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Railway applications — Aerodynamics

Part 7: Fundamentals for test procedures for train-induced ballast projection

National foreword

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généraux pour des procédures d'essais vis-à-vis des
projections de ballast générées par la circulation des
trains

Bahnanwendungen - Aerodynamik - Grundlagen für
Prüfverfahren für zuginduzierten Schotterflug

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European foreword

This document (CEN/TR 14067-7:2021) has been prepared by Technical Committee CEN/TC 256 “Railway Applications”, the secretariat of which is held by DIN.

1 Scope

This document discusses:

- economic aspects of ballast projection;
- comparison of methods in France and Spain for rolling stock;
- infrastructure assessment methods;
- review of available literature;
- next steps and recommendations regarding standardization and research.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 14067-4:2013+A1:2018, *Railway applications - Aerodynamics - Part 4: Requirements and test procedures for aerodynamics on open track*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN 14067-4 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

4 Symbols and abbreviations

For the purposes of this document, the symbols and abbreviations given in EN 14067-4 apply.

5 General aspects of ballast projection and state of the art

5.1 Introduction

The phenomenon of ballast projection has been caused in the past by lumps of ice or accreted snow falling from the train structure during extreme winter conditions, which then strike the ballast bed causing ballast to be ejected upwards, impacting the train underside or passing trains and leading to damage. Typically, this damage includes breakage of train underbody equipment, failures of train systems or reduced efficiencies, breakages of station or train windows, and impact damage to train or trackside structures. This type of ballast projection occurs to regional trains as well as to high speed trains and has been well-known for a long period in railways world-wide.

However, in the early 2000s there were a number of significant incidents of ballast projection involving high speed trains which were not caused by ice fall, but seemed to arise from aerodynamic causes. Substantial damage was caused to the underside of an ICE 3 train in one particular incident in Belgium in 2003. This phenomenon seems to be solely a high speed train phenomenon. The relevant contributory factors involve:

- the aerodynamic design of the train, particularly the train underbody;
- the air speeds generated under the train, due to the Couette-type flow created by the high speed train passing over the static track bed;
- train-induced pressures acting on the ballast;
- track vibrations caused by the traction engines and wheel passing over the rails.

The types of damage from this sort of incident principally includes: ballast stone impacts to the underbody structure and damage to the underbody equipment, pipes and cables of high speed trains, and damage to wheels and rails when ballast stones are trapped between them. Although possible, there seems to be little evidence of collateral damage to other trains or of injury to trackside workers.

It should be noted that although the aerodynamically-induced ballast projection incidents have resulted in some spectacular damage to trains, there is evidence of minor impact damage to train underbodies at lower train speeds that appears to be deemed tolerable by train maintainers. Furthermore, since the first upsurge in these incidents, there has been a complete cessation with no further incidents since 2004. This reduction in incidents coincides with measures introduced by many European Infrastructure Managers to reduce ballast levels relative to the top of sleepers.

Nevertheless, there is a widespread concern that this is still a valid train/infrastructure issue needing certain controls, which is supported by its inclusion in the LOC&PAS and INF TSIs as an issue, (albeit currently as an open point). Consequently, various national rules regarding the issue have been developed, mainly focused on rolling stock, leading to a burden on train manufacturers trying to introduce trains into different countries, as they are required to apply different methods to confirm their trains' performance with regard to ballast projection.

Within the revision published in June 2019, ballast projection is addressed in TSI LOC PAS and TSI INF as an interface issue relevant for operation with train speeds >250 km/h. The issue is connected to the essential requirements of safety and technical compatibility.

5.2 Summary of studies and incidents (by countries, manufacturers)

5.2.1 General

Table 1, reproduced from Claus [1], summarizes some of the major incidents up to 2006 of both types of ballast projection in this century (those due to winter weather are not exhaustive).

Table 1— Reported past ballast projection incidents

Date	Train Type	Location	Speed	Track Type	Weather Conditions	Remarks
2001	ICE 3	Fulda-Göttingen, Germany	230 km/h	Mono-block sleepers, lowered ballast	Winter conditions, snow	
2003	KTX	South Korea	300 km/h	Mono-block sleepers	No snow	See [Kw03] for details
2003	ICE 3	Lille-Calais, France	320 km/h	Bi-block sleepers	Winter conditions, snow	
2003	ICE 3	Belgium	300 km/h	Mono-block sleepers, ballast not lowered	No snow	Speeds up to 275 km/h did not cause problems in double traction
2004	ICE 3	France	320 km/h	Bi-block sleepers	No snow	During homologation test runs
2004	ICE 3	Mannheim-Stuttgart, Germany	250 km/h	Mono-block sleepers, lowered ballast	Winter conditions, snow	Foreign parts in the track have been found
2004	ETR 500	Rome-Naples, Italy	300 km/h	Mono-block sleepers, ballast not lowered	No snow	New track with ballast above the sleepers, see Fig 1
2006	ICE-T	Hamburg-Berlin, Germany	230 km/h	Mono-block sleepers, lowered ballast	Winter conditions, snow	

The following sections give additional details of incidents and the current status of ballast projection measures in different European countries.

5.2.2 Italy

During initial runs of the ETR 500 on the then newly constructed Rome-Naples high speed line in 2004 a ballast projection incident occurred. The sleepers were of the mono-block type, as shown in the photograph in Figure 1 taken at the time of the incident. It can be seen that the ballast was not specially lowered between the sleepers, and significant amounts lay on top of the sleepers themselves.

On the first high speed line, the 25 kV Turin-Milan route, problems arose for 300 km/h running of the ETR 500. Three levels of ballast height reductions were investigated with ballast impacts being monitored using microphones. The best ballast level was chosen for the maintenance target. Maintenance procedures were modified to ensure that ballast stones are properly placed, but the intervals between track maintenance have not been increased. Since the initial problems, there have been no further problems with flying ballast for trains regularly running up to the maximum speed of 300 km/h. Homologation for the ETR 400 (also known as ETR 1000) running above 300 km/h required special measures and configurations of track to ensure test running up to 360 km/h without problems.

There are no national notified technical rules for ballast projection in Italy. If ballast projection occurs, the operator of the train has to establish a settlement with the infrastructure manager.



Figure 1 — Part of the Rome-Naples line at the time of the ballast projection incident in 2004, [1]

5.2.3 Spain

Railway Gazette (2005) stated that Spanish Development Minister Magdalena Álvarez, when presenting a report in March 2005 to the Spanish Parliament on difficulties encountered with the Madrid - Lleida section of the Madrid - Barcelona high speed line, that train operations at speeds greater than 300 km/h caused 'ballast particles to be sucked up and thrown around'.

The Universidad Politecnica Madrid and Adif have studied ballast projection since 2008. Preliminary studies were undertaken in 2008-2010, followed by the AeroTRAIN Project (2010-2012), and then the Aurigidas Project (2012-2014). In all of the projects, detailed measurements of surface loads and induction phenomena were undertaken with ballast risk projection analysis. These were followed by Norm definition studies in 2015-2017. A national guideline on the issue is being prepared by Adif.

5.2.4 France

In France, the major incidents of ballast projection occurred in 2003 and 2004 during homologation tests of the ICE 3 running at 320 km/h (single unit). Damage to the train and the track was very significant and of a magnitude never seen to TGVs or other high speed trains running in France, even at higher speeds. Following this, different types of studies were carried out by German and French personnel to understand the origin of these incidents and to try to avoid or at least limit them.

As a result of this work, the underbody of ICE 3 running in France was modified and tests were carried out (air speed measurements in the track bed during train passing, microphones, video control, underbody inspection) in 2005, to check the behaviour of the modified train regarding ballast projection. These tests confirmed the decrease of the aerodynamic load on the track and the frequency and intensity of ballast projection.

A review of ballast incidents was carried out after one year of operation. Several incidents were identified, but have always been observed during cold weather (temperature close to zero and snow) in Germany.

Due to these incidents, for all new high speed trains running in France or for test running at speeds above 320 km/h, some specific monitoring has been required since 2004 on the trains (accelerometers or microphones for stone impact counting and video control), and air speed measurements in track have to be made for all new high speed trains.

A French regulation, SAM X 012 [4], was published by EPSF in 2015 to describe the methodology to assess a new high speed train regarding ballast projection. This methodology is based on air speed measurements in the track and consists of comparing the new train with an existing train or with an absolute criterion (cf § 7.2).

In France, ballast projection also occurs in winter due to snow/ice conditions. To limit these incidents, speed reductions are applied on French high speed lines.

5.2.5 Germany

The major incident of ballast projection of concern to Germany actually occurred not in Germany, but in Belgium, during homologation tests on the ICE 3 on a new high speed line. The ICE 3 had run without incident on high speed lines in Germany. The Belgian high speed line was fitted with mono-block sleepers, but no ballast lowering had been instigated. Successful trials had taken place with single traction units of 200 m length running at up to 300 km/h. However, when the double units were running at 270 km/h, ballast impacts on the train underside were audible. During one run severe damage occurred to the train underside, which led to Siemens having to investigate improved underbody designs to limit the problem.

Passenger reports on 15 Jan 2016 stated that an ICE travelling from Stuttgart to Frankfurt was hit hard by ballast stones. The incident was reportedly caused by ice lumps dropping from the train. Damage was caused to the train under-floor surfaces and side windows were cracked. The train continued at reduced speed.

(SOURCE: <https://rail-sim.de/forum/index.php/Thread/20576-Bahn-reduziert-H%C3%B6chstgeschwindigkeit-im-Fernverkehr/?pageNo=3>).

5.2.6 Great Britain

The High Speed 1 line (HS1) in Great Britain, runs from London to the Channel tunnel, and Eurostar trains using the line reach a top speed of 300 km/h. A form of rail damage, known as 'ballast pitting', has been reported, but no ballast projection problems have. This type of damage appears to be associated with small particles of ballast becoming trapped between the railhead and the wheels of rail vehicles. It is thought that the speed and the energy of trains cause an explosive crushing of the ballast particle, which damages both the railhead and the wheel. Inspection and maintenance records of train wheels on HS1 show that wheel pitting occurs predominantly on the front and rear bogies of a train with a steady reduction towards the centre of the vehicle. Quinn et al [2010], suggest that the vibrations and pressure pulse associated with the approaching train play a part in making ballast particles airborne as the trains travel in the reverse direction on the return journey.

High Speed 2 is a new line soon to begin construction in 2019, and will have a design speed of 360 km/h and an operating speed of 330 km/h, obviously, there are not yet ballast projection problems on this line.

5.3 Overview of ballasted track systems in Europe

5.3.1 General

There are several aspects of the design of ballasted track directly under passing trains, which may be relevant to the issue of aerodynamically induced ballast projection. These are:

- sleeper type and sleeper spacing;
- rail fastening systems, and whether these provide restraint to ballast movement;
- ballast size;
- ballast maintenance procedures.

How these aspects vary in different European countries could have an impact on risk of ballast projection on different railway infrastructure designs.

5.3.2 Sleepers

There are a number of different types of sleepers, which are used in varying proportions by European railways. They are used to support the rails in position on the ballast bed and are generally of similar sizes, and differ mostly in their construction materials. These are summarized in Table 2.

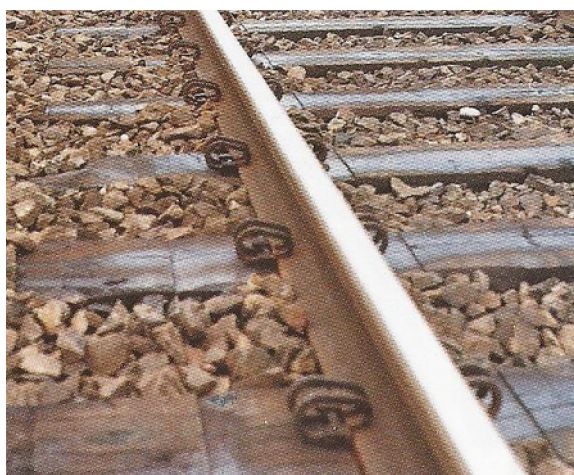
Table 2 — Common sleeper types used on European ballasted track.

Sleeper material	Size	Notes
Timber	Typically, 150 mm high, 250 mm wide.	Different types of wood can be used. Ballast longitudinal movements restricted by the sleeper, unless ballast above sleeper level.
Steel	Similar size to wooden sleeper.	
Concrete mono-block	Similar size to wooden sleeper.	Ballast longitudinal movements restricted by the sleeper, unless ballast above sleeper level.
Concrete twin- or bi-block		Consists of two blocks connected by a coupling rod or pipe to maintain separation of blocks. Ballast free to move longitudinally between blocks.

Of particular interest is the bi-block sleeper, where there is no constraint to the movement of the ballast in the direction of the train from the sleeper between the two end blocks.

Examples of the different sleepers are shown in Figure 2.

The sleeper spacing, which for instance varies between 600 mm and 800 mm in Great Britain, depends on the axle loading of trains using the line, track curvature and whether there are local track formation difficulties. This is to ensure the vertical and lateral stability of the track. Due to sleeper functionality, there is unlikely to be any systematic difference between European countries in sleeper spacing, although within a country there could be differences between lines depending on the factors above. For high speed lines, it is expected that differences in sleeper spacing between countries will be relatively small, (as axle loads will be similar, track formation will be of high quality and track curvatures will be larger than on conventional lines).



a) Wooden sleepers



b) Steel sleepers



c) Mono-block sleepers



d) Bi-block sleepers

Figure 2 — Examples of railway sleeper types

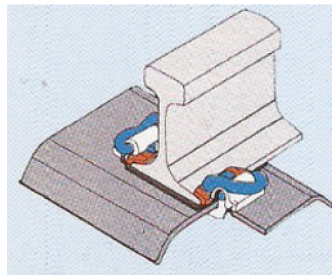
5.3.3 Rail fastenings

Rail fastenings are used to secure the rails to the sleepers and there are a number of different designs currently in use. Baseplates may be also used under rails to hold the rails in place and may be used in conjunction with clip devices.

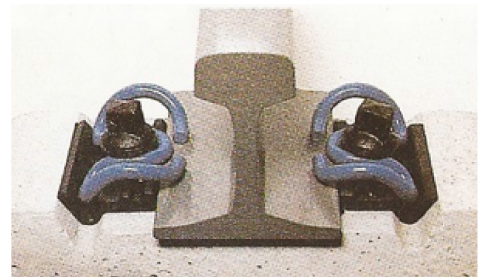
The DE (Deenik, Eisses) clip, shown in Figure 2 a), is widely used and can be fitted on concrete or wooden sleepers. A number of manufacturers have also produced other fastening devices, such as Pandrol, Vossloh, McKay, and Nabla. These other devices are shown in Figure 3.



a) Rail baseplate



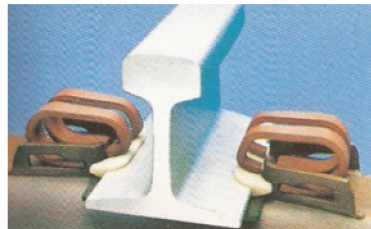
b) Pandrol clip



c) Vossloh fastening



d) McKay fastening



e) Nabla fastening

Figure 3 — Rail fastening systems

It can be observed that the rail fastening systems, although having differing designs, are unlikely to influence ballast movement or provide any significant impediment to aerodynamic ballast projection.

5.3.4 Ballast Size

EN 13450:2013 *Aggregates for railway ballast* specifies a standard for railway ballast sizes. Although currently withdrawn, the standard is still referenced in company standards e.g. by Network Rail in Great Britain. Essentially, ballast is graded according to the mass of ballast which passes through sieves with holes of varying sizes. Ballast particles range between a nominal 31,5 mm up to a maximum of either 50 mm or 63 mm. Within each of these ranges there are five sub-ranges referred to as grading categories, A to F overall. Figure 4 shows grade category A in the range up to 50 mm, and grade F in the range up to 63 mm, and represents the full range of ballast sizes and distributions. For each grade category there is also a further sub-range at each sieve size, indicated by a solid line at the maximum value and a chained line at the minimum. It can be seen that most ballast particles are between 20 mm and 63 mm, whichever grade of category they are in.

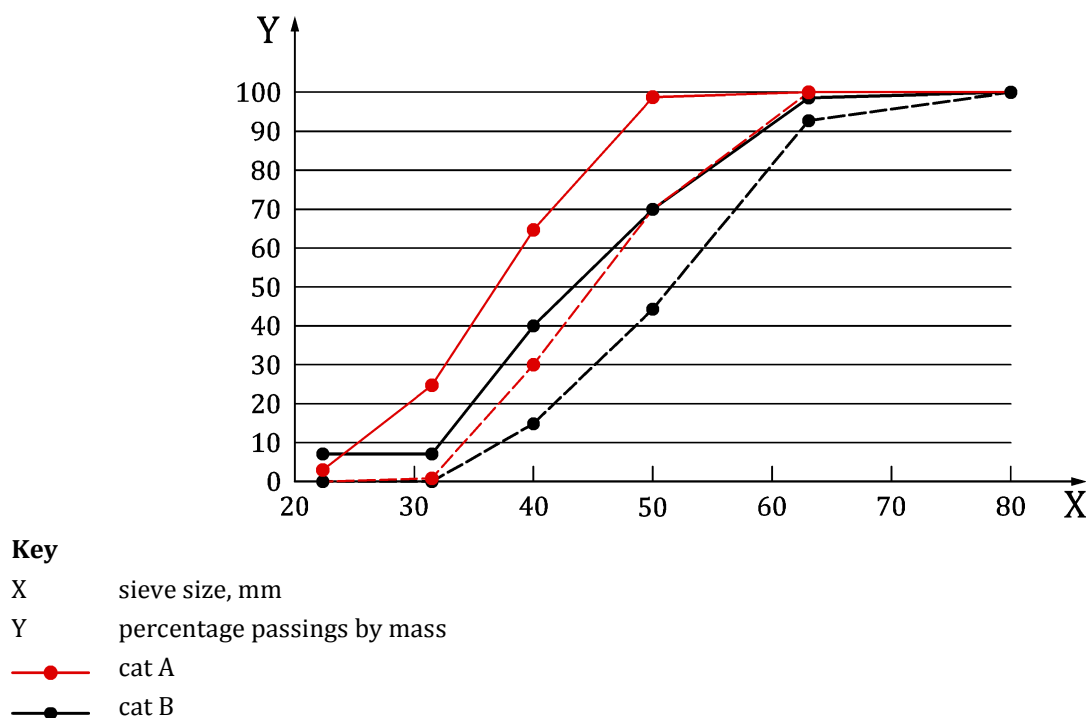


Figure 4 — Distribution of ballast sizes, Categories A and F

Ballast is maintained using a number of machines, such as stone blowers. These use smaller ballast particles, capable of passing through a 20 mm sieve, which are blown under the sleepers once the machine has lifted them, to maintain the track level. At worst, 80 % of this type of ballast will be large enough to pass through a 14 mm sieve. It is possible that these sized particles can find their way to the surface of the ballast bed.

There is no evidence known to the authors of systematic ballast size and shape distributions being different in different European countries.

5.3.5 Ballast maintenance regimes

5.3.5.1 General

An important consideration for aerodynamic ballast projection is where ballast is permitted to lie between the running rails, which will depend on the maintenance regime for high speed lines in each country.

5.3.5.2 Great Britain

5.3.5.2.1 Network Rail

A variety of railway sleepers are used on the standard railway lines in Great Britain. These include wooden sleepers, concrete mono-block sleepers and steel sleepers. Figure 5 shows a still image from a Network Rail ballast maintenance video; ballast stones can be seen on the sleepers, despite the commentary stating “No ballast must be left on the railhead, piled against the rail webs, over the fastenings or *loose on the sleepers*”. It is not clear if the instruction was eventually complied with in the video.



Figure 5 — Still from Network Rail video on ballast maintenance

5.3.5.2.2 High Speed 1

High Speed 1 is constructed using twin-block concrete sleepers on plain line and mono-block pre-stressed concrete sleepers in the vicinity of turnouts and switches. It uses a mixture of ballasted and slab track.

5.3.5.2.3 High Speed 2

High Speed 2 will be constructed with a mixture of slab track and ballasted track. No information has been obtained regarding the sleeper types to be used.

5.3.5.3 Germany

German infrastructure managers established a procedure to counteract damage by ice dropping instigating ballast projection. In late autumn the height of ballast is checked and lowered by a sweeping machine to 4 cm to 6 cm below the base of the rail. This maintenance work is performed according to internal rule 820.2010 7 (6) for every railway line above 140 km/h except for curves with small radius. As sleepers are then elevated compared to the ballast bed level, objects dropping from fast running trains will most likely hit the sleeper only, due to their flat-angle trajectory. The impact on sleepers is acceptable and avoids the swirl of further ballast stones from the ballast.

5.3.5.4 CER position paper

In 2015, the Community of European Railway and Infrastructure Companies (CER) and European Rail Infrastructure Managers (EIM) produced a joint position paper on aerodynamic ballast projection, CER/EIM (2015). This specifically addressed the open points relating to ballast projection in the LOC&PAS and INF TSIs and set out some principles that were felt should be respected when regulating for the issue. The paper acknowledges the full-scale track test procedure for the assessment of rolling stock set out in Annex A of EN 14067-4:2013+A1:2018 *Railway applications - Aerodynamics - Part 4: Requirements and test procedures for aerodynamics on open track*, but notes the absence of limit values or acceptance criteria. It notes and does not oppose the philosophy espoused in EN 14067-4 of the independent assessment of rolling stock (and by inference infrastructure), subject to the condition that such an assessment permits suitable controls to be put into place on other track infrastructure for safe operations.

The paper notes that the issue of damage resulting from ballast projection is a probabilistic issue, both in terms of ballast flight instigation and in serious damage arising from subsequent ballast impacts. The paper takes the view that a certain level/number of ballast impacts is tolerable and the aim should be to limiting the rate of impacts to being 'rare events'.

The paper then considers the infrastructure on the basis of, essentially, a reference rolling stock concept, rather as is considered for the cross wind issue, and note that there are limited possibilities to implement significant design changes in infrastructure, which could take decades to put in place. It then asserts that the most effective method to tackle the issue is to lower ballast levels, relatively easily implemented at the construction stage, but more difficult as a maintenance task on tracks with mono-block sleepers. Following this argument, it states that ballast lowering should not be mandatory, but only recommended. For track with bi-block sleepers, ballast gluing is proposed if normal maintenance is not sufficient.

Track fencing is suggested for sensitive areas to protect against 'projectile ballast'. The report acknowledges that incidents of ballast projections involve inadequate infrastructure maintenance and indicate ballast management best practice advice. The following is an important position statement:

"It is worth mentioning that issues related to the phenomenon of ballast pick-up due to aerodynamic effects are rarely reported and thus it is the view of EIM and CER that the validity of the currently implemented maintenance measures should be regarded as proven by experience."

Proposals are made for both rolling stock and infrastructure, which are summarized below.

Rolling stock — A reference limit for aerodynamic effects regarding the phenomenon of ballast pick-up should be established for rolling stock. New vehicles that do not fulfil this criterion should not be authorized.

Infrastructure — No requirement is needed for infrastructure for speeds up to 250 km/h. Measures currently applied on infrastructure in order to control the phenomenon of ballast pick-up due to aerodynamic effects for speeds in the excess of 250 km/h should be seen as TSI compliant. Measures, such as ballast lowering and maintenance procedures for clearing sleeper tops and fastenings of ballast, for effective design, construction and maintenance of ballast cross section are to be harmonized in the TSI.

5.4 Ice accumulation induced ballast projection

Issues also arise from ballast being projected up from the ballast bed and causing damage to the underside and underbody equipment of trains during winter conditions, but in these cases, aerodynamics plays no direct part. During relatively severe winter conditions in central Europe and under more usual winter conditions in Nordic countries, excessive falling snow or snow already on the tracks accumulates on the bogies, coupling gears between rail vehicles and on under-surfaces of vehicles, and under the action of wind and temperature turns to ice. Periodically, either due to the weight of ice accumulation or because of local temperature changes, large blocks of ice fall from the train, hit the ballast bed at high speed causing a spray of ballast to hit the vehicle, resulting in similar damage to that caused by aerodynamically-induced ballast projection. The primary cause of the ballast projection is the fall and impact of ice blocks into the ballast, although Kloow [2011] suggests that train underbody pressures, lifting of snow and ice located on top of the ballast and train-induced vibrations in the track bed, reducing friction between ballast particles, may also be influences.

The problem has long been encountered by railways, as described by Saito [2002] for instance:

“One unexpected problem started with a heavy snowfall at Sekigahara (between Nagoya and Kyoto) in December 1965. Shinkansen trains running through snowfall at very high speeds blow up the snow on the track. The blown snow sticks to the underfloor equipment and freezes rapidly into ice. When the train enters a warmer region, the frozen ice thaws and drops at high speed from the train causing the ballast to fly up and seriously damage the underfloor equipment. There was no immediate solution other than reducing speeds to 70 km/h in snow. Later, water sprinklers were installed along the track in order to melt the snow, but speeds in snow are still restricted even today (although not as low as 70 km/h in most cases), because excess water sprinkling can damage soil embankments. Drawing lessons from this, the Joetsu Shinkansen, which runs through a very snowy region north of Tokyo, was built entirely on concrete viaducts and large amounts of warm water are sprinkled during snowfall.”

Table 1 gives brief details of some significant winter ballast projection incidents in Germany and France in the period 2001-2006. Such events cause widespread disruption to services in countries for whom such winter conditions are exceptional rather than normal. The winter of 2009/2010 was particularly severe across Europe. Wiebe & Friedrich [2010] reported results for a UIC survey about the impacts on rolling stock and infrastructure in that winter. Of eleven countries providing information about the challenges for rolling stock, six reported problems with trains which picked up ballast that then damaged trains, and eight reported problems with ice blocks falling from trains.

It is perhaps obvious to state that problems due to falling ice blocks will increase with train speed, as the blocks will have greater kinetic energy to impart into the ballast bed and thus into individual ballast particles.

In the winter of 2010-11 Deutsche Bahn experienced severe disruption to train operations nationwide caused by snow, with long distance services being significantly affected. A preventive train speed reduction to 200 km/h resulted in delays and together with other issues, about 4 % of scheduled railway operations (based on running distance in kilometres) could not be realized in December. Although train speeds were reduced, damage still occurred to train underbody components (e.g. axles, pressure pipes, windows) due to ballast projection caused by ice falling into the ballast bed. As a result, the increased amount of maintenance work due was delayed by the additional time needed for de-icing trains in the maintenance plant prior to service.

The melting ice also affected electrical equipment due to short circuiting. Overall, up to 10 % of long distance trains were out of service on some days, leading to an increase in passenger demand. As other modes of transport were also affected by the winter conditions, passenger demand increased further due to mode transfer on important main lines by one third.

Several countermeasures were taken including technical improvements, namely impact protection on axles, short circuit protection measures; improved heating of the couplings of the ICE2; installation of three new de-icing stations; rental of train vehicles and several improved operational and maintenance procedures.

Also, the German infrastructure managers established procedures to counteract damage by ice dropping instigating ballast projection. Generally, the height of ballast is checked and lowered to about 5 cm below base of the rail in late autumn for every railway line above 140 km/h, see 5.3.5.3. As damage increases significantly with train speed, the so-called “Schneemeldeverfahren” (snow reporting procedure) is established for high speed lines with ballast track. It foresees visual observation of trains passing by traffic controllers about every 50 km, once a closed layer of snow is present. If snow is observed to be blown up by trains passing, the trains speed is reduced (200 km/h) on that line. The same speed reduction applies, if impacts in the underbelly region are audible to personnel on board of high speed trains. In the case of ballast flight, the speed can be lowered further to 160 km/h locally to check damage to the infrastructure.

Kloow (2011) and RSSB (2016) describe in some detail the range of winter problems that affect rolling stock and infrastructure, including ballast projection due to ice fall. Kloow (2011) also details the measures undertaken by railways to ameliorate ballast projection problems, giving both benefits and drawbacks, which are summarized below, with particularly interesting points being included:

- Lower the ballast height:

“In Finland, Norway and Sweden the ballast level has been lowered approximately 3-5 cm below top of the sleeper. The lowering is not done from aerodynamic reasons but primarily for letting the falling ice and snow crush against the sleepers’ concrete edges. Lowering the macadam level has in fact proven to be very effective for speeds up to 200 km/h and has led to the situation that some people do not consider ballast pick-up a problem any longer.”

- Reduce train speed:

This is the procedure in Germany and France where adverse conditions only occur a few days per year. However, this is not an acceptable solution in Nordic countries; as such conditions are more prevalent there during average winters.

- Decrease the distance between sleepers:

This reduces the amount of ballast that can be impacted by ice falls.

- Make the underside of the train as flat as possible:

“The underpressure below the train can be reduced if the train’s underframe is designed as flat as possible. However, bogies and ploughs will always create turbulence under the train.”

- Apply train designs that accumulate as little ice and snow as possible;

- Cover the ballast with a screen or other mechanism;

Some additional information on this type of solution is given in RSSB (2016);

- Use ballast-free tracks (i.e. slab-track) for high speed trains;

- Apply heat to surfaces on the train that accumulate snow;

- De-ice trains from packed snow and ice.

Management consultants Leigh Fisher (2012) made a presentation benchmarking NS and ProRail winter measures against international practice. Comparisons between four European countries were made of rolling stock measures applied to counter snow accumulation, see Table 3. Notably, speed reductions, ballast height lowering and train design feature among the measures. The use of de-icing of trains prior to entry into service is an increasingly used method, as shown in Table 4. Further details of de-icing techniques are given in RSSB (2016).

Table 3 — Rolling stock engineering measures used to mitigate snow accumulation in winter in Germany, Sweden, Great Britain and Switzerland, Leigh Fisher (2012)

Germany	Sweden	United Kingdom	Switzerland
Speed reductions down to 160 km/h are enforced to prevent snow build up and subsequent damage to trains (specific track related reduction)	- Elements of trains such as bogies are designed to minimise ice build up - SJ aims to de-ice trains on a regular basis; although this is not specifically done for effective measure - In case of heavy snow, train speeds are reduced to reduce snow collection and build up - Train drivers can report the amount of accumulated snow as part of standard maintenance reports	- Ballast height reductions is used as a measures to prevent impact from ice falling of trains - Speed reduction for high speed trains down to 100 miles per hour are enforced to prevent snow build up and subsequent damage to trains - Operating companies are testing new technical solutions to improve resilience like: introducing ice-breaker trains, modifying the electric brake to use the resistors to melt ice in the roof area's and test a silicon-based coating to prevent ice sticking to under frames	- On tracks with a high risk of snow and ice falling of trains, train speed is reduced for all trains on that track - During stationing, trains are quickly checked. When large pieces of accumulated snow or ice are present, train speed is reduced, only for that particular train. - There are no specific measures taken for S&C (apart from switch heating) - Modern trains have flat bottoms to prevent snow and ice accumulation

Table 4 — The use of train de-icing in winter in Germany, Sweden, Great Britain and Switzerland, Leigh Fisher (2012)

Germany	Sweden	United Kingdom	Switzerland
- De-icing is currently not a standard practice - De-icing is set-up since this year but because of mild winter (in terms of snow) no real experience yet - The de-icing facilities use a combination of hot air and hot water	- SJ has longer experience with de-icing of trains and has tried multiple methods - Earlier methods could take up to 8 hours to de-ice a trains - Best practice de-icing method is with hot air; SJ has best experience with hot air 25°C, blown at a speed of 50 m/s - New de-icing method has reduced de-icing time significantly; de-icing of an 8-car EMU takes 2 hours - SJ is increasing de-icing capacity; the 'old' method to circulate rolling stock through the whole country as the south generally did not suffer from strong winters but this proved to be unreliable for the last couple of years	- Not much is done for de-icing trains, primarily carried out at major station - During winter 2011/12, Scotrail deployed under-train power shower systems based on Finnish practice. - Scotrail have also piloted the use of temporary 75m "polytunnels" to melt the ice from trains in a warm controlled environment. A three car unit takes approximately 2 hours to defrost	- No specific de-icing techniques are in use or on trail - Trains that have accumulated a lot of snow are put in a shed to de-ice

With regard to the issue of train design, Kloow (2011) summarizes some measures from published literature for good train designs to reduce snow and ice accumulation under trains as summarized below:

- cover moving surfaces with e.g. plexiglass on foam rubber to reduce ice formation;
- use rounded and low friction surfaces;
- use deformable low friction covers to reduce snow packing;
- avoid flat surfaces that move towards each other; introduce sharp edges on one of the flat surfaces;
- use an open bogie design;
- install air spoilers to direct air and snow flows around the bogies and car body components;
- avoid aerodynamic stagnation points in the bogie region;
- consider localized heating on critical parts of the vehicle underbody.

CEN/TR 16251:2016 “*Railway applications – Environmental conditions – Design guidance for rolling stock*” provides design guidance for avoiding problems with snow and ice accumulation. It recommends an assessment of the aerodynamic environment on a vehicle’s undersurface at the design stage. In addition, it suggests that:

- consideration is given to design to ensure that suspension travel is not blocked by ice and snow accumulation, perhaps using bellows to cover springs;
- air pipes should not be located next to moving parts and should be protected from damage;
- snow and ice build-up in critical areas should be prevented;
- visual inspections of snow build-up should be carried out in critical winter conditions and de-icing considered.

6 Economic judgement of damage

6.1 Cost of reported damage

A survey was started to collect data about the cost of reported damage to rolling stock and to infrastructure. The limited number of responses to the survey was for several reasons, e.g.:

- 1) Projects with incidents had unexpected cost and hence dispute about the responsibility;
- 2) Transparent cost reports could reveal cost of components and working processes to competitors;
- 3) Damage not leading to failures in operation may have been detected a long time after the incidents, i.e. during maintenance. Hence, the origin of the damage would not be clearly stated.

As the operational speed of vehicles running on ballasted tracks increases, the number of incidents and reported damage regarding ballast projection increases. However, it is not always possible to define the reason for these incidents. Ballast movement can be induced by the aerodynamic load of the rolling stock, but it is more likely to be created by ice drop-off hitting the track bed. Therefore, during winter conditions or on vehicles running in cold climates, it is difficult to attribute the root cause of the reported incidents.

Nevertheless, one way or the other, consequences observed on the rolling stock due to ballast projection induced damage can be summarized as:

- **Damage to the air reservoir of the secondary suspension.** The impact of ballast particles causes cracks and material loss to the air reservoir of the secondary suspension. This implies that there are regions where the thickness of the reservoir is reduced below an allowable level according to European standards (EN 286-4). Therefore, the reservoir should be repaired or replaced by a new one;
- **Damage to the electric cable of the inductance filter.** The electrical cable of the inductance filter located on the underframe of the car body may be unprotected against ballast impacts. This problem can cause the malfunction of electric equipment;
- **Antennae.** The antennae located close to the gauge limits are likely to suffer ballast particle impacts. This may lead, in the best case, to deformation of the metallic cover, and in the worst-case scenario may lead to interference with the equipment performance;
- **Exposure of oil pressure and oil level control sensors in DMUs.** These sensors, located on the traction motors, are exposed to ballast particle impacts, which can cause the following problems:
 - **Oil pressure control sensor.** This can cause the cessation of the traction motor and oil leaks due to malfunction of this component;
 - **Oil level control sensor.** This can result in the engine not starting and possible oil leakage due to malfunction of this component.
- **Impacts on wheelsets.** The ballast particle impact can cause damage and material loss to the wheelset of the units. This is a critical problem, since it can lead to crack propagation and fatigue problems in the wheelsets;
- **Window breakage.** In cases where a train crossing can take place, induced particle motion can lead to ballast particles trapped between and impacting the sides of both vehicles leading to damage to the windows of both units.

Apart from the abovementioned problems, there may be some cases where the reported incidents cannot be associated only with ballast impacts, but to a combination of such phenomena with the accumulation of snow/ice. As an example, the following reported incident can be described:

- **Breakdown of levelling rods.** The impact of ballast particles can cause the damage or breakdown of the levelling rods of the secondary suspension. This can lead to different scenarios:
 - The secondary suspension can lose air due to a malfunction of the levelling rods which will lead to a deflated secondary suspension. This can have an impact on the comfort of the passengers;
 - The levelling rod can be blocked in a position where a non-stop airflow into the secondary suspension results. This will increase the height of the unit and can lead to metal to metal contact of the bump stop that can jeopardize safety.

All the elements that lie on or near to the train-track interface are subject to suffer ballast impacts, and therefore, the infrastructure is an additional element to be considered. In fact, it can play an important role, since poor maintenance of the infrastructure can increase the possibility of ballast particle motion due to elements that may be placed on the track.

Infrastructure damage due to ballast projection can be summarized in the following points:

- **Communication equipment.** The impact of ballast particles can damage beacons and additional devices placed close to the track to interact and communicate with the passing trains. This can lead, in the best case, to deformation of the metallic cover and in the worst-case scenario can lead to interference with the equipment performance;
- **Impact on tracks and sleepers.** Ballast impact can cause damage and material loss to the tracks and switches. This can be a critical problem, since it can induce unwanted vibrations to the rolling stock due to the wheel/rail interaction, which in the worst-case scenario could lead to wheel damage.

Eventually, apart from the infrastructure and the rolling stock, the risk of injuring people has to be considered. Ballast projection may be hazardous for people doing trackside maintenance work, since the impact of a ballast particle could cause serious injuries to a human body. The potential injuries may range from little wounds, to bone fractures and even death if an unprotected part of the head is hit by a stone.

Damage to infrastructure primarily causes repair costs. As reported from the homologation runs of the ICE 3, the repair costs included rail grinding, replacing parts of track sensors and fixing (minor) damage to adjacent buildings.

For each rolling stock project, the potentially damaged parts are marked. From reports of incidents or possible incidents linked to ballast projection, the sum of repair costs is estimated in a relative manner. The more exposed parts there are, the more incidents were reported or the greater severity of the incidents, the higher the damage and repair costs are assumed.

Figure 6 shows the roughly estimated damage costs to rolling stock for projects for which there was a clear indication of ballast related damage. The proposed specific cost measure per million passenger kilometres is derived, assuming a service lifetime distance of 12 million kilometres for all rolling stock with an average occupancy of 70 %. The highest values are based on Deutsche Bahn data, but these estimates also have the highest confidence.

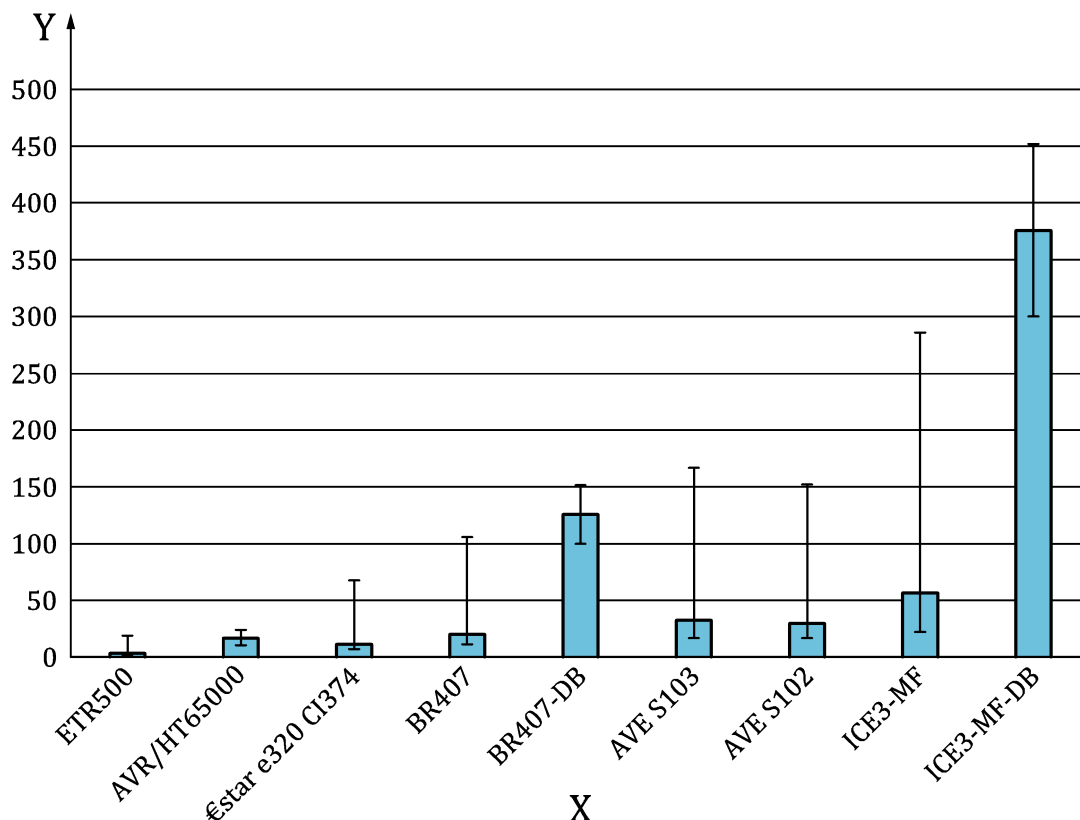


Figure 6 — Specific costs estimated for damage to trains from ballast projection occurring over the project lifetime. Error bars show the underlying uncertainty for each project.

More detailed information with real numbers was available for three projects, i.e. the AVR, BR407-DB and ICE 3-MF-DB. These still contain estimated components, leading to an uncertainty of roughly 20 %. Error bars mark the underlying range of uncertainty. For the other projects, the uncertainty was derived from the deviation of the reported costs and a blind a priori estimation made without any numbers available for the same project (i.e. BR407 vs. BR407-DB and ICE 3-MF vs. ICE 3-MF-DB).

The overall picture shows a great variation between projects, as well as the large uncertainty of the estimates. Even though ad hoc estimation of damage costs can be compared to estimating the volume of an iceberg using its peak height above sea level, it is obvious that there are potentially significant costs for certain projects compared with others.

The more reliable the available information became, the higher the total costs got.

From the survey response, the following costs in Table 5, from incidents not related to winter conditions, were reported for the ICE 3 MF (BR406) and the succeeding model ICE 3 (BR407). According to these numbers, the cost of extra maintenance work due to sporadic damage is the main contributor. This part was not considered appropriately in the estimation process and hence led to an underestimation of the total damage cost.

Table 5— Cost of initial and extrapolated rolling stock damage for two projects. The red numbers are provided by the fleet owner.

RST	BR407	ICE 3-MF-DB
A	RST initial damage during first high speed tests	RST initial damage during first high speed tests
Incidents	Tests on a new line running both directions on one track speed up to 320 km/h	Double unit test > 280 kph in Belgium ballast in unfavourable condition + tests in France 300 km/h to 320 km/h
Repair [Mio €]	0,7	2,0
Tests + monitoring [Mio €]	0,5	1,5
C	RST damages after Change (sporadic)	
Total cost estimation of fleet maintenance over 30 years [Mio €]	7,65	7
Damage cost RST/Mio_passenger_km [€/km]	127	377
Note For the ICE 3-406MF the full life cycle was taken, not just the 7 years of operation in France.		

In comparison, the specific cost of damage is much higher for the BR406 than for the BR407, because the vehicles started running at high speeds without adaptation or protection against the issue. The maintenance cost after adaptation to the critical ballast bed is still high for both projects (a factor of 2.5 higher for the BR406 if divided by the number of trains).

For the infrastructure, no costs were reported but it may be assumed that there was at least track surface damage. An extra grinding of some kilometres of track and the resulting reduction in the lifetime of the tracks are estimated to cost of € 0,1 M to 0,5 M. To derive the cost per million passenger kilometres for infrastructure, a frequency of 4 trains per hour with 400 passengers each is assumed. The number hence corresponds to 11 € to 55 €/million passenger kilometres.

Comparing these numbers to the above values for the specific damage costs to rolling stock shows the latter to be significantly higher than for infrastructure.

6.2 Cost of homologation, measures to rolling stock and infrastructure

6.2.1 General

The costing survey also requested data about the cost of homologation and, in particular, measures on rolling stock and infrastructure. The small number of responses to the survey also applied to these topics. Cost estimation is hence used here as the basis to analyse and compare the rolling stock and infrastructure cost. As outlined above, the available data is used to estimate the uncertainty of the estimation process.

The estimation, in principal, looks at the cost of required remedial actions and materials. By considering national hourly labour and equipment costs, this evaluation can only be thought of as an initial rough estimate. The results are hence indicative at best, useful for relative comparison, only.

6.2.2 Cost of homologation

The cost of homologation is split into the cost directly attributable to the assessments of rolling stock and infrastructure, (as described in Clause 7), and the indirect cost due to making those geometric changes that are significant in terms of aerodynamic properties. The latter requires a re-assessment of TSI aerodynamic requirements (i.e. slipstreams, pressure signature in tunnels and, in extreme cases, crosswinds) or the aerodynamic requirements of the customer.

Some assumptions have had to be made regarding the nature of the assessment tests and the components required for cost estimation to be undertaken. For this purpose:

- assessment tests were assumed to be similar to those in SAM X 012 [4], the Spanish guideline [17] or in EN 14067-4:2013+A1:2018; and
- the costs of design / preparation / components have to be considered.

Figure 7 shows the estimated specific cost for homologation. The cost is similar for all trains which ran through an assessment. The ICE 3 has an elevated cost due to the small number of trains over which the fixed costs are distributed. Additionally, the repetition of tests after rolling stock modification and the usage of different test setups multiplied the cost.

As there is no homologation procedure for ballasted track, the cost for infrastructure is currently zero.

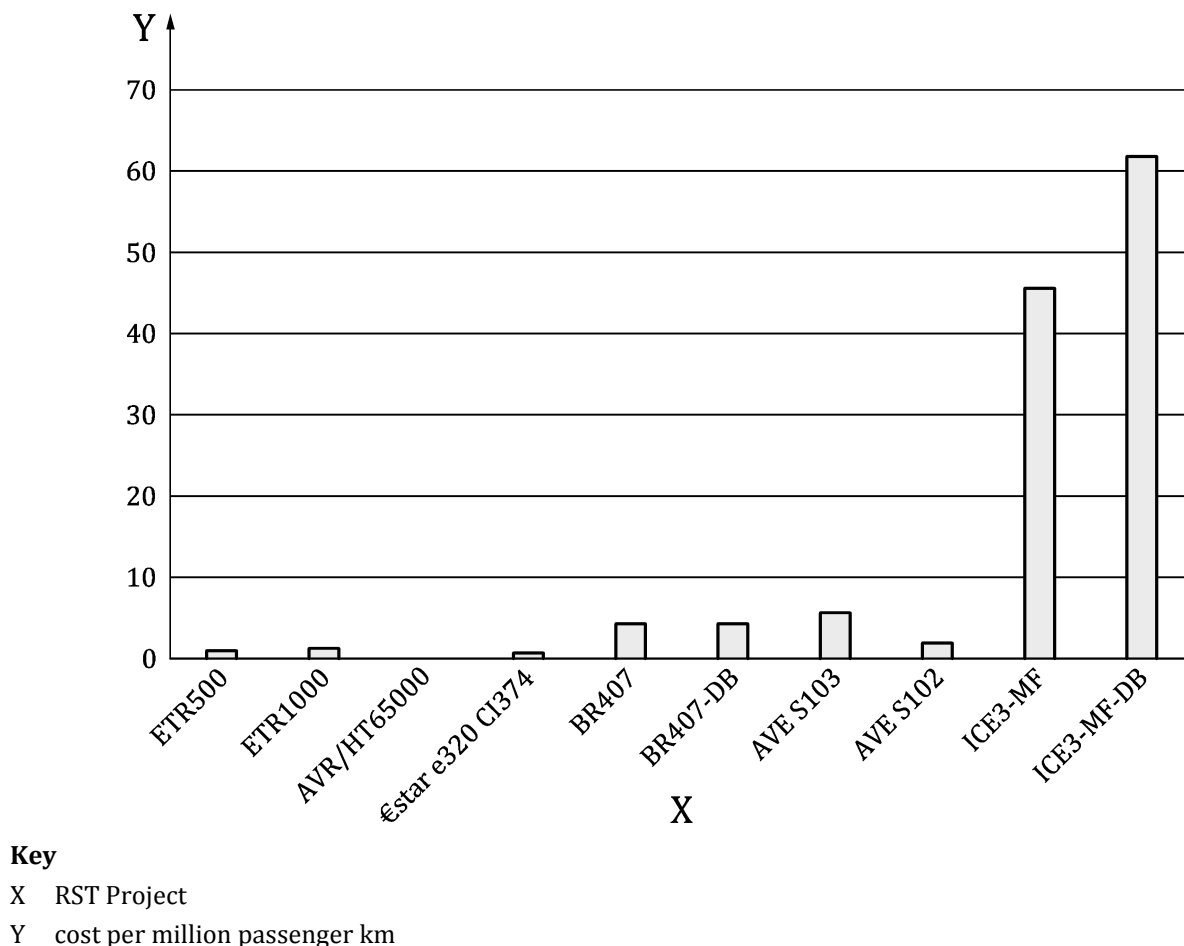


Figure 7 — Specific cost estimation for the homologation of trains regarding ballast projection

6.2.3 Cost of measures

To obtain cost estimates of measures, publicly available photographic evidence of rolling stock, e.g. as shown in Figure 8, and infrastructure adjustments has been collected, and the costs derived for the engineering, manufacturing, homologation and maintenance of the added components.

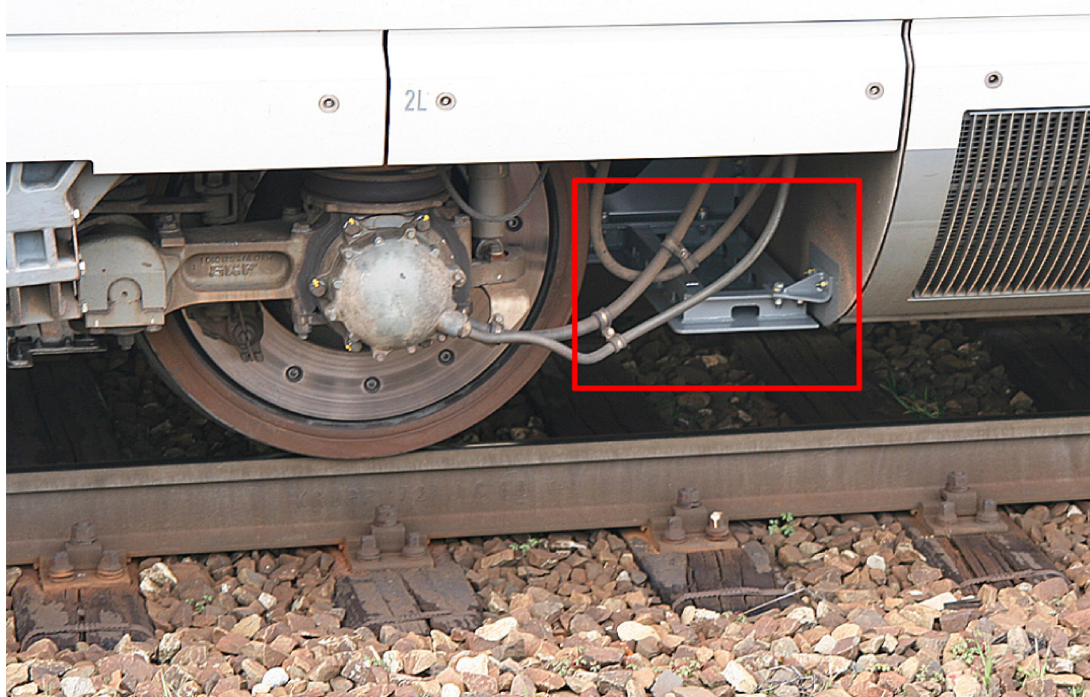


Figure 8 — Example of photographic evidence of a protective measure at the ICE 3 (SOURCE: wikipedia.org: 20:12, 25. Dec. 2006. Sese Ingolstadt, *Zusätzlich angebrachte Windleitbleche am ICE 3MF im Bereich des Drehgestells*,|Author: S. Terfloth, 21.10.2006)

Figure 9 shows the initial results of this approach, applied to eight rolling stock projects. The cost covers the full life cycle cost per train transformed into the specific cost per one million passenger kilometres.

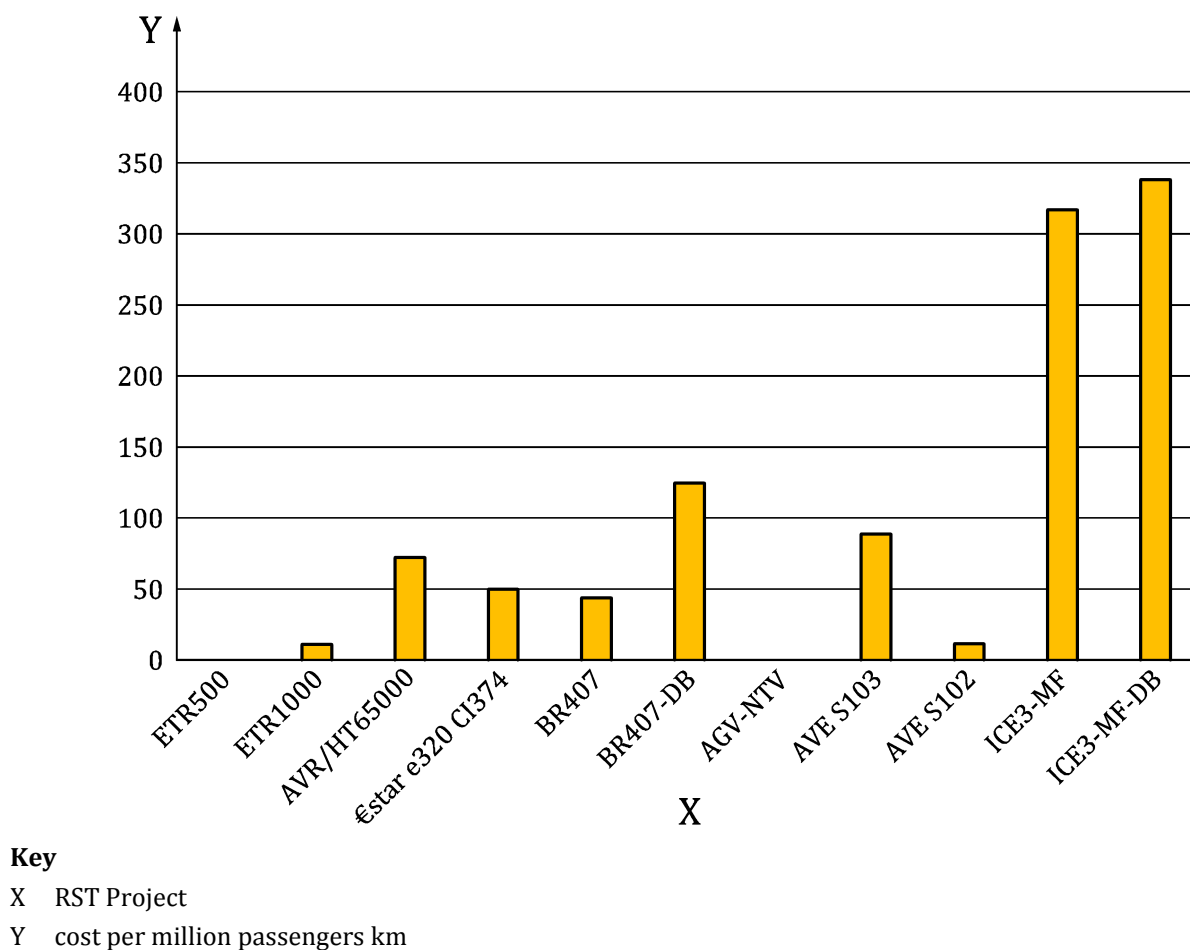


Figure 9 — Specific cost of rolling stock measures for ballast projection

From Figure 9 the following may be concluded:

- 1) The adaption to sensitive ballast conditions implemented as a post-project measure is much more expensive per unit than when directly integrated into the initial train design (ICE 3-MF-DB vs. BR407-DB);
- 2) The cost is very low or zero if the ballast bed is less sensitive or adapted to the conditions (ETR500 and ETR1000);
- 3) The cost is zero or very low, if the rolling stock is well adapted to the ballast bed condition for historical reasons (e.g. AGV or TGVs (not shown in the diagram)). These high speed products were evolved to run under the local adverse conditions with speeds increasing over the decades.

Figure 10 provides the estimated total cost for high speed RST/INF projects. A ranking from most to least reliable data reads: ICE 3, BR407, S103, AVR, CI374, S102, ETR1000, ETR500, AGV.

Again, the specific infrastructure cost takes a small part in the total cost balance.

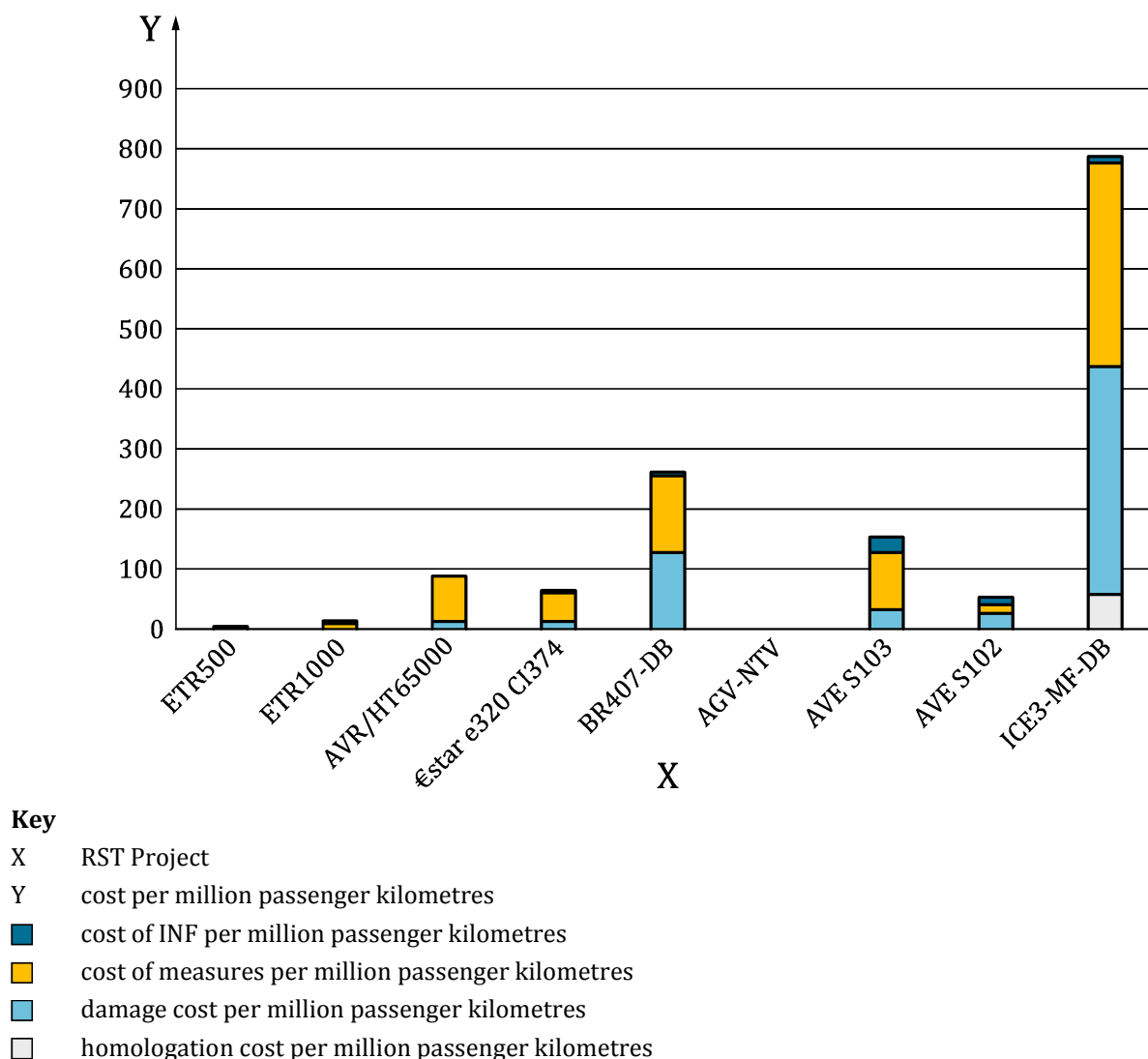


Figure 10 — Estimated total specific cost for high speed train projects

6.3 Cost benefit analysis

6.3.1 General

Despite the uncertainty in the cost analysis, a picture of relative costs is evident.

6.3.2 Average damage cost versus cost of national or European regulation

The cost balance of options and estimated costs considered are:

- 1) Different national rules apply with specific tests and criteria: €200K per country per train type;
- 2) One test with different post-processing for each national regulation, (reducing the number of tests, allowing transfer of results): € 200K+ € 50K;
- 3) No testing if the train is similar to current rolling stock already in operation, risking damage and late modifications: € 0K ... € 10M;
- 4) Demonstrating that the underfloor aerodynamics is satisfactory by simulation/analysis: €50K;

- 5) Track quality measures and monitoring: (unknown cost). None, if covered by the usual procedures;
- 6) Ballast bed improvements (e.g. gluing): probably too costly to be considered as a solution, and difficult or impossible to maintain;
- 7) Speed reductions, opportunity cost and plus traffic disturbance fee in the case of restrictions due to accidents (value unknown).

7 Homologation concepts

7.1 General

This section will examine some general aspects to deal with ballast projection homologation, starting with existing technical approaches. Then different stakeholder responsibilities and interests will be explored, with the intended interface definitions are looked at. Finally, different conceptual approaches are proposed, starting from first principles.

7.2 Existing technical approaches

7.2.1 General

Various methods are already known from previous research developments and can be applied to quantify and manage ballast projection phenomenon.

7.2.2 Impact counting for a train running on current track

This approach is relatively simple to implement and is commonly used. The counting can be done by use of sensors located on the underbody of the train (using e.g. microphones, acceleration sensors, video, laser), or by inspection of the underbody after running. The main difficulty is then to correctly identify the impacts and their severity. A certain level of ballast projection impacts has to be considered as acceptable, (e.g. number of impacts per N km). This method is clearly limited to track currently operated on, and there is no common method description (namely regarding test track quality, running direction, number and type of sensors, severity of impacts, analysis, etc.).

7.2.3 Measuring the aerodynamic load over a standardized ground configuration or a specific track, with analysis using a risk modelling parameter

The aerodynamic load is a relevant parameter of ballast projection, and methods were developed (using inter alia some of: pressure sensors, pitot tubes for air speed measurements, forces on a stone), to characterize it and use it as a basis for a train assessment or a risk analysis. Different methods were carried out and compared in the AeroTRAIN Project (measurements and risk analysis methods), and one of the outputs is the measurement methodology introduced into EN 14067-4 (i.e. air speed measurement on a standard track configuration). The French (SAM X 012 [4], SSIA (see 8.2.3)) and Spanish [17] methodologies are also based on aerodynamic load measurements.

7.2.4 Simulating the aerodynamic loads exerted on a standardized ground configuration

This approach can be used to assess a new train or an existing, but modified, train without carrying out a full scale test. Simulations have to be carried out for the investigated train and for a reference train, and a relative comparison has to be made. An absolute criterion can be also used if available, and if the simulation method is validated.

7.2.5 Model scale testing (alternative to CFD and full scale)

Recently, methods to analyse the aerodynamic load on track, the underfloor flow and ballast projection using reduced scale models have been developed (Ido et al. (2013), Jönsson et al. (2013)). Similar to using simulations, these approaches can be used to compare two trains or to evaluate the impact of modifications on a train.

7.2.6 Passing a track mounted test set-up and count stones moved or loads on an instrumented model stone

In Soper et al (2017) tests are described of the use of an instrumented ballast stone subjected to the loads generated under a high speed train. It is possible, although as yet undemonstrated, that such an approach or one based on counting stones actually moved by trains passing could be used to compare two trains or to evaluate the impact of modifications on a train.

7.2.7 Improve protection measures

By improving the train, ballast projection is not avoided, but the damage is reduced or minimized. Two kinds of improvement can be achieved:

- 1) limit generated aerodynamic loads;
- 2) protect the train from stone impacts.

The following is a check-list of protective measures or generalized aerodynamic measures that may be applied:

- avoid large underbody cavities;
- add fairings on sensitive elements;
- optimize the underbody to avoid chain reaction;
- avoid ice agglomeration spaces.

7.2.8 Strength determination of infrastructure without train runs

Initiation of stone movements exposed to air flow was investigated by wind tunnel testing (e.g. Kaltenbach 2008).

7.2.9 No requirements

Only recommendations and best practice towards rolling stock and infrastructure design are provided. If incidents occur, appropriate measures should be taken on infrastructure and rolling stock or speed reductions should be applied. This approach accepts the inherent risk to generate ballast projection for the combination of rolling stock and infrastructure.

7.3 Responsibilities, interests and intended interface definitions

The following statements are assumed by the authors and were not checked with the respective stakeholders.

Rolling stock manufacturers require a standard containing methods and criteria with which to comply only once (and not at a national level). This standard should show how and describe methods to estimate the effectiveness of train modifications and to predict potential risks e.g. by CFD (computational fluid dynamics), prior to full scale testing.

Infrastructure managers have stated that they have undertaken all measures to improve existing track (via maintenance, lowering ballast), see 5.3.5.3, and if any problems remain it is one of rolling stock and the maximum speed of affected train should be lowered.

Infrastructure managers need a specification and/or a test case for new tracks or track renewals to qualify their infrastructure for the high speed operation of any train.

Operators of rolling stock want to ensure the maximum train speeds to reduce travel time, ensure timetables can be met (under non-perturbed operations) and to avoid damage or maintenance costs.

7.4 Conceptual approaches

7.4.1 General

This section introduces conceptual approaches derived from first principles. Their pros and cons are provided in each case.

7.4.2 Approach 1: Relative train comparison

The most widely-used approach is to ensure that new trains are better than/equal to existing trains without problems. The use of this approach for ballast projection requires the definition of a standard test set up, assessment method and the definition of a reference train or pass/fail criterion.

- A test set-up is already defined in EN 14067-4. The assessment quantity is based on air speed measurements, and EN 14067-4 provides three approaches for the assessment quantity;
- SAM X 012 [4] defines a test set up at a national level with the parameter PCEB, an assessment quantity, referring to French tracks;
- the set-up and methodology as applied in Spain [17] can also be used in this context;
- counting and comparing stone impacts for existing trains already operating and for new tested trains could be an applicable solution, too.

Also, further thought needs to be given to the choice of reference trains and their operational experience on several (ideally international) networks, as well as to the general availability of their test results (or the reference train itself for comparative testing) to allow them to be compared to those of a new train.

Pro: Suitable if ballast projection as an issue is limited to small sections of the European network.

Cons: (1) No conclusion is drawn for ballast projection on other networks beyond the one of the reference train.

(2) The reference train may be too good in ballast projection issue, thus the requirement on new trains may be too conservatively.

7.4.3 Approach 2: Demonstration on the most vulnerable track

Identify the most vulnerable, but well-maintained, track in Europe and define it as a reference for new trains. The new train must then prove that no ballast projection occurs on this track.

Choosing and comparing different tracks in order to select the most vulnerable track in Europe is a major and costly exercise. Bearing in mind differences in track gauges, line voltages, signalling system types, etc., the access of the test train to the test sections may be impossible. In addition, it is highly desirable to realize rolling stock testing in any country.

An alternative approach is to define the most vulnerable track for a defined network or national network. Therefore, several vulnerable reference tracks could be defined within Europe.

The train's performance on the vulnerable track would have to be determined and documented in homologation to ensure network access.

Infrastructure managers would need to choose the most vulnerable track by means of an assessment methodology or from noting sufficient positive (i.e. no incidents) operational experience with a demanding train operating on the network segment.

New infrastructure would need to be proven to have better performance than the most vulnerable track, or its stability with the most demanding train would need to be demonstrated.

Pro: Sets up a demanding, but clear, requirement for rolling stock to pass.

Cons: (1) Using the most vulnerable track in Europe (instead of a defined network) is the most demanding requirement for rolling stock and does not reflect the actual intended network of operation.

(2) The new test train must be able to get access to the most vulnerable track, which itself needs to have a defined maintenance level (i.e. track has to be preserved in initial/reference conditions).

(3) Moves the responsibility for improvements completely from infrastructure to rolling stock.

7.4.4 Approach 3: No homologation requirement; counter measures if needed

Assuming that a certain amount of knowledge is available in the railway sector, the responsibility to design trains and tracks properly could be delegated to manufacturers, operators and infrastructure managers. Therefore, no homologation requirement would be foreseen at the European level, except for some information on the existence of the topic as a possible limitation to operation.

Drawing from the operational experience and the surveillance of the safety of track-side workers, monitoring would be needed to see if ballast projection remains at an acceptable level. In the case of unacceptable aerodynamic ballast projection experience, mitigation measures would need to be defined including improvement of track maintenance, train performance or limitation of maximum speed.

The approach cannot ensure sufficient recognition of ballast projection at the design stage. In procuring a train, the quality level of the train could not be defined; making comparing the economics of different procurement carry a risk. In the case of ballast projection, responsibilities would not be clearly defined.

Pro: Minimum effort and cost, if the risk of ballast projection does not result in damage.

Cons: (1) Leads to different rules in different countries.

(2) Increased risks in homologating (for the manufacturer) or operating a train on new lines (for the operator) regarding the contract or intended use at full speed.

7.4.5 Approach 4: Requirement only at national level

This is the present state in Europe. Spain, France and Belgium have encountered ballast projection issues, and have therefore established testing procedures at national level. France has established a requirement as a notified national technical rule (NNTR). The guideline SAM X 012 [4] provides a recommended and accepted method of assessment including a criterion. Spain intends to publish a guideline containing an assessment method recommended in case of ballast projection. For regulation at a European level, reference may be made to the national approaches.

The national requirements need to be transparent to the railway sector using the National Notified Technical Rule mechanism in TSI. To minimize testing effort and avoid country-by-country testing, the assessment criterion should be harmonized with a common EU assessment.

Pro: Easy to change (national level).

Con: Different national approaches require manufacturers to satisfy different approaches to sell their trains in each country, leading to higher costs.

7.4.6 Approach 5: Minimum testing in homologation; counter measures if needed

Minimum testing is basically the observation of ballast impacts (counting impact on the train and/or the track). When impacts occur, more detailed assessments can be made.

This method gives information about the behaviour of the train on a specific track and can be used at first step before expensive measurements.

Pro: Low cost/easy to implement.

Cons: (1) No criterion for train design included.

(2) Not easy to identify correctly impact on the underbelly of a train or on the track/besides the track.

(3) Number of km / test runs needed for validation not clearly defined.

(4) Increased risks in homologating (for the manufacturer) or operating a train on new lines (for the operator) regarding the contract or intended use at full speed.

7.4.7 Approach 6: Full-scale testing and criterion

Full-scale testing with an appropriate criterion represents the ideal outcome for the assessment of the rolling stock and infrastructure. It needs a test procedure to be developed for the separate assessment of rolling stock and for infrastructure.

Pro: Assessment available for separate assessment of the rolling stock / infrastructure interface.

Con: Medium to high cost, depending on whether can be integrated with other testing easily. May require special permissions to locate equipment (aerodynamic measurements, plates isolating ballast etc.) between rails. Methodologies not yet developed and agreed upon on a European basis. Practical experience of single methodologies is not yet available.

7.4.8 Approach 7: Check train underbelly design at the design stage

This approach consists of undertaking an aerodynamic assessment of the underbelly region and demonstrating the acceptability of the aerodynamic characteristics by simulation.

Strengthening measures regarding the vulnerability of train underbelly consist of:

- Identifying exposed elements and surfaces;
- Checking identified elements and categorize them in a matrix regarding loss susceptibility versus extent of damage in case of loss;
- Dealing with elements having high susceptibility and high damage consequences by:
 - Relocating the element to a non-exposed area;
 - Strengthening the element or surface to withstand ballast impact, (by increasing wall thicknesses or using more robust materials);
 - Installing a ballast deflection element upstream of the element to be protected.

Pro: Helpful for reducing risks of ballast projection problems once train is developed. Adds protection to vulnerable equipment and components for ballast impacts.

Con: Judgement with experience needed to identify vulnerable components. Could add unnecessary cost and weight protecting components not at risk.

7.4.9 Approach 8: Make recommendations for testing and initial operations

- Stabilize the ballast of the relevant infrastructure with reworked ballast bed by running initial trains at increasing velocities in the main (i.e. normal operating) direction.
- For test runs with new train types, increase the velocity in each run.

Pro: Based on previous running experience. May identify speed at which ballast projection problems start to occur (ICE experience problem free running at 320 km/h in one direction but problems at encountered at 280 km/h in reverse direction).

Con: Does nothing to prevent ballast projection problems.

8 Comparison of existing methods

8.1 France

8.1.1 General principles

The train assessment method performed in France for ballast projection is described in the guideline SAM X 012 [4]. This method consists of air speed measurements at defined positions in the track during train passing, and the determination of a flying ballast parameter, “PCEB”, derived from these air speed signals.

The measurement to assess conformity can be made with a set-up in the track, either according to the French regulation (air flow over a ballasted track), or according to the informative Annex in EN 14067-4:2013+A1:2018 (air flow over uniform plates). Conformity is achieved by comparison to the absolute reference value of PCEB, if using the French set-up, or by comparison of the PCEB of the assessed train to that of an existing train operated in France measured on the set-up according to EN 14067-4.

Additionally, a risk assessment method of flying ballast based on the stress-strength interference analysis (SSIA) was also developed. With this methodology, a ballast flying probability can be calculated (number of ejected ballast grains), based on air speed measurements in the track and by the simulation of ballast movement to characterize the strength of track bed systems with regards to aerodynamic loads on ballast.

8.1.2 Train assessment methodology (SAM X 012)

8.1.2.1 Test conditions

The required measurements to apply the methodology are:

- train speed on the measurement site;
- meteorological conditions, (air temperature, air pressure, air humidity, wind speed and direction with respect to the track);
- air speed on the track (as described below) during passing train.