) as well as two versions of the TGAAR1B gauge; the new and moderately worn profile versions. Figure 25 shows the application of the SP Gauge on a switch point in the NS yard.


Figure 25: SP (80° notched) Gauge in use.

While both the 80° notched gauge and the 75° gauge Severe Profile Gauge (SP Gauge) were judged by the Expert Review Panel to be useful for determining conditions of switch points and providing an indication of potential for wheel climb derailments for a severely worn wheel (see Figure 25), there was still some concern regarding these as "final products." The 75° gauge was deemed to be more conservative in that it may condemn marginally good points. The 80° notched gauge was considered non-conservative in that it may pass some marginally bad points. It also proved a little harder to use because of the size of the notch. Both gauges also had a question regarding actual alignment and placement, with the possibility that they did not accurately reflect the wheel flange position, particularly on the straight side of one of the turnout designs examined in the yard.

The Expert Review Panel and researchers discussed ideas for improvement of positioning that included a longitudinal reference frame to position the gauge more accurately and a tab to offset the gauge to match true wheel path vs. always flanging on stock rail (which is the case with the current design).

The Expert Review Panel judged the modified Gauge 2 (Figure 17), which reflects US practice and designs, to be very useful and recommended it for adoption by US rail systems.

The Expert Review Panel likewise evaluated the AAR1B new wheel profile (Figure 19) and judged it to be very useful for determining conditions of switch points. The Expert Review Panel members all agreed that if the wheel-switch point contact is below the 60º mark, then there is definitely a problem (See Figure 3 on page 9). The moderately worn AAR 1B profile was deemed to be less useful.

During the meeting of March 26, 2014, the Expert Review Panel, researchers and NS research staff members discussed a recent (March 2014) Amtrak derailment at Penn

Yard in Philadelphia where an AEM7 locomotive with high truck rigidity derailed at a switch point with possible high gauge face wear angle and track geometry warp condition (1¼" warp). This was a wheel unloading condition that generated a high L/V and associated wheel climb at the switch point. This was consistent with the flattening of the gauge face, as noted in the discussions in the section "Gauge Face Wear Angles," and the associated increase in risk of wheel climb with this worn gauge face angle. It was also consistent with the Swiss (SBB) gauge that measured this gauge face wear angle, as illustrated in Figure 15.

Thus, review of the recommended gauges was expanded to include a modified version of the SBB gauge, and a new gauge was added to the list of recommended gauges to match the gauge wear face angle limit, currently proposed as 32º. This gauge is illustrated in Figure 11 on Page 14 and is similar to the SBB gauge shown in Figure 15 (Page 17). This new gauge, which measures a 32º gauge face angle gauge, specifically addresses the potential for wheel climb under high L/V conditions.

Conclusions and Recommendations

The researchers and Expert Review Panel judged the following gauges to be useful, effective and a helpful aid to inspection[9] based on the findings of this project, including the three sets of field tests:

- Gauge No. 2 or the Chipped Point (CP2) Gauge: This gauge addressed chipped or damaged switch points. The modified version based on US wheel and switch designs was deemed to be useful and valuable.
- TGAAR1B Gauge: This is the US version of the Network Rail TGP8 gauge, using an AAR 1B new wheel profile. Switch point contact below the 60° mark appears to be an undesirable condition, and thus the gauge was judged to be a helpful aid to inspection.
- Severe Profile Gauge (SP Gauge): This is the new (third) generation severely worn profile gauge that appears to work well in the field and gives an indication of the potential for wheel climb derailment for a severely worn wheel. While both the 80° notched gauge and the 75° gauge versions of the SP Gauge were judged to be useful, they still require a degree of judgment that makes them less of a go/no go gauge and more of a guide to switch point problems. Additional development work is required for their use as a go/no go inspection tool.
- Gauge face angle gauge (GFA Gauge) with a 32º gauge face angle: This gauge is also recommended as a check on gauge face angle and the potential for wheel climb, particularly for high L/V conditions.

[9] All gauges should be mounted on a track level or equivalent rod in order to reference the adjacent rail in order to provide for an accurate measurement.

Based on the above tests and evaluations, these four gauges show real potential as useable, field deployable measuring tools for dealing with the important problem of derailments at switch points. Of the above four gauges, three are deemed directly useable as presented in this report (CP2 gauge, TGAAR1B Gauge and GFA Gauge) and one still requires some additional development work (SP Gauge). In all cases, the gauges will next require a field validation and implementation phase. The researchers together with the Expert Review Panel thus recommend that a follow-up field validation and implementation phase be conducted.

Such a field validation would entail the manufacture of multiple sets of these gauges, which would then be provided to railroad and/or transit inspectors working on at least two railroads or transit systems, where numerous switches of various types and conditions are present. The inspectors would use these gauges for a two to four month period and document their experience with switches that "fail" these gauges, to include their assessment of the condition for the switch. This assessment should also include recommendations for improvement of the design of the measurement gauges. Norfolk Southern, Amtrak, and SEPTA have already expressed interest in serving as field validation sites.

In addition, as part of this implementation phase, a fourth round redesign of the SP Gauge should be carried out. Norfolk Southern and the rest of the Expert Review Panel have indicated interest in continuing to work in this redesign activity. This fourth round of redesign should finalize the design of the SP Gauge. At the conclusion of this redesign, the SP Gauge will be added to the other three gauges used by the inspectors in the follow-up field validation.

As part of this recommended follow-up field validation and implementation phase, an implementation report would be prepared for distribution to the railroad industry. This report would include detailed drawings and templates of all the recommended gauges, to allow any railroad or transit system to manufacture them (they are all simple to manufacture in a machine shop, no special tooling is required). The implementation report would also include detailed instructions on how best to use the gauges, failure criteria, and sample forms for recording switch point inspection data.

Concurrent with this follow up activity, the researchers and Expert Review Panel recommend that information regarding the development and use of these gauges be disseminated within the railroad industry, to include articles in such railway journals as Railway Track & Structures, presentations at conferences such as AREMA or TRB, and direct distribution of information to railroad engineering departments.

Finally, the researchers and Expert Review Panel recommend that automated inspection systems for switch profiles be developed and implemented (such as the currently available Automated Switch Inspection Vehicle, or ASIV). Such inspection systems would provide for comparable analyses of the key derailment parameters defined in this report, such as by developing electronic versions of these gauges and applying them to the switch profiles throughout the length of the switch point as part of their analysis process.

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