Squealing noise in curves - Catalogue with best practices

Report on subtask 3.5.1 of Rail4Earth

Europe's Rail

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Summary

Curve squeal is the highly annoying sound (tonal or broadband) that is radiated by trains running through sharp railway curves. There are many factors that influence curve squeal. The combination of those factors will determine whether the phenomenon occurs. For tonal curve squeal, two different mechanisms have been described than can explain the occurrence of the lateral stick-slip motion of squealing wheels: falling friction and mode coupling. In practice, both mechanisms can play a role at the same time. There is no easy way to find out which mechanism is dominant in a certain situation. For broadband curve squeal, flange contact is considered as generation mechanism.

In this catalogue different mitigation measures are described that reduce the duration and strength of curve squeal. The information for this catalogue was gathered in a literature survey and during interviews with several experts in this field. The performance of the described measures in terms of (average or peak) noise reduction varies considerably. Successful treatments in one situation will not always work in other situations. Furthermore, even if squeal is reduced significantly, there is no guarantee that noise annoyance and complaints will decrease accordingly. This is because curve squeal is easy to notice and particularly distracting to the human ear, unless it can be avoided (almost) entirely.

Among the track-based measures, the treatment with friction modifiers and/or flange lubrication is most widely applied. However, there are major differences in strategies and preferences between the infrastructure managers. Some prefer general noise measures, such as noise barriers, rather than installing devices that need maintenance and special care.

A technical solution to considerably reduce curve squeal is in principle available from train and bogie manufacturers: active steering. However, a healthy business case for such steering control devices seems to be easiest on urban rail transit systems (many curves in populated areas, only a few vehicle types, medium range top speeds without stability issues).

Train-based measures may become much more cost-effective on large railway networks if the costs of track damage are taken into account. This is because measures that aim at reducing track damage in curves will probably also be beneficial in reducing squeal noise. To this end, the instrument of Track Access Charges is used on some national networks (Sweden, Switzerland, UK) to encourage train operators to invest in track-friendly vehicles. Train operators will then pay higher access fees for conventional vehicles than for track-friendly vehicles. The existing fleet can also be made more track-friendly by refurbishing the bogies with so-called hydrobushes, a form of passive steering. Whether the application of hydrobushes leads to a reduction of squeal noise could, however, not yet be clarified in a Dutch measurement campaign that was carried out in 2024.

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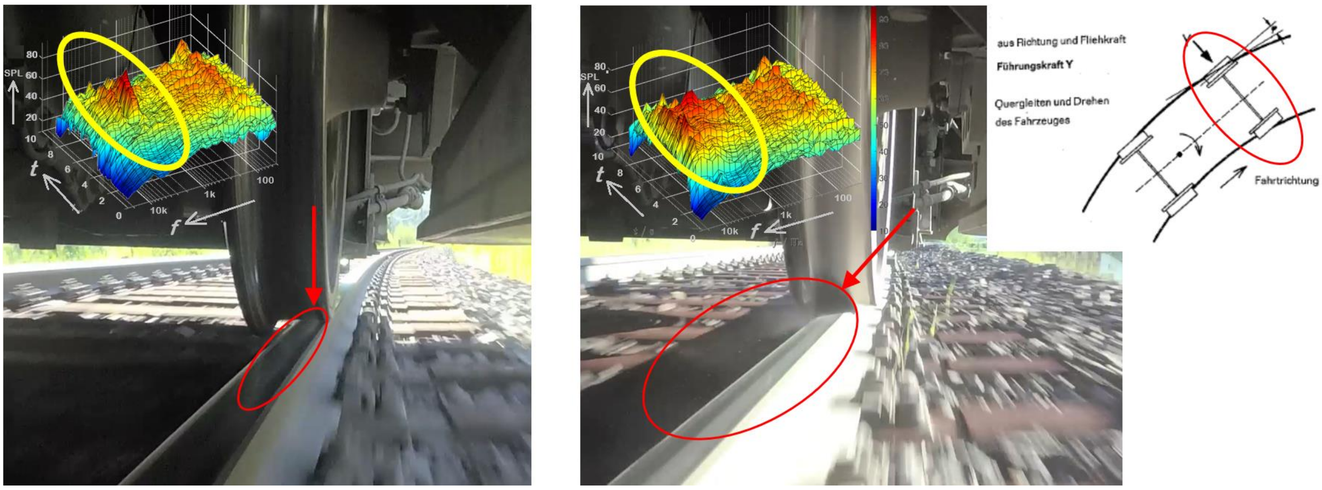
1 Introduction

1.1 Curve squeal

Curve squeal is the loud screeching sound that trains can produce while running through sharp curves and switches. The sound is usually tonal: it has a distinct pitch. This pitch corresponds to a certain vibration mode (natural frequency) of the train wheel. For tram wheels the squealing frequency is usually lower than 1 kHz. For train wheels, the frequencies lie generally between 1 and 5 kHz, in which range human hearing is most sensitive. This, in combination with its tonal nature, causes curve squeal of trains to be extremely annoying to residents. Also flanging noise is sometimes considered a form of curve squeal noise. Flanging noise is a (usually intermittent) broadband high frequency noise, sounding like (repetitive) ‘tsss’ or ‘tsh’.

Curve squeal and flanging noise are illustrated in Figure 1. These images, that are used with kind permission from the Austrian Railways (ÖBB-Infrastruktur AG), are video stills from the leading wheel at the front of a train with the corresponding spectrogram (frequency against time-history).



(a) (b)

Figure 1 Video stills and waterfall spectra of a wheel in a curve: (a) inner wheel turning right (inset: tonal noise); (b) outer wheel turning left (inset: broadband noise). (Photos: courtesy of ÖBB-Infrastruktur AG, graphs from TU Vienna)

Figure 1a is of the inner wheel (i.e. the wheel to the inner side of a curved track). The curve is turning right. The yellow oval of the spectrogram marks the high-pitch tonal noise associated

with curve squeal. The video shows that dust is blown away from the contact surface (red oval). This may eventually lead to corrugation at the inner rail of the curve.
Figure 1b shows the outer wheel in a curve turning left. The spectrogram shows a broad band increase of noise, associated with flange contact. Here, the dust seems to originate from the position of the wheel flange rubbing against the side of the railhead.

Annoyance by curve squeal

The annoyance caused by curve squeal has not been investigated thoroughly. For example, in the exposure-response relationships for railway noise published by the WHO in 2018, no distinction is made between residents living near curves and residents elsewhere along the track.

In an Austrian study, featuring a laboratory test with 30 listeners, an attempt was made to compare the annoyance caused by tonal as well as broadband curve squeal with the annoyance caused by rolling noise [Kasess 2022]. It was found that the annoyance associated with broadband squeal was comparable with the annoyance associated with rolling noise that was about 5 dB louder (with 1.7 dB standard deviation). This effect was found to be independent of the rolling noise level. When tonal squeal was added instead of broadband squeal, there was a similar effect, but this effect became smaller with increasing rolling noise levels. Eventually, at levels around 70 dB(A), there was no additional annoyance effect left for the tonal squeal.

Finally, combining all test results (rolling noise with or without broadband or tonal squeal), it appeared possible to derive a linear relationship between the annoyance effect (expressed in decibels relative to rolling noise) on the one hand and the difference between the total high frequency energy (>1.6 kHz) and the energy of the 1 kHz octave band on the other hand. In other words, the differences in perceived annoyance between tonal and broadband squeal seemed to be fully explained by the differences in high frequency energy content between both types of squeal noise.

Apart from the highly unfavourable acoustic properties of squeal noise, also non-acoustic factors could be relevant for the degree of annoyance associated with curve squeal. Such non-acoustic factors are not accounted for in the Austrian laboratory experiment, as the listeners were not selected from residents that were actually living nearby a squealing railway curve. David Hanson described a possible process that could lead to a higher degree of annoyance than solely explained by acoustic factors [Hanson 2021]. According to him, for residents “a train is a train”, and it is therefore difficult to accept that one train squeals loudly while another one does not. It is then likely that this phenomenon is perceived as a maintenance problem. The apparent inability of the train operator or infrastructure manager to solve such an obvious technical problem can reinforce the frustration of residents. Ultimately, it may be perceived as ‘deliberate neglect’.

1.2 Causes of squeal

1.2.1 Theory

Curve squeal may occur when a bogie with two wheelsets is negotiating a curve. This may be a curved track, but also a turn-out of a railway switch. This phenomenon typically appears in curves with radii below 300 m for railways and below 200 m for light-rail, but squealing noise may also be generated in less sharp curves [Verheijen 2019].
In case the wheelsets are connected to the bogie in such a way that the axles stay parallel (i.e. the yaw stiffness, that keeps the axles parallel, is high), the front wheelset will generally have a certain angle of attack. This means that the axles are not aligned radially, see Figure 2 (left-hand side). While the wheels will roll in the forward direction, the required lateral motion in curves can only partly be realized by the conicity of the wheel profile. In sharp curves additional lateral motion goes along with lateral slip, causing axial wheel vibration modes to be excited. This is audible as squeal.
Theoretically, vehicles with radial steering (right-hand side drawing) do not cause squeal noise, unless the curve is so sharp that the conicity of the wheel is insufficient to enable the wheelset to gently follow the curvature. In practice, the performance depends on the applied technology.

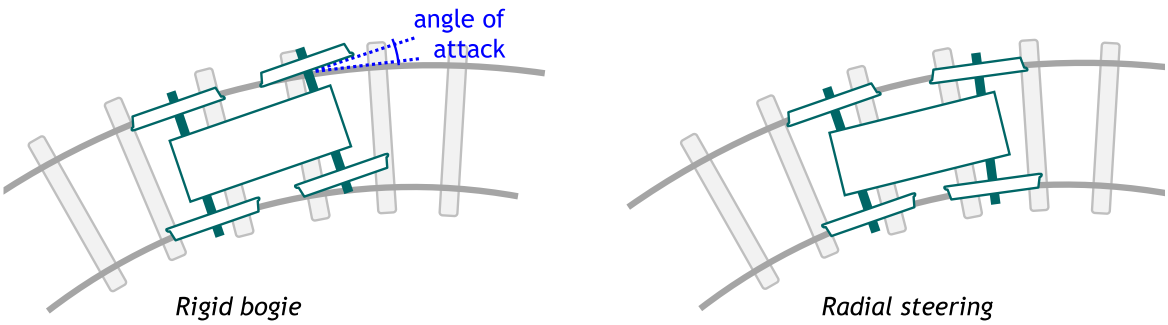


Figure 2 Curving behaviour of a rigid bogie and a bogie with steerable axles.

There are at least two plausible mechanisms that can explain how curve squeal is caused. ‘Classically’, curve squeal is regarded a consequence of falling friction, but more recently an explanation is given in terms of mode coupling:

- Falling friction: it is possible that the friction coefficient within the contact patch of wheel and rail decreases with the lateral sliding velocity of the wheel tread. In these circumstances lateral stick-slip may occur.
- Mode coupling: when a coupling is assumed between the normal and tangential dynamics of a wheel in a curve, it can be shown that lateral stick-slip is possible even in the case of constant friction (instead of falling friction).

In practice both mechanisms can play a role. Mode coupling can reinforce the falling friction mechanism, or it could reduce it. Generally, the friction coefficient needs to be quite high for

mode coupling to occur[1]. Mode coupling is less likely if the friction coefficient is around typical values of 0.3 or 0.4. A more detailed description of both mechanisms is given in the overview article by Thompson et al.[2]
As the effective value of the friction coefficient in the contact area of wheel and rail can only be determined indirectly, it may be difficult to decide which mechanism is most relevant in a certain case with curve squeal. However, the relative phase between vertical and lateral response can be measured and this can be an indicator of whether mode coupling could be involved. In cases with mode coupling as main mechanism, treatment with friction modifiers may not be appropriate to tackle curve squeal.

Flanging noise

Like with tonal squeal, the generation mechanism behind flanging noise is also not fully understood. Due to the unstable (noisy) nature, it is difficult to investigate what parameters are influencing flanging noise in field measurements with trains running in curves. However, results from modelling suggest that *radial* wheel modes are involved in flanging noise [Thompson 2018]. This would explain the fact that flanging noise has a higher frequency content than curve squeal. Evidence that supports this prediction is found in measurements in a test rig and in a field test (in a 150 meter radius curve) [Kim 2019]. By comparison of the spectra of curve squeal and flanging noise measured in the test rig as well as the curved track, radial wheel modes could be associated with flanging noise. Further research has demonstrated that flanging noise is caused by intensive rubbing from the wheel flange to the gauge corner of the rail [Luo 2022]. In this contact patch irregularities with high roughness levels are present. Numerical modelling of the situation suggests that the generation mechanism is impulse excitation.

1.2.2 Practice

Influencing factors

There are many factors that influence curve squeal. The combination of those factors will determine whether the phenomenon actually occurs.
It has been pointed out that curve squeal should not be regarded as a single phenomenon – there may be different mechanisms involved in apparently similar cases and these require different treatments [Thompson 2018]. This will be directly clear, considering the fact that not in all field tests that were explored in detail, the leading inner wheel was found to be the one squealing. This also means that in a situation where the factors determining one squealing mechanism have been treated, a different mechanism may become dominant.

The factors that are most relevant for curve squeal are:

- Curve radius, wheelbase, yaw angle, yaw stiffness
- Rail and wheel transverse profile including flange distance, track gauge and cant, train speed, contact position
- Various dynamic properties of the wheel, the track, and the wheel/rail contact

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[1] *Personal communication David Thompson*
[2] *2018, A state-of-the-art review of curve squeal noise - phenomena, mechanisms, modelling and mitigation*

- Lateral friction characteristics, axle load
- Environmental conditions such as air temperature and relative humidity, rail temperature and dew point

Other factors

- It has been observed during an Austria test research project (ESB) that vehicles with newly reprofiled wheels tend to squeal more often than vehicles with untreated wheels [Maly 2019]. Also, freight trains with cast-iron braking blocks had less squeal noise, compared to trains with other braking systems. This is because trains with cast-iron blocks produce much more rolling noise, so the relative difference with the squeal noise sound power is less [Maly 2015]. Another Austrian observation is that train acceleration in a curve after station could also be a cause for a squealing type of noise in some locations under some (environmental) conditions.[3]
- At the Stockholm metro it was observed that after rail grinding the tendency of curve squeal increased, likely due to the change of the rail profile (moving the lateral position of the contact patch)[4].
- In Australia most squeal problems are related to freight trains. Bogies that had a high angle of attack and tended to squeal, were removed from service for inspection and maintenance. As invariably all tolerances of such bogies were found to be within specification, the bogies were put into service again without improved curving behaviour. Only after extensive studying it was concluded that the steering performance is determined by the bogie design and bogie configuration, rather than by the maintenance condition [Hanson 2021].

Rules of thumb

In general the probability of trains squealing in curves increases with:

- Decreasing curve radius and/or increasing wheelbase (within a bogie)
- Increasing yaw stiffness between the axles and the bogie frame

There is no simple rule of thumb for how squeal depends on most of the other factors from the list above. For example, laboratory tests suggest that squeal increases with relative humidity, but a statistical analysis of a long measurement campaign of the Stockholm metro showed no clear correlation for one curve, while the correlation for the other depended on temperature [Świerkoska 2019]. In an Austrian measurement campaign the effect of rail temperature below dew point was quite similar as the effect of rainfall: in both cases the relative number of tonal and broadband squeal events was reduced significantly [Maly 2019].

The rail squeals too

The rail will generally squeal at the same frequency as the squealing wheel [Świerkoska 2019]. Therefore, the occurrence of squeal can easily be detected by accelerometers attached to the

[3] *These observations made in Austrian literature were kindly shared by Günter Dinhobl*
[4] *Personal communication Astrid Pieringer*

rail. Nevertheless, as it is a certain wheel mode that is excited, and as the wheel is a more efficient radiator than the rail, the wheel will be the dominant source of curve squeal.

And suddenly curve squeal became an issue

In practice, it often occurs that curve squeal unexpectedly becomes an issue: a situation without curve squeal suddenly changes into a situation with persistently curve squeal. This could be due to a change in the track or a change in train service.

- In the Móstoles curve (220 m radius) in the Madrid region, a change from wooden sleepers to concrete sleepers around 1995 is regarded the starting point of an increase of curve squeal. Also in the Sydney area in Australia, upgrading from a track with timber sleepers to concrete sleepers was observed to increase the occurance of curve squeal [Hanson 2014].
- In an Australian study, poor rail grinding was observed to double the incidence of curve squeal. If the grinding leaves facets ate the gauge corner, lubrication could be prevented to migrate to the contact zone, and/or two-point contact is introduced [Hanson 2021].
- In the village of Soest in the Netherlands, a change in train service led to severe squeal in a 300 m radius curve, starting December 2015. The cause was the bogie configuration of the traction unit ‘mDDM’, see Figure 3. This unit has three bogies. This type of rolling stock was never used before on that rail link.

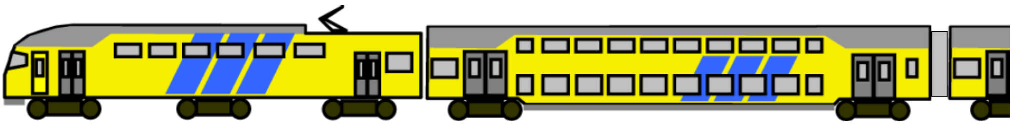


Figure 3 Dutch multiple-unit train with 3 bogies under the mDDM locomotive (to the left).

And suddenly the curve squeal measure was withdrawn

In several urban rail transit systems, vehicles with radial steering (see Section 3.5) are applied. This will reduce both wear and curve squeal. However, the situation can easily turn into a problem when the existing fleet has to be replaced by new rolling stock.

- After the rolling stock on the Zurich city tram system changed from radial steering vehicles (Cobra) to non-radial steering vehicles (Flexity) [5], curve squeal needed to be suppressed with over 150 trackside friction management units.
- The Alstom vehicles on the Copenhagen S-train, in service since 1996, have passive hydraulic steering. It turns out that the tender for a new generation of trains does not impose any special requirements on steering.
- In the UK, a fleet of DMUs (diesel multiple unit) were fitted with constraint layer dampers in the 1980s to prevent cornering squeal. Many years later, the reason for the dampers had faded into the background and it was decided to remove the dampers from the wheels to make maintenance easier. Fortunately, this intention was first made known to the same consultants who were involved in recommending the fitting of wheel dampers. Otherwise, the problem of curve squeal would have arisen again.

[5] https://www.nzz.ch/zuerich/nicht-mehr-so-leise-wie-die-cobras-ld.914502

These cases suggest that the knowledge about the advantages and disadvantages that underpinned the original choice for a particular fleet may erode faster than the lifespan of rail vehicles.

1.3 Measurement methods and monitoring methods for curve squeal

For various reasons, there may be a need to characterize a situation with curve squeal noise by means of measurements.

1. Measurements before and after applying a certain measure, in order to quantify its effect.
2. Measurements to determine the precise nature of the problem so that appropriate measures can be selected, possibly after the situation has been examined in a scientific model on the basis of the measured values.
3. Monitoring measurements to assess the extent of the problem or the long-time performance of a anti-squeal measure.
4. Measurements to determine which source terms for curve noise should be applied in a calculation model for environmental noise (for example for noise mapping and action planning).
5. Measurements to assess new rolling stock for curve squeal behaviour.

For the first two purposes it may be necessary to measure a large number of parameters. Guidance can be found in measurement protocols [Verheijen 2000]. For the third goal unmanned measurements are most appropriate. These could be trackside monitoring stations or vehicle-mounted devices. The development of practical trackside monitoring systems is the subject of subtask 3.5.2 of Rail4Earth and is recently also a task within CEN/TC 256 – Railway Applications (NWIP WI00256A1M). For fourth purpose in this list, measurement of source terms, the new draft standard EN 17936:2023 is suitable. The ACOUTRAIN measurement protocol can be used for the fifth purpose [Dittrich 2015].

1.4 Curve squeal and noise regulations

Due to the stochastic and unpredictable nature of curve squeal, it is not easy to account for it in railway noise legislation. It is also not easy to include curve squeal in calculation methods for environmental noise. Among the countries that include curve squeal in calculation methods are Germany, Switzerland and Austria.

The effect of curve squeal is incorporated in a simplified way in the European calculation method CNOSSOS, which is mandatory for action planning and noise mapping under the Environmental Noise Directive. For tramways there is a correction value of 5 dB, to be added to the rolling noise source power, if the radius is 200 m or less. For railways the correction value equals 8 dB for 300 m radius or less, and 5 dB for a radius between 300 m and 500 m. These are default values. Correction values based on measurements may be used instead.

2 Track-based measures

2.1 Introduction

Part of the track-based measures against curve squeal in this chapter were already listed in the toolbox of the Curve Squeal Project of UIC of 2003 [Müller 2004]. Besides the ‘classical’ friction controlling measures, also two experimental measures were mentioned that had not yet or hardly been tested in practice at the time. These are rail coatings and asymmetric rail profiles. Since then, some new solutions have emerged.
All these measures are discussed in this chapter. The final section of this chapter discusses best practices, as some measures may be more effective than others in specific curves.

It goes without saying that noise barriers can be particularly effective against curve squeal noise (if there are no reflective buildings on the other side of the track). However, general measures against railway noise are not described in this catalogue.

2.2 Friction modifier (top-of-rail)

Friction modifier is a substance that keeps the friction coefficient in the contact area between wheel and rail at an intermediate level. It should be applied on top of the inner railhead if the inner wheels tend to be the wheels that are squealing in a curve. If the system is properly adjusted, passing train wheels will spread the fluid further along the railhead.

Although the operating principle is relatively simple, the main challenge is to make the system work smoothly for a long time under varying conditions (weather, dust). For example, overdose and blockages must be prevented. Also, environmental aspects should be considered as the product will end up in the ballast. Recently, an attempt has made to investigate the parameters relevant for optimal application of top-of-rail products [Trummer 2021]. Their empirical model was tuned using test rig data. It will require further research to extend the model for various operational circumstances on a real track.

Experiences from several railway infrastructure managers are found below.

Austria (ÖBB-Infrastruktur AG)

The occurrence of broadband flanging noise and tonal squeal was examined in several railway curves in Austria [Maly 2015, 2019]. The sharper the curve, the more noise. Tonal noise appeared mostly on the inner side of the curves. Broadband noise could not be linked to a specific side. The location of the wheelsets with either broadband noise or tonal squeal within a train appeared to depend on the train type. Top-of-rail application, tested as a measure against

curving noise, turned out not to be always effective in these trials because there were problems with obtaining sufficient fiction modifier on the rail head. It should be applied to the inner rail [Maly 2015].
There are only 2 test stations for top-of-rail application. For safety reasons (braking) this measure is only allowed for tracks with a low gradient (<10 ‰). The use of friction modifier should not lead to short-circuit of rail insulation joints. Also, there may be concerns with contamination in environmental protection areas, e.g. pollution of the ballast, bridges above the water.

Figure 4 System by RPD, Central Station Cologne, 2024 (Wikimedia *Schienenkonditioniersystem Hbf Köln* / User:Mpns / CC BY 4.0)

Switzerland (SBB)

SBB prefers general noise measures such as noise barriers or façade insulation rather than new components in the railway system. However, at present, for the purpose of mitigating curve squeal about 30 to 40 top-of-rail application systems have been installed on 6 locations. Some of these are near (roof-covered) stations to avoid annoyed passengers. Some other systems are for residents, for example where noise barriers were not possible. The top-of-rail application systems at the SBB network are from 2 different suppliers. For maintenance, one engineer of SBB visits the systems to verify that they are working properly. On average, once every 3 month the supplier needs to check and refill the systems.
The current form of contracting suppliers does not lead to a desired solution for curve squeal. A problem is that the required performance has not been settled in a contract. At present, the effectiveness of applying friction modifiers is not quantifiable and therefore not optimal. It is not actually known how well these application systems works. Residents hardly experience the realised decrease in curve squeal as an improvement (shorter duration, lower sound level, less

events). SBB would prefer a form of contracting where the supplier is paid for the achieved performance. Therefore, a pilot project is being set up where the relevant parameters are measured (e.g. speed, train type) in order to quantify curve squeal and to quantify the required performance of curve squeal solutions. The evaluation software will be open source and made available to suppliers/contractors. Once the performance requirements have been quantified, a tender with new suppliers can be started.

Spain (ADIF)

A sharp curve with problems of excessive rail wear and squeal noise is located East of Móstoles Central station. This curve, 400 m long with radius 220 m, lies in a residential area. In order to mitigate the problems, the following measures have been taken:

- Installations with top-of-rail friction modifier
- Speed reduction from 50 to 30 km/hour
- Modified sleeper spacing, to change the vibration modes of the system
- A harder rail has been applied on one track

At present, it is not possible yet to quantify the effects of these measures.

Figure 5 Móstoles curve: main view, rail wear and friction modifier systems. (Photos: courtesy of ADIF)

United Kingdom (Network Rail)

Friction modifiers are used in many dozens of curves from the perspective of track maintenance and/or squeal noise. Currently there are about 3 or 4 different brands of track-based systems in operation, either using water-based or oil-based lubricants. There are a lot of optimization options in the area of application of the friction modifiers, for example application only on the inner rail, the (rail) length of application, and the precise (lateral) position on the rail. The skills of maintenance personnel are also important for efficient dosing. Increasing the dose does not necessarily increase the performance in terms of curve squeal mitigation. Optimization aims at improving performance whilst maintenance costs and contamination of the ballast bed will be reduced.

Germany (DB InfraGO)

In the railway network of DB InfraGO, top-of-rail application units are used to reduce abrasion. Reduction of curve squeal is regarded as a positive side effect.
Tests and measurements with application systems were reported in [KP-II 2012] and [I-LENA 2022].

Sweden (Trafikverket)

Trafikverket has around 10 application systems in about 7 curves. The instalments started about 10 years ago. In the Stockholm area some new top-of-rail equipment will be tested. The noise in the present situation has been measured since about one year. Lulea University is involved in measuring and modelling.

The Netherlands (ProRail)

ProRail has more than 2,200 top-of-rail applications units for friction modifier in operation. Most of these have been installed at railway yards during the past decades. A smaller part has been installed along railway lines on an ad hoc basis, along curves with a lot of squeal noise. Examples of ad hoc placement are curves in Soest, Hilversum and Deventer (the latter also in the context of a permit for the railway yard). Other recent installations that are part of permits are: Nijmegen, Delft, Amsterdam, Zwolle. In the past, also some installations were financed by municipalities (Oss and Eindhoven), but in recent years these have been taken over by ProRail.

Refilling of the applications units is necessary once or several times a year. The systems are from one supplier. Contractual management is based on operation and availability, not on performance in terms of noise reduction. Contractual requirements include speed of fault recovery, insight into faults, number of maintenance visits, sufficiently large volume for friction modifier per location. There was a verification period after awarding the maintenance contract. Among other things, the adhesion had to be verified (measured with a rail tribometer), and the operational track length with friction modifier had to be verified.
An ECO label is required for the friction modifier. There are no known issues with contamination of the ballast bed.

Maintenance costs for the 2,200 systems are approximately 1.2 million euro per quarter of a year. Investment costs are around 20,000 euros per installation (1 installation has 2 dosing heads). ProRail is looking at options to reduce the maintenance costs of installations.

A recent development with a positive side effect on curve squeal is the unbundling of railway junctions, a national project in which many switches are being removed. For example, in one of the main national junctions, in Utrecht, the number of switches is reduced from 186 to only 60. The remaining switches are often 1:15 switches, with a larger curve radius than the older ones. This has a beneficial effect on squeal of flanging noise in switches.

Suppliers:
Elpa elpa.si
Hy-Power www.hy-power.eu
IGRALUB igralub.com
L.B. Foster Europe lbfoster.com
P.A.L. Italia www.palitalia.net
Rail Partner Holland www.railpartnerholland.com
RS Clare & Co Ltd www.rsclare.co.uk

2.3 Lubrication (gauge face)

Gauge face lubrication is a method to reduce wear at the wheel flange and the gauge corner of the outer rail in a curve. As the lubricant (grease) will reduce the friction, for safety reasons it should never be (accidently) applied on top of the rail.

In most of the interviews conducted with experts of the infrastructure management organisations, gauge corner lubrication was not brought up as means to control curve squeal. Nevertheless, lubrication of the outer wheel/rail contact may reduce flanging noise and in certain cases also squeal noise [Hanson 2021]. There are around 170 lubrication systems in curves of the ÖBB-Infra network.
However, there is no guarantee that it works against curve noise. For example, in a 300 m radius curve of an elevated corridor of New Delhi metro, gauge face lubrication had no effect on flanging and squealing noise [Garg 2010].

Suppliers:
Most of the supplier mentioned in section 2.1 also have gauge face lubrication systems. An additional supplier is:
Robolube www.rblinc.com

2.4 Rail transverse profile design, rail gauge, cant

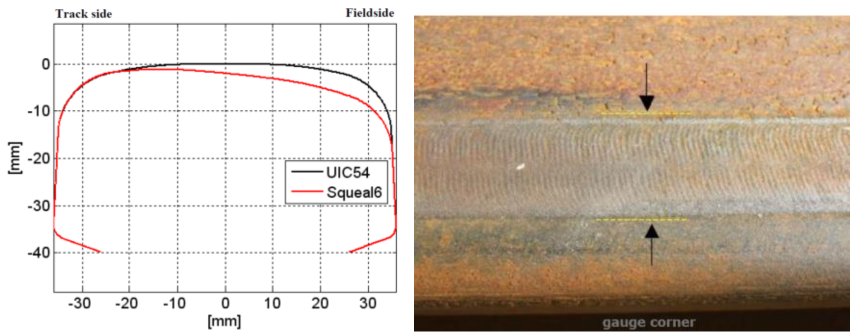
Rail gauge and rail profile are factors that are relevant for the occurrence of squeal, as they change the lateral contact position. The basic idea is that the contact position on the leading outer wheel is to be moved away from the flange, while the contact position of the leading inner wheel is shifted nearer its flange. This way, the bogie is caused to traverse the curve more gently [Thompson 2009].

It requires modelling to determine which modifications to the track transverse profile are required to reduce curve squeal. Some universities develop their own scientific models, but there is also commercial software like VAMPIRE for multibody dynamics or engineering tools like SONIA for curve squeal prediction [Tufano 2023]. This latter tool takes into account falling friction and mode coupling, see Section 1.2.1.

Because the wheel profile and train speed also determine where the contact position is located, the degree of success of adjusting the track gauge and rail profile will also depend on factors over which the infrastructure manager has no influence.

Asymmetrical rail profiles

A field test in Switzerland in 2006 showed only effects for one type of passenger train [Kruger 2013]. In the Netherlands, a special anti-squeal rail profile (the ‘Squeal6’ profile in Figure 6a) applied to the inner rail in a 200 m radius curve resulted in 3 dB lower squeal levels on average, but the percentage of trains squealing was not reduced [Hiensch 2010]. As it is known that rail profiles in curves are subject to (heavy) wear, a further test was conducted with a treated railhead. The same anti-squeal profile was taken, but now tungsten carbide was impregnated within the contact area, see Figure 6b. This reduced the number of squeal events from 74% to 26%. Also, the average L_{Aeq} of the squeal events was reduced by 4 dB. However, due to increased wear it was decided not to proceed with this measure.



(a) (b)

Figure 6 (a) Anti-squeal rail profile for the inner rail [Hiensch 2007]**; (b) impregnation** [Hiensch 2010]

Optimized rail transverse profiles were also explored for a 1000 m radius curve of a South African heavy haul freight line, as an alternative to top-of-rail friction modification[6]. From numerical simulations it was concluded that grinding the outer rail with a target profile that is shifted 5 mm inwards is the best solution. Because grinding already takes place 3 to 4 times a year, the costs of this measure are lower than the maintenance costs of an application system of friction modifier [Fourie 2017].

Besides transverse profile design, also the track gauge in a curve can be chosen either wider or narrower than standard. It will depend on the wheel profile which of these two options is best suitable to mitigate curve squeal [Thompson 2018]. In practice it may be difficult to obtain the exact specifications of train wheels from the manufacturers. On tracks with many different

[6] *This South African track type is quite different from European tracks, also the wheel profiles are different.*

operators and train types, this may complicate the development an optimal track design for reduction of curve squeal and wear[7].

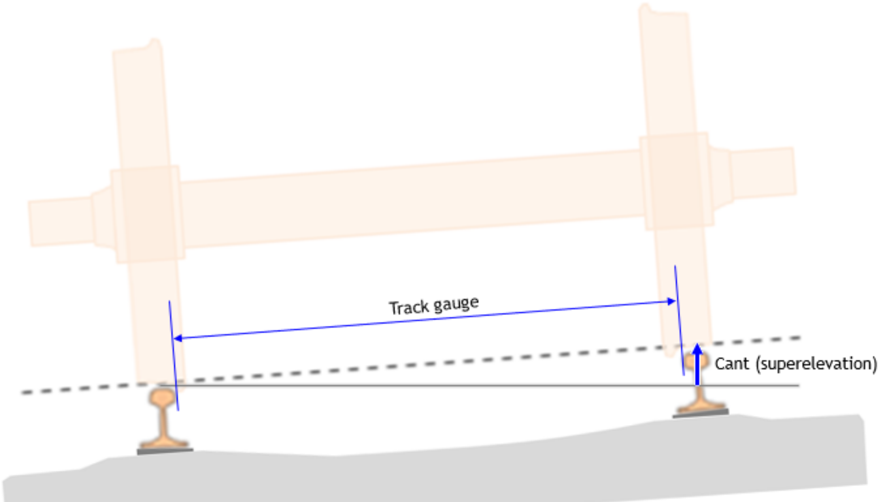


Figure 7 Cross-section of a track in a curve.

Gauge widening was explored in combination with wheel profiles in simulations for the Tokyo subway Liner Metro [Adachi 2011].

The observation that upgrading sleepers from timber to concrete leads to more severe curve squeal suggests that the dynamic track gauge is also an influencing factor. When a train passes, the rails will bend slightly sideways if the track construction is sufficiently flexible. The application of softer rail pads is therefore believed to provide the lacking flexibility in such curves [Hanson 2021].

Finally, the cant in a curve can possibly be adjusted as a measure against wear and squeal noise. This is because cant in combination with train speed will partly determine the angle of attack between the wheel and the rail. Statistical analysis of many freight wheelsets passing a curve near Sydney, however, showed little effect from speed on the angle of attack. This would suggest that cant excess or cant deficiency will not have much influence on squeal [Hanson 2021]. An approach of measuring and modelling could help to better understand what is happening here.

Software suppliers

Vibratec vibratec.fr (SONIA engineering tool for curve squeal)
Vampire vampire.clyx.net (Vampire Pro railway vehicle dynamics simulation)

[7] *Personal communication Jamie Wilkes.*

2.5 Rail damping

Though the rail may also resonate along with the squealing wheels in a curve, the wheel is the dominant noise source. If the application of rail dampers nevertheless proved successful in preventing or significantly reducing curve squeal, as sometimes has been reported, it is unclear how this works [Thompson 2009]. It would then be worthwhile to examine this further.

Figure 8 Rail dampers (Wikimedia original photo: *Schienenstegdämpfer im Bahnhof Rathen,* 2011, Norbert Kaiser, CC BY-SA 3.0)

2.6 Best practice

The dependence of curve squeal on track and wheel dynamics is a complex interplay of factors. Which measure is most appropriate for a certain curve, is not easy to predict. Completely avoiding squeal noise has not yet proven to be possible with track-based measures alone. With the vehicle-based measure *radial steering*, it should theoretically be possible to completely prevent the occurrence of curve squeal, but only limited practical evidence is available. Track-based measures can reduce the number of squeal events, shorten the duration and/or lower the noise level, provided that these measures are well-maintained. It is therefore important in communication with residents not to give the impression that the problem can be completely solved.

In the interviews conducted with rail infrastructure managers, friction control measures were mostly mentioned. It should be noted, however, that a poor friction condition ('falling friction') is not the only mechanism to cause squealing wheels: also 'mode coupling' can play a role. Apart from that, flange contact could be involved. In those cases friction treatment will probably not have the desired effect. Unfortunately, there is no simple method to find out which mechanism is (mainly) responsible for squeal in a certain curve.

Other track-based measures are related to the track transverse profile (rail profile, track gauge, cant). Maintaining the transverse profile in optimal condition requires frequent rail grinding. These measures attempt to improve the curving behaviour of the vehicle by shifting the lateral contact position. On tracks with mixed traffic this will probably be less successful. Though the performance of friction control measures is observed mostly to be explored on a trial-and-error basis, it requires in-depth modelling to determine the necessary modifications to the track transverse profile.

Regarding friction control, literature suggests that it depends on the situation whether to opt for gauge face lubrication or top-of-rail friction modification. If the outer wheels are the ones squealing in a certain curve, lubrication of the gauge face could be considered (even though the events were categorised as tonal squeal, rather than broadband flanging noise) [Thompson 2018]. In practice these systems are mainly used for wear control reasons: squeal mitigation is not the main goal of gauge face lubrication. If the inner wheels in a curve are squealing, top-of-rail application of a friction modifier will probably be more successful. The performance in terms of noise reduction may critically depend on how well the automated application systems are functioning under different conditions (dust, weather).

3 Vehicle-based measures

3.1 Introduction

Though curve squeal is caused by a complex interaction of track and wheel characteristics, it is possible to prevent squeal by solely modifying one of the interacting systems: the vehicle bogie. Unfortunately, there are some risks involved for trains running at higher speeds. Other vehicle-based measures are less challenging in this regard, but also generally have less effect on curve squeal.

3.2 Lubrication

In principle, train-based application of friction modifiers can be expected to be more efficient than track-based applicators, because more curves can be addressed and also because the liquid can be sprayed more precisely on the part of the wheel surface that is in contact with the railhead. However, a convincing business case for this approach has not yet been shown[8]. When setting up a programme for train-based friction modifiers in a railway network, the following should be taken into account:

- It requires close cooperation between the infrastructure manager and the train operator(s). This may be difficult to arrange if the responsibilities for track maintenance and train operation lie with different organisations.
- It is generally not possible to control where the trains with such lubrication systems will run. Usually, they will run on different lines on the whole network[9]. It leads to higher costs if more trains are included in the lubrication fleet.
- With standard lubrication systems on locomotives, the amount of lubrication cannot be managed remotely. The train driver can independently decide to turn off the system for safety reasons[10].

Because of these reasons, it will be more feasible to consider vehicle-based lubrication in urban rail transit systems.

France

Tramway networks in France may have problems with severe curve squeal, typically where new networks for city trams have been developed in the past decades[11]. Measures are mostly friction modifiers, as these are feasible (no new homologation necessary). Wheel absorbers are not applied much in France.

[8] *Personal communication Jamie Wilkes*
[9] *Personal communication Günter Dinhobl*
[10] *Personal communication Nils Yntema*
[11] *Personal communication Martin Rissmann*

On various tram lines in Nantes, curve squeal is the main source of inconvenience. There are trackside lubrication devices and water sprinkling devices, but also the majority of the trams is equipped with on-board rail lubrication devices. Friction conditions in curves without trackside devices are controlled remotely by these on-board systems [Nantes 2017].

Germany

The Berlin tramway network of BVG has many sharp curves. The on-board rail lubrication systems are connected to the windscreen wiper sensor to avoid unnecessary lubrication during rainfall[12]. They are programmed to apply a friction modifier on the inner wheel tread.

Figure 9 Systems for flange and top-of-rail application (ProRail, [WRC 2012])

Suppliers

Most on-board systems are pre-installed by the vehicle manufacturer. Most of the suppliers mentioned in Section 2.1 will provide lubricants and friction modifiers.

3.3 Wheel design

Modifying the wheel web profile (see Figure 10) may reduce the vertical/lateral coupling of wheel vibration. It is known how this affects rolling noise and it may also affect squeal[13]. The effect on squeal is to be explored by Chalmers University in Rail4Earth.

Suppliers

Wheel web design is an expertise of wheel manufacturers, universities and engineering companies.

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[12] *Personal communication Markus Hecht*
[13] *Personal communication Astrid Pieringer*

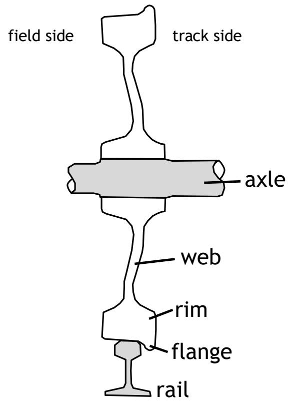

Figure 10 Cross section of a train wheel.

3.4 Wheel damping

Wheel dampers intend to suppress the vibration that causes wheels to radiate rolling noise or squeal noise. In case the wheel dampers need to reduce squeal noise, they should be tuned to all modal frequencies that can be excited during negotiating a curve. It may not be sufficient to damp just one single modal frequency, as the wheel could then start squealing at a different modal frequency[14].

There are different types of wheel dampers: plate dampers, sandwich dampers, ring dampers, constrained layer dampers, friction dampers. Dampers are usually mounted on the web or rim of the wheel.

Spain

Constrained layer dampers, tuned to the squealing frequency of about 790 Hz of the tram wheels to which they were attached, yielded a squealing noise reduction of 25 dB in Vitoria-Gasteiz (Spain) [Meridino 2014].

United Kingdom

In the UK, constrained layer damping has been installed on a fleet of DMUs in the 1980s. They were put on at the factory and are still working[15].

The Netherlands

For the main intercity double decker, type VIRM, one of the two wheelset manufacturers has equipped the integrated wheels with ring dampers. This was due to the large-scale overhaul in which bandaged wheels were replaced by integrated wheels, as to avoid an increase of rolling

[14] *Personal communication Astrid Pieringer.*
[15] *Personal communication David Thompson*

noise[16]. Because these manufacturers' wheelsets are interchangeable, some wheelsets of the VIRM have ring dampers while others do not. Squeal noise was not a reason for this overhaul.

Germany

Though the Wuppertaler Schwebebahn, a mono-rail suspension railway, has not very sharp curves, the wheels are known to squeal. For this purpose wheel dampers have been applied, see Figure 11, and the rails were isolated with rubber cushions[17].

Figure 11 Wuppertal suspension railway with wheel dampers. (Wikimedia original photo left: *Wuppertaler Schwebebahn in Elberfeld,* 2011, User:W-tal-1, CC0, right: *Antriebssatz,* 2015, Matthias Böhm, CC BY-SA 4.0)

Suppliers

BVV: www.bochumer-verein.de
Lucchini: www.lucchinirs.it
Schrey & Veit sundv.de
Valdunes: www.valdunes.com
CAF: www.cafmiira.com

3.5 Radial steering

Improved curving behaviour can be achieved by applying steering axles, see Figure 2. In theory, bogies with radial steering would not be expected to cause squeal noise at all. However, in practice squeal noise may still be found at a reduced level [Hur 2024].
In order to guarantee sufficient stability at high speeds, bogies with radial steering require certain technical solutions. These may be passive (mechanically, hydraulically) or active (electronically controlled).

[16] *Personal communication Jasper Peen*
[17] *Personal communication Markus Hecht*

3.5.1 Passive steering

Unlike active steering bogies, which use electronic controls and actuators, passive steering bogies are based on mechanical design principles. A passive steering bogie has mechanical components that allow for some degree of rotation of the wheelsets relative to the bogie frame. They are self-steering, which means that the angle-of-attack is reduced in curves, minimizing flange contact and reducing track and wheel wear.

One group passive steering bogies features articulated frames, in which the axles are connected in such a way that allows them to pivot slightly when entering a curve. An early design is the cross-anchor bogie from the 1970s, in which the wheelsets are diagonally stabilised. An improved version is applied in the TVP2007 bogie in Austrian freight wagons. Monitoring results show less wheel wear as compared to the reference (non-steering) bogie Y25, leading to 30% longer mileage until reprofiling [Domanicky 2016].

A more emerging method of passive steering uses flexible suspensions, commonly called hydrobushes (named after the hydraulic damping mechanism). Hydrobushes can mostly be fitted into existing bogies, replacing the conventional rubber bushes in the trailing arm suspensions (Figure 12). While rubber bushes provide stiffness and a limited level of damping in different directions, hydrobushes are designed to combine low longitudinal stiffness with large high-frequency dynamic stiffness [Qu 2023]. As a consequence, the axles are allowed to steer in curves (low frequency forces), while on straight track sections (high frequency forces) the stiffness is high enough to stabilize the axles as to reduce bogie hunting and prevent derailment.

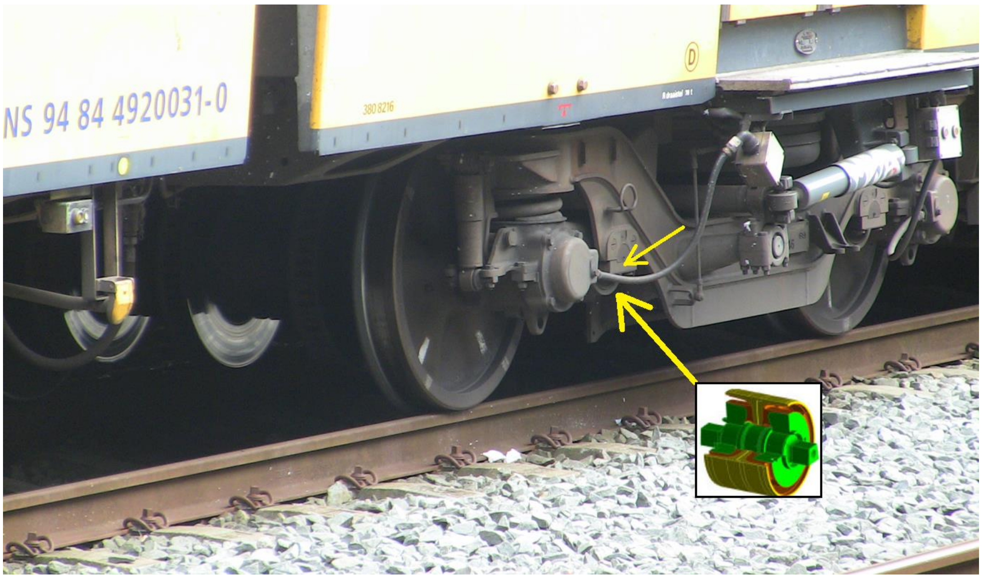

Figure 12 Position of the trailing arm suspension with hydrobushes. (photo: Edwin Verheijen)

The Netherlands

During the last decade, part of the bogies of an EMU (electric multiple-unit train) of type VIRM has been retrofitted with hydrobushes. Within subtask 3.5.3 of ERJU project Rail4Earth onboard noise measurements were performed on several of such VIRM trains to investigate the occurrence and strength of curve squeal noise and also to evaluate the ACOUTRAIN measurement methods [Jansen 2025].
VIRM trains have different bogie configurations: certain motorized bogies are equipped with hydrobushes that allow for passive steering. Certain wheels have ring dampers while others have no dampers.

Also trackside measurements were part of this measurement campaign. These were carried out in curves in Amsterdam, Den Bosch and Arnhem, using 4 microphones at the inside of the curve. Several accelerometers were mounted on both rails to identify squeal events per bogie pass-by. Additionally, meteorological data such as relative humidity and dewpoint were logged.
The onboard measurements took place on two intercity routes with many curves. The equipment was installed inside the trains. A microphone was placed in the wagon interspace between two trailing bogies and an accelerometer was mounted to the floor.

The VIRM intercity train produces mainly semi-broadband noise in the frequency range of 2 kHz to 20 kHz, which could be classified as flanging noise. In order to quantify this noise, it appeared necessary to slightly modify the ACOUTRAIN procedure, using the pass-by sound spectrum difference ΔL_{10} between a straight track and a curve.

The trackside measurements revealed a large variation of flanging noise for all train types, not only over the monitoring period, but also during pass-bys of single trains. For the pass-bys of VIRM trains an attempt was made to determine the noise emitted by individual bogies and/or wheelsets, separately. Unfortunately, the uncertainties were high as a result of the short averaging times per wheelset, which severely limited drawing conclusions about noise reductions attributed to hydrobushes and ring dampers. Besides that, the effects of hydrobushes or ring dampers on the noise levels were not consistent for the different trackside measurement locations.

The costs of retrofitting bogies with hydrobushes are limited if the refurbishment is carried out within the normal overhaul cycle for the rubber components in bogies (average lifespan of 8 years). Apart from the retrofitting costs also maintenance costs are important for a business case. As the costs will depend on several factors, a business case needs to be made.
The new ICNG train (maximum speed 200 km/h) has hydrobushes upon delivery.

Switzerland

The bogies of several train types in Switzerland have been refurbished with hydrobushes. Especially since the track access charges have been reduced for these types of trains, the application of hydrobushes has increased. See also Section 3.7.

Sweden
The narrow-gauge urban transit system Roslagsbanan, which runs from Stockholm to the north, has new trains equipped with hydrobushes. The speed is being upgraded from 80 km/h to 120 km/h. The effect of the hydrobushes on stability at higher speeds, wear and curve squeal is not known yet[18].

Suppliers:
Trelleborg www.trelleborg.com (HALL bushes)
Continental www.continental-industry.com (guiding bushes)
Wabtec www.wabteccorp.com (hydrobushes)

3.5.2 Active steering

Active steering requires sensors that estimate the curve radius in real-time and steering driving units that adjust the angle between the front and rear axle in the bogie.

With active steering systems it is necessary that there are facilities that prevent the train from derailing if the electronics fail. For this purpose modern designs are typically equipped with fail-safe mechanisms. In the event of a defect in the steering control unit, the system may revert to a passive state where the wheelsets are locked. The bogie then behaves more or less like a conventional non-steering bogie.

Trains with active steering are more expensive than conventional trains, though the additional costs may be less than 1% of the costs of a new train[18]. Maintenance of such trains is more complex, requiring special skills to ensure safe functioning and also specific tools for repair. It is therefore a very big step for train operators that have a mixed existing fleet to introduce such a technically more complex train type. For these reasons, trains with active control are mainly used in urban transit systems, with only one operator and usually only a few train types. There are generally also more curves per network kilometre, so that the benefits of less wear and tear in curves weigh proportionately more.

South Korea
In an urban rail system with curves of 300 m or less, active steering led to a maximum noise reduction of 4.7 dB for the car body [Hur 2024]. Especially the squeal noise in the range of 300 to 2000 Hz was affected.

[18] *Personal communication Markus Hecht*

Suppliers:
Rolling stock manufacturers

3.6 Other solutions

3.6.1 Small wheels

In general, a smaller wheel diameter causes less noise to be radiated from the wheel. Smaller wheels also allow for more passenger capacity, as there is more space left above the bogie. Where normal double deck trains have 50% more capacity than trains with one deck, it may go up to 80% with small wheels[19].
Small wheels also have disadvantages, for example the permissible axle load is smaller (UIC leaflet 510-2), which may also affect passenger capacity.

3.6.2 Application of a dither force

An innovative concept against curve squeal that is being explored by Chalmers University is the application of 'dither' [Kropp 2019]. This means that a lateral vibration force of a very high frequency, well above the usual squealing frequency, is applied to the wheel or rail, as to disturb the stick-slip process during build-up. The dither force can be generator for example by a piezo actuator. The wheel will then squeal with much less sound power, even though it may radiate some sound at the dither frequency. Proof of concept has been demonstrated in the Chalmers squealing noise test rig.

For a practical application many technical challenges still need consideration. For example, the actuators could be on the wheel or on the rail. They should be rather compact for practical reasons, but the source strength should be sufficiently large.

3.7 Incentives by Track Access Charging

In principle, track access charges (TAC) can be an effective incentive for train operators to use vehicles that impose lower costs on the railway system. TAC are the fees that train operators must pay to infrastructure managers for using the railway network. Ideally, reimbursements should depend on the relationship between causes and costs, such as maintenance costs [Marschnig 2021]. If one vehicle causes more damage than other vehicles, the charge for that vehicle should be higher than average.

For Member States of the EU, their system of TAC must be in line with European legislation. Implementing Regulation 2015/909 under Directive 34/2012, declares that a Member State of the EU may allow its infrastructure manager 'to modulate the average direct unit costs to take into account the different levels of wear and tear caused to the infrastructure' (Article 5). This

[19] *Personal communication Markus Hecht.*

means that Member States may differentiate TAC for vehicles based on the wear that they cause to, for example, railway curves.

In Switzerland, Sweden and the United Kingdom the TAC systems are partly based on the calculated contribution to wear and tear in curves, as caused by single vehicles [Marschnig 2021].

- The Swiss TAC system features a charge based on wear and/or damage to straight tracks, curved tracks and switches. For damage (by RCF, rolling contact fatigue) and wear of the rails in curves, a contact patch energy model is used as an indicator.
- The Swedish TAC system is similar to the Swiss one regarding the calculation of damage and rail wear in curves. The main difference is in the calculation of cost associated with wear.
- The UK TAC system is simpler than the above ones. It requires less vehicles data: only axle load, speed, unsprung mass and gross-tonne-miles.

It must be noted that the occurrence of squeal noise is not considered within these TAC systems. However, as the mechanism behind squeal noise is related to the cause of wear in curves, vehicle-based measures against wear are also expected to lead to less squeal noise.

For TAC to work as an incentive for a track-friendly vehicle fleet, the train operator (and/or vehicles owner) must be able to trust that the charging system will remain in force for a longer period. This makes it possible to recoup investments. As wear will not only affect the track but also the wheels, an investment in track-friendly vehicles may also be beneficial for the train operator.

In Switzerland a significant change in properties of rolling stocks can be observed in Figure 13. It shows the fleet development over time [Nerlich 2024]. Each dot represents a certain vehicle type. The size of the dot represents the fleet size. Bogies with a high primary yaw stiffness generally cause more curve wear (and squeal) than bogies with a low primary yaw stiffness. Some older fleets are partly refurbished with HALL bushes and now have low primary yaw stiffness. For example, the fleet introduced in 1994 (yellow dots) is now being refurbished. Some refurbishments were scheduled with HALL bushes before the new TAC was introduced. All the new vehicles (red dots), mainly operating are track-friendly again.

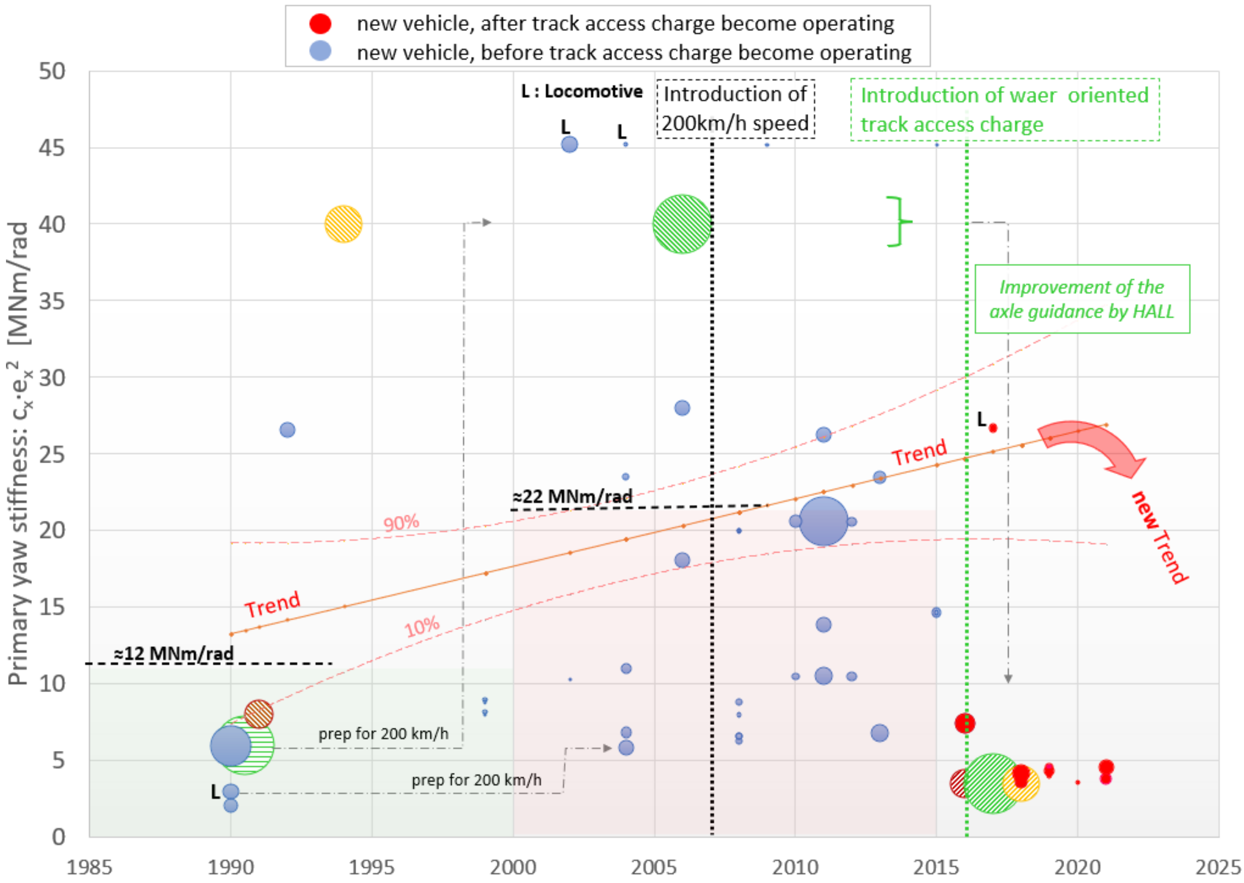

Figure 13 Diagram showing fleet size and primary yaw stiffness over time [Nerlich 2024]. (Graph: courtesy of Ingolf Nerlich)

3.8 Best practices

Radial steering is expected to be effective in limiting wear on wheels and rails. Also most likely, radial steering will reduce curve squeal noise. A form of radial steering that is applicable to existing vehicles is refurbishment with hydrobushes. This retrofitting solution has a limited impact on investment costs and vehicle maintenance and is applied in various countries, especially those where track access charges are lower for trains that cause less damage to the railway tracks. Whether the application of hydrobushes can effectively reduce curve squeal has not been proven yet.

Track access charges can stimulate train operators to invest in new track-friendly vehicles and also in retrofitting the existing fleet, as it can help to establish a healthy business case if the savings on wheel damage control do not outweigh the investments.

4 Conclusions

4.1 Short summary

Curve squeal is a high-pitch sound that is radiated by trains running through sharp curves. The dependence of curve squeal on track and wheel dynamics is a complex interplay of factors. Which measure is most appropriate for a certain curve, is not easy to predict.

At best, track-based measures can *reduce* the number of squeal events and/or *shorten* the duration and/or *lower* the noise level, provided that these measures are well-maintained. Regarding vehicle-bases measures, especially radial steering is effective in limiting wear on wheels and rails. Due to improved curving behaviour, radial steering is also expected to beneficial in reducing curve squeal noise. For active steering, as the most advanced form of radial steering, curve squeal noise reductions up to 4.7 dB have been measured. Whether a passive form of radial steering, i.e. the application of hydrobushes, can also effectively reduce curve squeal has not been proven yet.

The mostly applied track-based measures are friction modification, gauge face lubrication and rail transverse profile design. The main vehicle-based measures are radial steering (passive or active), wheel damping and lubrication. Infrastructure managers can indirectly encourage the application of radial steering by setting appropriate vehicle-dependent track access charges.

4.2 Prospects for future developments

From the literature studied for this report and the information provided by the experts in the interviews, the following themes with respect to curve squeal mitigation are suggested for further development:

- A guideline or road map that can be used to find the most appropriate measure for a given problem curve. Preferably the majority of cases can be covered by a combination of observations and simple measurements. This way, an expensive trial-and-error approach can be avoided.
- Optimising the application of friction modification. Failures or poor performance may go unnoticed for the infrastructure manager and for the maintenance contractor if there is no proper information about the actual suppression of squeal at a location. Wasting fluid should also be avoided.
- Measurement and modelling methods, with test rigs and field tests will have to be further refined, not only to develop new measures and optimise existing ones, but also to start understanding the various misunderstood situations with squeal mentioned in literature.

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- Nils Yntema (Dutch railways, ProRail)

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Colophon

Title short
Catalogue of curve squeal measures

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