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Optimisation of railway switches

INTRODUCTION
As well as some blue-sky research, S&C is benefiting from an unprecedented level of needs-driven research. Previous issues have described fixed crossing studies and ways to improve ballast. This paper focuses on switches from three complementary viewpoints: wheel/rail interaction, point equipment interaction and non-ballasted support. These can be treated separately, and the improvements brought together from any or all to create improved switches.

This paper draws from three papers resulting from a collaboration between the University of Huddersfield (UoH), Embedded Rail Technologies (ERT) and Andy Foan Ltd (AFL) and presented at Railways 2018 [1-4]. This work was funded by the European Commission within the Shift2Rail projects In2Rail (I2R) and In2Track (I2T).

[2] considers how nine sampled switches apply actuation locking and detection in different ways; computes and compares their behaviour and recommends improvements. [3] reviews how switch machining is constructed and generates a multiplicity of combinations of features, some of which are subjected to multibody simulation so that the effect of key features on the wheel-rail interaction can be better understood. [4] describes a framework for developing switches for embedded track, and also identifies a practical application of flange-back steering for embedded switch diamonds.

OPTIMISING SWITCH OPERATION
Arguably the least studied aspect of switch behaviour is its lateral flexure and its relationship with the point operating equipment (POE) or actuation, locking and detection system (ALD). The behaviour of switches in service and the failure modes that arise are complex [5, 6]. While novel concepts [7] look to radical methods to improve performance, this paper examines the potential to get the best out of what we already have.

Switch flexure analysis studies the relationship between thrust and stroke using proven analytical tools. Thrust is the force in kN required to move the points and associated mechanism to the desired position, against its own stiffness and frictional resistance forces. A set of working rules, methods, assumptions and caveats are set out in the AFL’s Switch Flexure Handbook [8]. A generic study of switch behaviour [8] derives some patterns in behaviour across a broad range of switch sizes. A paper on optimisation further describes this work [10].

Even assuming a dependable prime mover, insufficient thrust and stroke distribution can be responsible for failures in service. Headroom, (the margin between available thrust and thrust demand), and obstruction detectability, (the ability of the detection subsystem to ‘see’ and warn of obstructions holding the switch rail open between drives), depend on the level of thrust available. Both need to be assessed for dependable and safe switches.

Table 1: Selected switches

<table>
<thead>
<tr>
<th>Switch</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NR CVs</td>
</tr>
<tr>
<td>2</td>
<td>NR SGVs</td>
</tr>
<tr>
<td>3</td>
<td>SNCF 150.11</td>
</tr>
<tr>
<td>4</td>
<td>SNCF 120.05</td>
</tr>
<tr>
<td>5</td>
<td>NR CVs</td>
</tr>
<tr>
<td>6</td>
<td>NR SGVs</td>
</tr>
<tr>
<td>7</td>
<td>DB 1200</td>
</tr>
<tr>
<td>8</td>
<td>DB 1300</td>
</tr>
<tr>
<td>9</td>
<td>NR CVs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Switch</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Indirect Mechanical Supplementary</td>
</tr>
<tr>
<td>2</td>
<td>Indirect Mechanical Supplementary</td>
</tr>
<tr>
<td>3</td>
<td>Direct Mechanical Supplementary</td>
</tr>
<tr>
<td>4</td>
<td>Direct Mechanical Supplementary</td>
</tr>
<tr>
<td>5</td>
<td>Multiple Actuators</td>
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<td>6</td>
<td>Multiple Actuators</td>
</tr>
<tr>
<td>7</td>
<td>Direct Mechanical Supplementary</td>
</tr>
<tr>
<td>8</td>
<td>Direct Mechanical Supplementary</td>
</tr>
<tr>
<td>9</td>
<td>Double-Indirect Mechanical Supplementary</td>
</tr>
</tbody>
</table>

Figure 1: Aggregated thrust v headcut length
Figure 2 - Headroom: before (left) and after (right)

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SWITCHES COMPARED

Nine switches from three countries are compared and contrasted. The aim was to study a short switch and a long switch from each administration. See table 1.

Switches #5 and #6 have direct-acting actuators. All the others distribute actuation using a mechanism. Switches #1 to #5 use a single longitudinal bar to carry both the tension and compression stroke, while #7 to #8 use a double bar so normal and reverse strokes are carried in tension. Switch #9 uses a torsion tube, which behaves the same in both directions.

The drive equipment sees a total thrust aggregated from contributions from individual drive positions. From the computations, the lowest aggregated thrusts in each group occur with DB switches (#7, #8) which have 160mm toe stroke and consequently a higher mechanical advantage. The highest thrusts occur on short switches with shorter toe strokes. The heel flexing length and whether foot flange relief is used determine how high.

A number of straightforward measures are compared, which can be applied to improve the behaviour of some switches. Figure 1 shows the results. The shorter switches are shown in blue; longer switches are in red.

HEADROOM

Figure 2 shows thrust demand before and after implementing improvements to shorter switches. The result is demonstrated as headroom, or the difference between thrust available and thrust consumed at a working level of slideplate friction. A reasonable minimum headroom for dependable performance is around 33%.

Using #1 as an example, if we establish a maximum available thrust of, say, 3.6kN, then the headroom is currently (3.6-3.1)/3.6 = 14%, which is insufficient. If we make practicable improvements we can increase the headroom to (3.6-2.3)/3.6 = 36%, which is satisfactory.

SUPPLEMENTARY DRIVES

Figure 3 shows is a functional diagram of a typical mechanical supplementary drive indicating where in the mechanism we can expect flexibility. A perfectly stiff supplementary drive might behave well, with plenty of lost motion and adjustment, but if flexibility is introduced into the mechanical linkages the computation model predicts that much of the stroke available from the switch toe is used up. This is important in longer switches.

Some switches, particularly longer ones, fail due to deficiencies in available stroke and not just lack of thrust. The behaviour of a supplementary drive is complex with high redundancy in its setup and adjustments, requiring additional computation.
The arrangement shown in figure 4 is used in the UK for point machine driven switches.

In switches driven by RPCL (Rail Clamp Point Lock), IBCL (In-Bearer Clamp Lock and HPSS (High Performance Switch System), the actuator drives the switches and the switches drive the supplementary mechanism. These could be termed ‘double indirect’ as shown in figure 5.

Most of the thrust needed to drive a switch passes into the switch via the supplementary drive; very little of it is consumed at the switch toes. In the indirect method, no more stroke can be directed to the rear of the switches than is used near the toes. On switches where the supplementary drive is driven directly or indirectly from the switch rails (#1, #2, #9), the mechanical advantage would be significantly higher if it were driven directly (as in #3, #4, #7, #8) provided the actuator is capable of higher stroke.

In the DB r300 and r1200 switches (figure 6) and the SNCF tg0.11 and tg0.05 switches (figure 7) the actuators are connected directly so that whatever stroke is available goes straight into the supplementary drive. Reduction of the stroke input to the switches takes place in parallel via a local locking device.

**COMPARISON**

The shorter CVs switch (#1) can be improved by switch rail design, yielding a significant improvement, but the most dramatic potential is in the longer SGVs switches. Again, the shorter switches are shown in blue; longer switches are in red.

Whereas the SNCF tg0.05 switch (#4) and the DB switch (#8) have more headroom, by using the direct supplementary drive connection the SGVs (#2 … #2c) can be brought within range of the others (figure 8), achieving a worthwhile effect on switch reliability.

**SWITCH PROFILES OPTIMISATION**

A team of researchers at the University of Huddersfield has been working with AFL under the Shift2Rail initiative In2Track to help increase the current knowledge and understanding of the performance of switches. The work stems from the fact that a wide number of industrial practices have been developed over many years by different infrastructure managers and S&C suppliers, but as a matter of fact the knowledge about the influence of each design choice remains scattered and mostly unavailable to key stakeholders.

Research has often focused on one specific design feature and lacked a broader view in terms of end user application (local installation conditions, traffic conditions, duty load conditions, etc). Therefore, in this project,
many options are combined and analysed to understand the interaction between features and their effect on performance. Representative cases are then assessed in a systematic and scientific manner using advanced vehicle dynamics simulation software, and considering the details of the wheels rail interaction.

CONTRIBUTORY FACTORS

The switch-wheel interface consists of four elements:

- a fine point protected from front attack;
- a tapered length which guides the wheel and which must resist side attack leading to derailment - this area is prone to wear and chipping and usually determines the end of useful life;
- a broader part which transfers the wheel load from the stock rail to the switch rail;
- a transition to as-rolled rail.

A switch configuration is defined by a combination of top view geometry, topping (or lowering), and head profile (usually the machining cutter profile). Each uses the same reference plane, usually the conventional 14mm gauge point below top of rail crown. An acceptable result is one which is safe when new, provides a smooth passage for most wheels, and transfers load where there is sufficient breadth of contact on both rails. An optimal result does this over a broad range of tolerances and wear so that the product lasts a long time in service and degrades predictably. To start with, the basic rules [11,12] and existing improvement methods [13,14,15,16] were collected.

HEADCUT

The term ‘headcut’ refers to the part of the switch rail where the rail head is machined to a taper. The depth at the toe and location where the topping runs out at the back of the headcut can vary between designs.

TOPPING, OR LOWERING

Switch designs commonly have multi-slope topping defined by cut depths at the toe and distances from the toe. The second cut is often half the length of the first. Alternatively some switches have topping defined by a curve. The use of a conformal profile cutter leads to a lowering of the passing wheels relative to the stock rail which in turn requires less topping depth. A deep topping cut leads to a broad position of load transfer but may increase the risk of climb near the toes. A shallow topping cut leads to a more exposed blade which may be considered a breakout risk.

INSIDE HEADCUT

The convention for switches uses the stock rail gauge line as the reference line for the inside headcut.

### Table 2: Reducing complexity by threading

<table>
<thead>
<tr>
<th>Geometry family</th>
<th>intersecting / secant</th>
<th>tangential</th>
<th>non-intersecting / cycloidal</th>
</tr>
</thead>
<tbody>
<tr>
<td>geometry size</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>stock rail</td>
<td>190/250m</td>
<td>650/760m</td>
<td>1200m</td>
</tr>
<tr>
<td>inclination</td>
<td>vertical</td>
<td>1 in 20</td>
<td>1 in 40</td>
</tr>
<tr>
<td>toe relief</td>
<td>none</td>
<td>toe retraction</td>
<td>65deg relief cut</td>
</tr>
<tr>
<td>topping style</td>
<td>single slope</td>
<td>double slope</td>
<td>spline</td>
</tr>
<tr>
<td>machining profile</td>
<td>basic (re-radiussed)</td>
<td>conformal</td>
<td></td>
</tr>
<tr>
<td>switch / stock</td>
<td>basic (thro’ running edges)</td>
<td>inset (tapered 10mm from toe)</td>
<td>augmented (3-6mm)</td>
</tr>
</tbody>
</table>

 Alternatives are:

- augmented switches, that is, the stock rail machining is shifted laterally into the stock rail to increase the thickness of the switch rail throughout at the expense of the stock rail;
- inset switches, where this shift is a maximum at the toes and runs out at the headcut;
- kinematically gauge widened switches (kgw), where there is a lateral shift of the inside headcut, but instead of being parallel to the gauge line, it is 15mm at the middle of the headcut running out to zero at each end;
- modified stock rail switches (msr), e.g. catfersan, where the crown profile of one or both stock rail head profiles is machined.

The virtual models in figure 9 show four different approaches to the profiling of switches. Top left is a GB CV switch in which the machining profile is a simple combination of a flat top cut and a re-radius, and the inside rail interface (between switch and stock rails) is inclined at 1:4 and follows the stock rail gauge line. Top right is the same switch geometry.
but the machining profile is conformal, (much more like the running rail), and the inside rail interface tapers from a 10mm inset into the stock rail at the switch toe to zero inset at the back of the headcut (known as an inset switch). Bottom left uses a shallow depth switch rail profile with an augmented inside profile, (shifted towards the stock rail to leave more material on the switch rail at its toe). Bottom right has the inside interface inset 15mm at the midpoint of the switch headcut, running out to zero at each end of the headcut (known as kgw).

The purpose of all these concepts is to modify the steering of the wheelset by acting on the position of contact and therefore the rolling radius difference between the two wheels of each axle. Some also have the added benefit of increasing the robustness of the switch rails by shifting the loads where more material is available to resist those.

TOE RELIEF
Toe relief (see figure 10) is an additional machining usually to modify the angle of incidence of approaching wheels. Not all switches have such a cut, as indeed a good topping design should prevent any contact with the toe for all shapes of wheels.

DESIGN OF EXPERIMENT
Table 2 outlines switch families and a range of features which determine the wheel/rail interaction. This number of combinations makes for a very complex study in which it would be difficult to resource the work and understand the output. Some thought about the design of the experiment reduced the complexity and number of combinations. Certain features are, (at least to start with), expected to be more relevant to some switch sizes than others.

For example, conformal topping can be compared with basic for the CV switch, but is already used on the larger switches. The inset option is more relevant to shorter switches, while augmented, kgw and msr options are more applicable to longer switches.

Table 2 shows how four workstreams were evolved:

- **1CV** - The GB CV switch has been extensively studied as a benchmark. It has a 245m intersecting radius and is vertical.
- **2E2** - The European 760m radius tangential switch has undergone extensive study as a benchmark. The new intersecting GB E switch has a radius of 645m and 1/20 rail inclination with conformal topping and augmented, and there may be similarities.
- **3DB** - Some work has been done on the tangential DB 1200m radius switch has a UIC geometry and a 1/40 rail head profile and is very similar to a new GB SG switch which has a tangential 1178m radius and 1/20 rail inclination.
- **4H1** - At the high speed end there is a 2798m radius, NR60 H, augmented and with 1/20 rail inclination and a clothoidal switch entry.

Table 2 shows how the variants were developed through to dynamic analysis. The table shows the key parameter values for each option. Prior to dynamic study, automatically generated drawings of the wheel/rail interface through the switches were used to estimate the position of first contact and of wheel load transfer.

Some options weren’t studied and are greyed out as being of interest or for future consideration.

DYNAMIC SIMULATION
The University of Huddersfield conducted multi-body simulations in order to compare and contrast the behaviour of the wheel/rail interaction through the switches using a range of vehicles and wheel shapes to fully cover the wide range of possible kinematic interaction. Before running simulations, data preparation and results reporting were automated. A huge amount of useful data was produced.

Figure 12 shows, for example, a set of time histories for the four switch types using a single wheel profile in the diverging direction, both facing and trailing. Each graph summarises the different switch machining options applied.
This set compares the total dynamic contact forces $B_{dyn}$.

As well as $B_{dyn}$ plots for other vehicle types, cumulative contact pressure and wear/RCF plots were produced for all routes. These showed expected contact bands and level of damage along the switch-stock component for each simulated switch (Figure 13). Clear differences were observed between usage (facing-trailing), between families and between design options within a family.

**A SIMPLER SWITCH DIAMOND**

The I2R project assessed the potential for a number of radical switch ideas, one of them being flange-back steering (FBS). This represented a step-change innovation aiming at eliminating the thinnest and weakest part of conventional switch blades and instead using FBS to provide the switching function. An embeddable FBS switch diamond was also studied, partly as a by-product of research into hybrid track forms. A $5^\circ$ gauge physical model was used to visualise the concept, as shown in the photographs below. See Figure 14.

The obtuse diamond crossings has the only permitted length of unguided track in the railway. In this length the wheelsets are able to drift laterally. For a range of obtuse crossing angles the leading wheel crossing the gap is unchecked by its opposite wheel, which is crossing its gap at the same time.

Figure 14 shows what can happen if the permissible unguided length is exceeded. The plan view to the right of the photographs shows the wheelset positions as the bogie is rolled through the crossing. Picture (a) shows the leading wheel of a bogie about to leave the point rail and engage with the check rail. In picture (b) the leading wheel has passed the knuckle of the obtuse crossings, but it is no longer properly guided so it can drift laterally to the position shown in picture (c). From here, further rolling leads to lateral drift, which can direct the leading wheel and bogie to attack the opposite point rail with the potential to take the wrong route out of the diamond.

Standards [11] define the allowable extent of drift, but at angles from 1 in 8 upwards, (i.e. finer angles), measures must be taken to address the problem. Up to 1 in 9 it may be possible to effectively shorten the unguided length by raising the level of the check rail. Further than this, currently a switch diamond is needed which introduces complexity and cost. Switch diamonds can suffer from seasonal thermal distortion problems.

Instead, a moveable check rail could potentially be used to close the gap. Figure 15 shows a moveable check rail closing the gap and positively guiding the bogie through the normally unguided area.

This innovation was identified late in the project as a potential use for flange-back steering.

**SWITCHES FOR EMBEDDED TRACK**

The disadvantages of ballasted track can be eliminated by surface-mounting on concrete track slab and incorporating two layers of resilience, but putting all the resilience in the surface mountings requires sophisticated rail fastening systems. Also surface-mounted track is more noisy than ballasted, and mitigation requires add-on noise management.

**EMBEDDED RAIL**

Embedded rail track resiliently supports the rail while limiting rail roll, emits less noise, is less sensitive to adverse environmental conditions, and is retained safely in the unlikely event of a rail failure. However, its advantages are not fully exploited unless the same rail profile as in the main tracks can be used throughout the S&C. Consequently there is a need for S&C which makes best use of such a profile.

In ballasted S&C it is important to maintain track support and nowhere is this more important than through the switches. However this is the area where there are many actuating rods, stretcher bars and cross-track cables and these inhibit ballast maintenance. Innovations such as hollow bearers help by providing protection for such equipment, which promotes tamping, but often the switches are still feared and ignored by the tamper.
SWITCH CONCEPT

An embedded ‘conventional’ rail switch was studied in view of the significant benefits identified in prior research, many of which would also apply to the switch, e.g. simplicity, noise reduction, low maintenance, low LCC, etc. The following considers how one might achieve an embedded switch design.

The switch uses the rectangular rail with its elastomer layer and shell, (figure 16, figure 17) with as much as possible embedded, while a minimum is exposed where direct contact along the tapered part of the switch rail is needed and also over that part which flexes laterally when the switches are actuated. Special slide chairs support the switch rail. Practically continuous support means that the switch rail is capable of supporting wheel loading. Where the main rail elastomer and shell is interrupted, a special cap seal protects against water and detritus, and further optional sealing of any spaces protects against ice and snow build-up.

Further details define a workable switch, for example the heel blocks, distance blocks and drive point attachments. Some of these are illustrated in figure 18.

Drive point attachments are usually via bolts through the switch rail web or foot, but this rail profile doesn’t have a foot. Bolts through the web usually require clearance between the switch and stock rails, although large countersink head screws have been used, and often the attachments nearest the toes use thin-headed bolts.

Switch movement is usually effected by sliding the switch rail on slideplates, which may employ rollers or friction-reducing surfaces. An embedded slideplate may be inclined so that frictional resistance doesn’t come into play until the rails are nearly closed. It can sit above an elastomer layer similar in behaviour to that surrounding the main rails.

The switch rail is housed in a recess in the stock rail which, when the switch rail is closed, helps to secure the coupled rail pair under wheel loading. An optional gauge support bar keeps the stock rails apart under all...
circumstances, including rail compressive stress which may not be a significant problem anyway for embedded rails.

ADVANTAGES

Using the embeddable designs there is no need for the numerous components usually used in switches.

Obviating the ballast and keeping the switches clean has a further benefit. Ordinarily care must be taken in designing the actuation system so it has sufficient thrust and stroke to drive the switches reliably [8], while having enough sensitivity to enable the detection system to warn of obstructions in the way. Such a compromise makes it difficult to find an ideal balance across a range of switch sizes. Without ballast and rubbish, and with the proper control of alignment and level afforded by non-ballasted track, a more dependable and cost-effective actuation and locking system can be developed.

With designed-in drainage within the track slab, the switch area can be kept clean and in good working order with a minimum effort. Applicable to short switches for low diverging speeds through to long switches for high diverging speeds, long switch panels would be embedded in a series of carefully aligned and joined modules made accurately under factory conditions.

The ALD interface brackets are relatively high to promote accessibility. Once housed under protective covers at rail crown level, (also at the surrounding slab level), it would be easier, (than it would be in ballasted or surface mounted switches), to walk or drive over the switches when authorised to do so.

CONCLUSIONS

The conclusions reflect the recommendations of the I2R and I2T projects relating to railway switches.

The switch flexure optimisation work points in the direction of much-needed research in which more needs to be done to achieve the anticipated practical and cost-effective improvements. The work should bring the mechanical detail and switch rail interfaces into the analysis. The effect on passing wheels, ie obstruction detectability and run-through behaviour, is not currently understood to the level necessary to support the safety ruleset used by designers.

Output from the dynamic simulations needs further study to provide a clearer picture of the available possibilities to enhance switch reliability and also help drive further research to bring about further improvement. FE analysis and MBD tools should be added to the mix to challenge the assumptions made and crucially to compare with reliable and relevant measured data.

REFERENCES
