Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

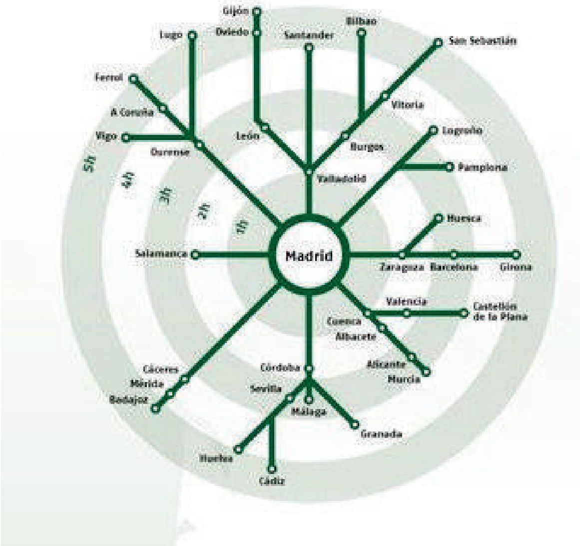
RAIL SYSTEM | UIC Train–Track Interaction (TTI) Sector Plenary Meeting

SWG Acoustics and Aerodynamics

Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

OVERVIEW OF BALLAST PICK-UP

Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

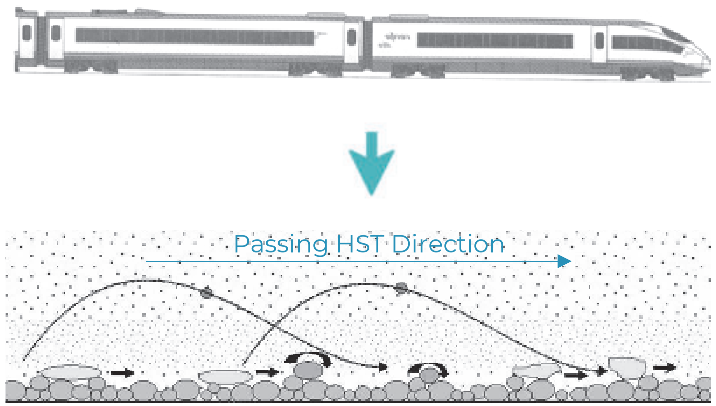


/ **3,621 km** long High-Speed network, the second largest in the world.

/ **1,815 km** of High-Speed lines under construction, or in project phase

OVERVIEW OF BALLAST PICK-UP

The phenomenon of ballast pick-up in the high-speed trains was entirely unexpected !



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OVERVIEW OF BALLAST PICK-UP

A new phenomenon known as ballast pick-up or flying ballast, which occurs due to train-track interaction under normal weather conditions was detected.

The first incidents were detected during the homologation tests of the ICE3 in France (2003) and Belgium (2004).

This phenomenon has also been observed, to a lesser extent, in the TGV at 300 km/h.

Other incidents related to this issue have been detected in Italy, during homologation tests in Spain with the S-103 and S-102 trains, and in the Korea Train Express (KTX).

The ballast pick-up phenomenon involves both the aerodynamic design of the trains and infrastructure aspects such as the geometry and characteristics of the ballast bed, superstructure, and track dynamics.

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OVERVIEW OF BALLAST PICK-UP

Safety and Infrastructure Risks

Displaced ballast particles can damage trains and tracks, posing significant safety risks to passengers and infrastructure.

Impact of Train Speeds

Increasing train speeds intensify aerodynamic forces near the track, worsening ballast pick-up and maintenance challenges.

Importance of Understanding Phenomenon

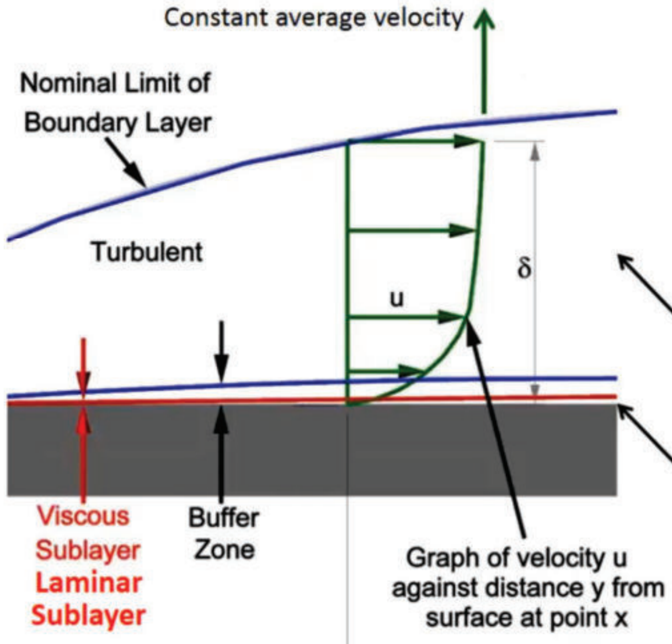
Studying ballast pick-up is essential to improve **operational safety, reduce maintenance costs, and ensure rail service reliability.**

TSI open point

OVERVIEW OF BALLAST PICK-UP

As an example, let's look at what happens in a river with its bedload.

Boundary layer divided into turbulent sublayer (10s of cm to m thick) and laminar sublayer (basal mm or less of the boundary layer)

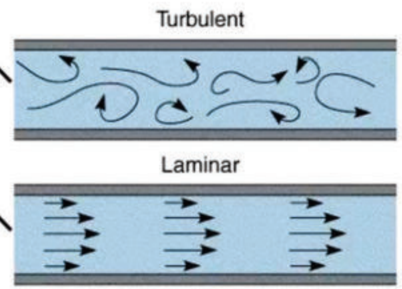


Turbulence controlled by relative importance of inertial vs. viscous forces (Reynolds number Re)

$$Re = \frac{\rho u D}{\mu}$$

Density, velocity, depth

Viscosity



Re > 2000

Re < 500

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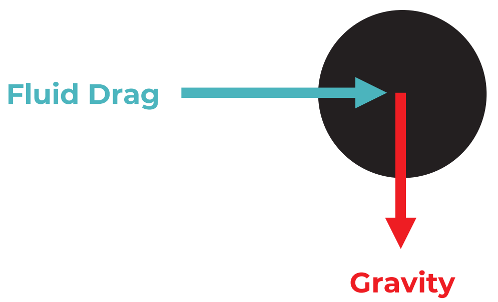


Forces hindering movement

Forces promoting movement

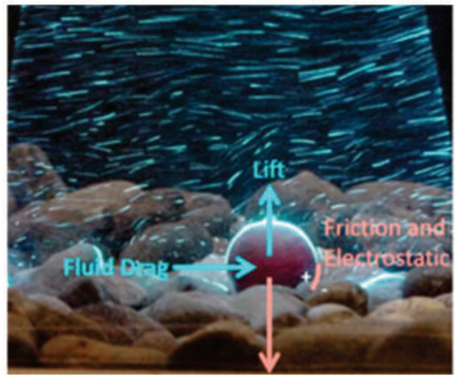
Fluid velocity necessary to create moving force:

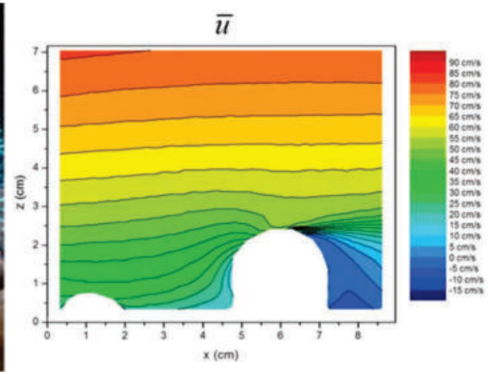
$$E_{grain} = \frac{1}{2} V (p_{fluid}) u^2$$

Mass is volumen x density

Flow velocity decreases close to the bed surface, due to frictional interaction between the water and the sediment

This interval of reduced flow is called the **boundary layer**



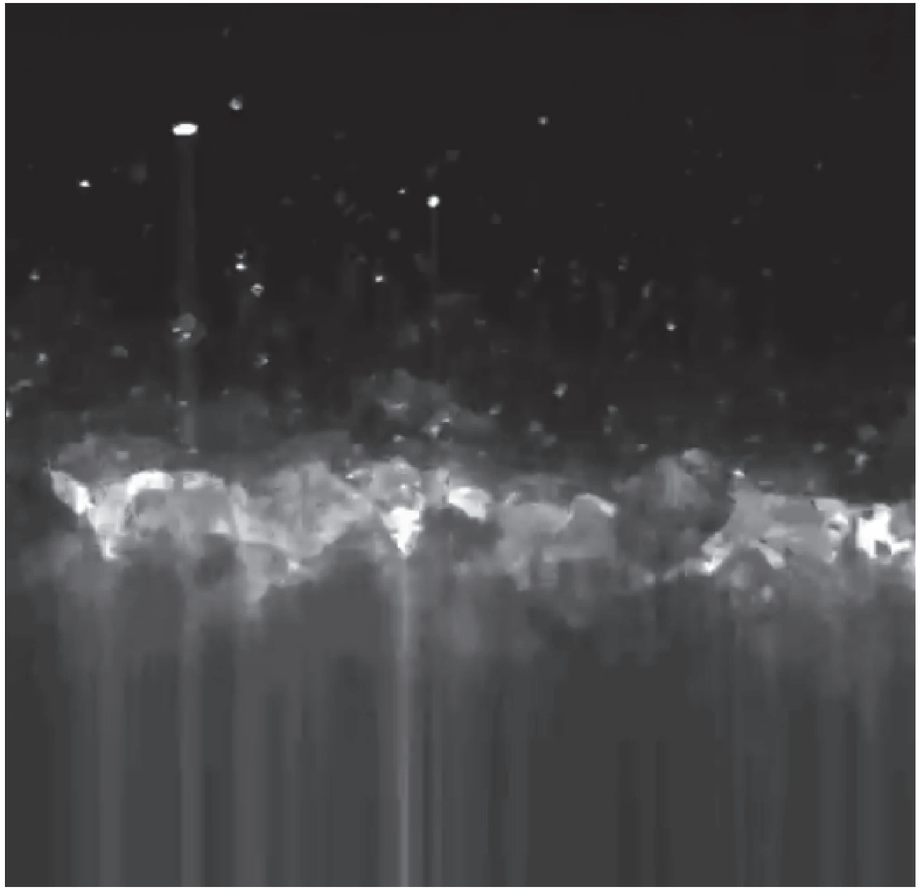


OVERVIEW OF BALLAST PICK-UP

Folowing water transport sediment as:

- **Bedload**- particles roll, slide, or bounce along bottom

- **Suspenden load** – particles carries above bottom by fluid turbulence and grain collisions



OVERVIEW OF BALLAST PICK-UP

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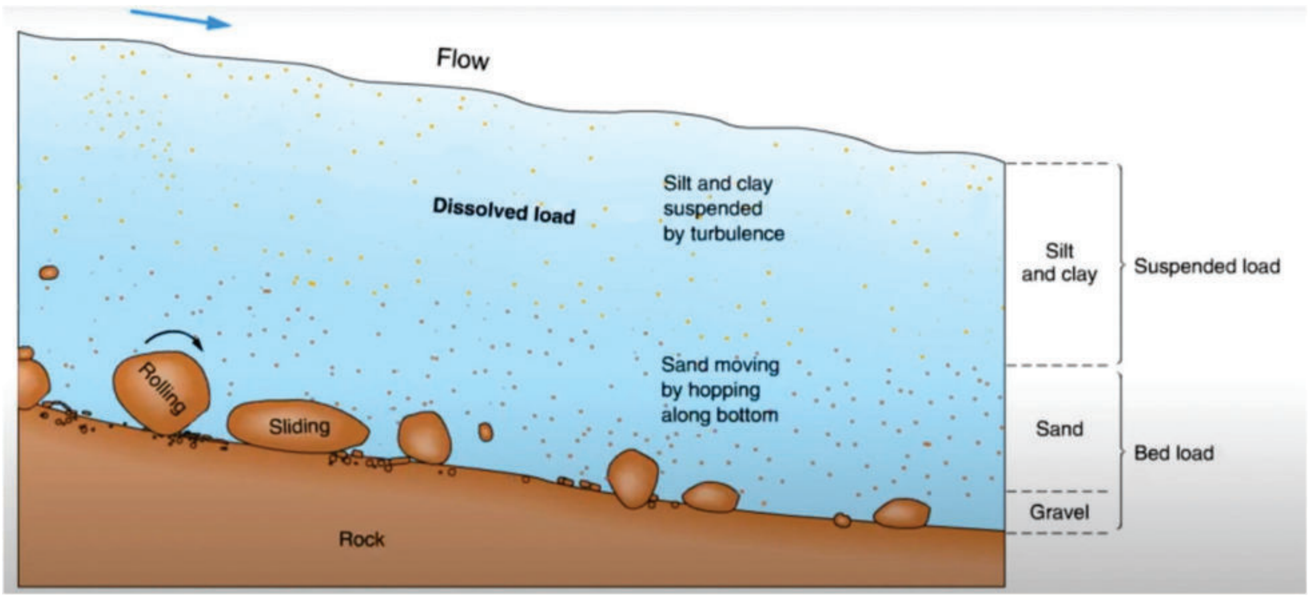

DEFINITION OF THE PROBLEM AND EXPERIMENTAL TESTS ON TRACK

INDICE

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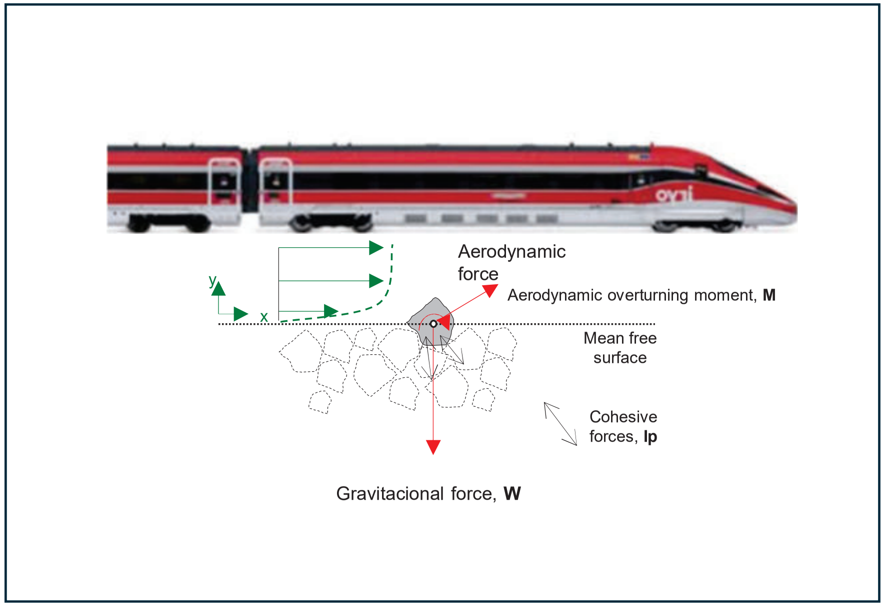

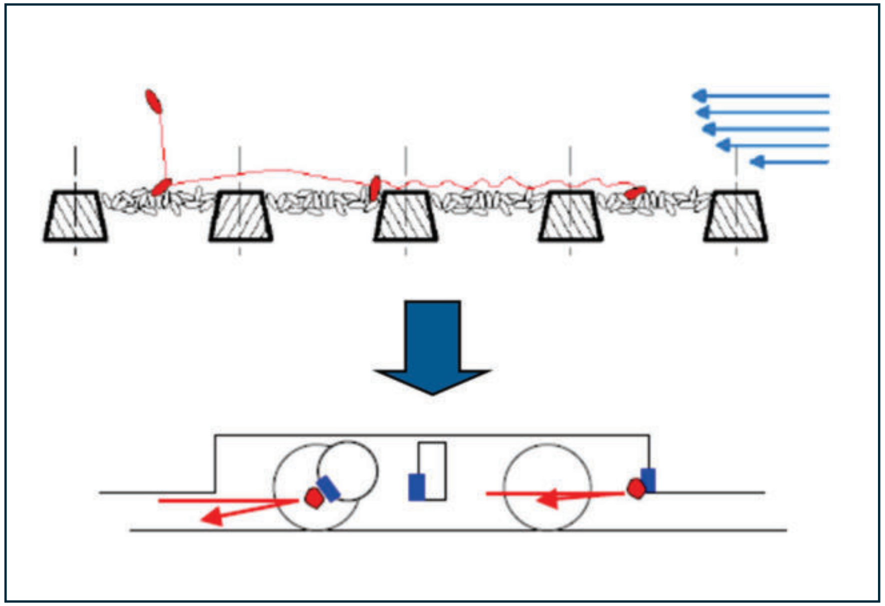

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DEFINITION OF THE PROBLEM AND EXPERIMENTAL TESTS ON TRACK

Preliminary questions to be resolved

- Statistics in situ campaign to analyze the displacements of ballast particles
- To record the ballast transport with high resolutions camera in order to understand the phenomena.
- Clarify in which position on the track ballast projection is detected.
- Define the type of ballast moving by saltation, rolling or sliding
- Mitigation measurement

Specifics objectives

- Clarify in which position on the track ballast projection is detected
- Study the influence of mass, geometry (oblate, spherical, bladed or prolate) , ballast levels, sleeper shape, granular size, vibrations, types of HS trains...
- Define in which position of S-100, S-102 or S-103 trains start the displacements of the different ballast particles.
- Measurement of the aerodynamic flow under different trains at different speeds with three heights of ballast configurations of 400 m each one.
- Define the key parameters that govern the ballast projections phenomena. Obtain the methodology to determine the influence of both track and trains

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DEFINITION OF THE PROBLEM AND EXPERIMENTAL TESTS ON TRACK

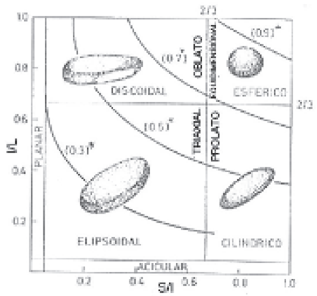
1:1 test at high speed line Madrid – Barcelona | Experimental parameters

Weight of ballast particles

24 g……………………………………………………………358 g

Geometry of the ballast

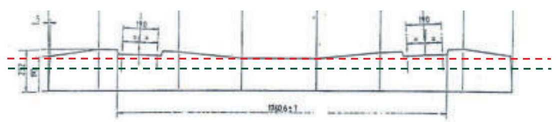
Tipo	Definición	Propiedad aerodinámica	Ilustración
A	Clase III elipsoidal	Muy variable con respecto a la dirección del viento	
B	Clase II esférico	Poco variable con respecto a la dirección del viento	



Clase	b/a	c/b	Forma
I	> 2/3	< 2/3	Oblato (discoidal)
II	> 2/3	> 2/3	Equidimensional (esférica)
III	< 2/3	< 2/3	Triaxial (elipsoidal)
IV	< 2/3	> 2/3	Prolato (cilíndrico)

Two ballast leves and three tack configuration

Ballast surface at the top of the sleepers - - - -
Ballast surface 3-4 cm under the top of the sleepers - - - -



Three types of HSP trains

Talgo – Bombardier 330 (Serie 102) / ICE Siemens (Serie 103) / Alstom (Serie 100)

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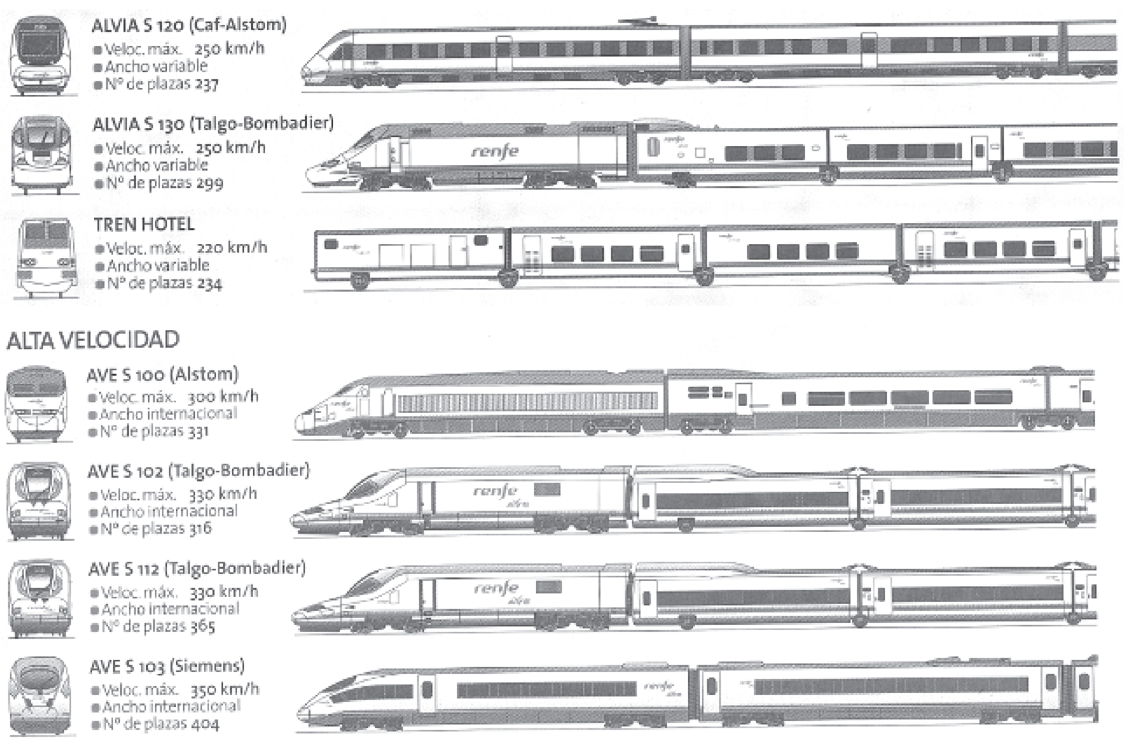
6 types of High Speed trains



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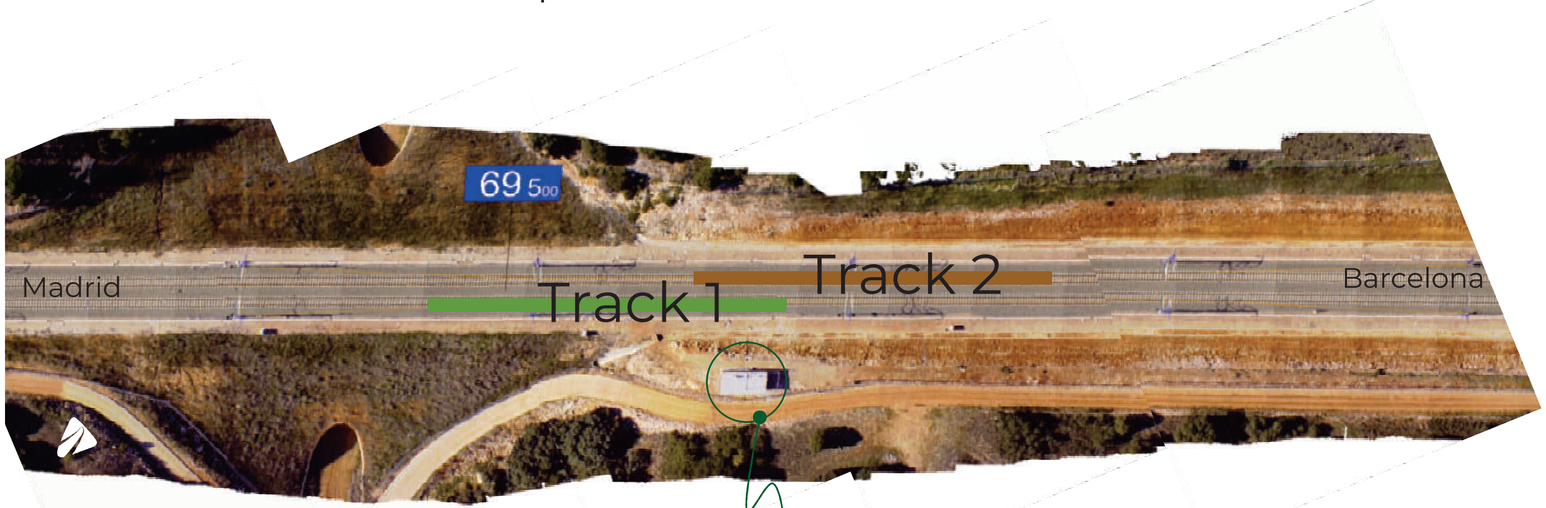
DEFINITION OF THE PROBLEM AND EXPERIMENTAL TESTS ON TRACK

Two sections were prepared in the high speed railway line between Madrid and Zaragoza, at around K.P. 69+500 in vicinity of Guadalajara town.

Line Madrid – Barcelona is operated at 300 km/h with S-102 and S-103 HST



Control center and meteorological station, presently in service.

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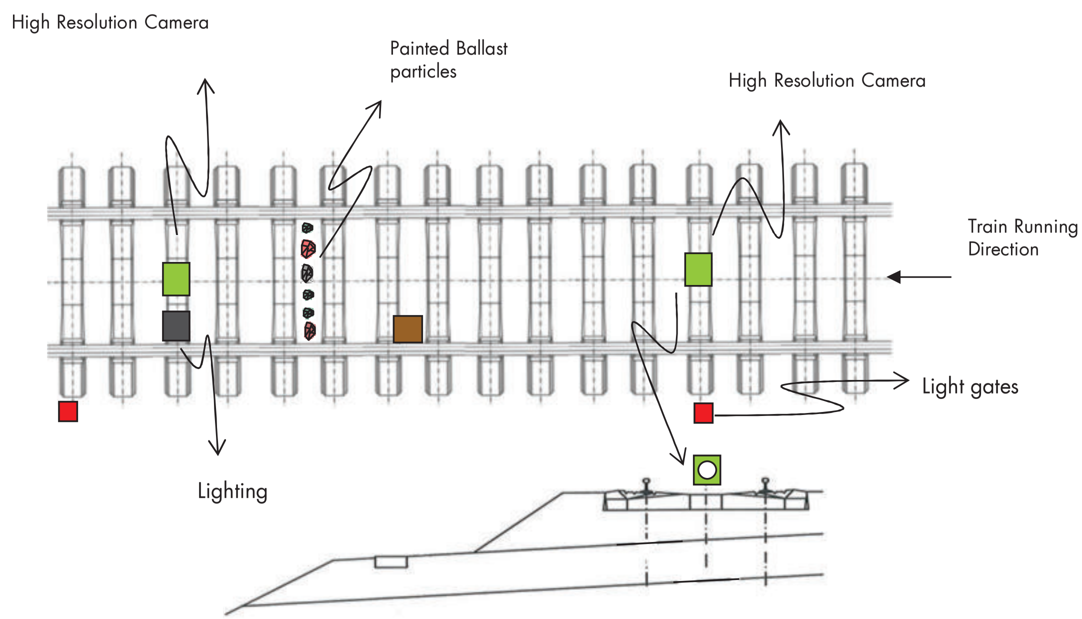
The axels and the speed of the passing trains were measured by separate light gate systems of ADIF.

The movement of ballast particles was monitored through the use of CCD cameras

The real time ballast transport visualization system consists of two DALSA (CCD – 300 fps) cameras and a PROSILICA (CCD – 100 fps) camera. A camera acquisition system was accomplished by ADIF internal existing programme GigErecorded tool.



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DEFINITION OF THE PROBLEM AND EXPERIMENTAL TESTS ON TRACK

General view of test track section showing CCD camera and painted ballast particles upstream and downstream of the cameras

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DEFINITION OF THE PROBLEM AND EXPERIMENTAL TESTS ON TRACK

- The position of ballast particles on track for the test was concentrate on the top of the sleeper. It is important to mention that in the high speed track configuration **no ballast particles on the top of the sleeper are present**.

- The experiments were conducted in a track section of high speed line. In order to prepare each experimental set up it was necessary access to the track and placing the particles in the defined position. This allows making only **three tests per day**.

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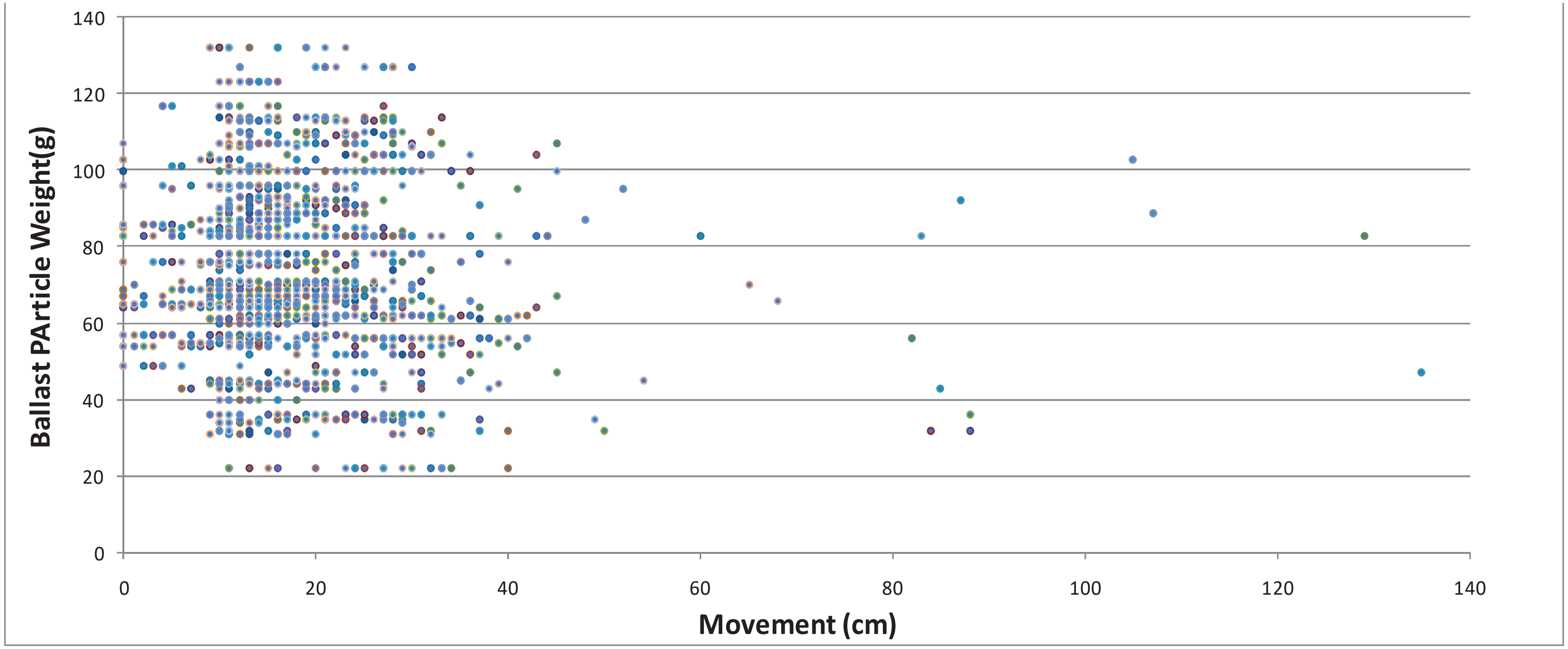
DEFINITION OF THE PROBLEM AND EXPERIMENTAL TESTS ON TRACK

Statistics in situ campaign. Single unit

Samples: 1900 ballast particles.

A total of 19 trains. Speed 300 kph

19 particles pass the first sleeper, which represents 1% of the total sample, **ONE Impact**



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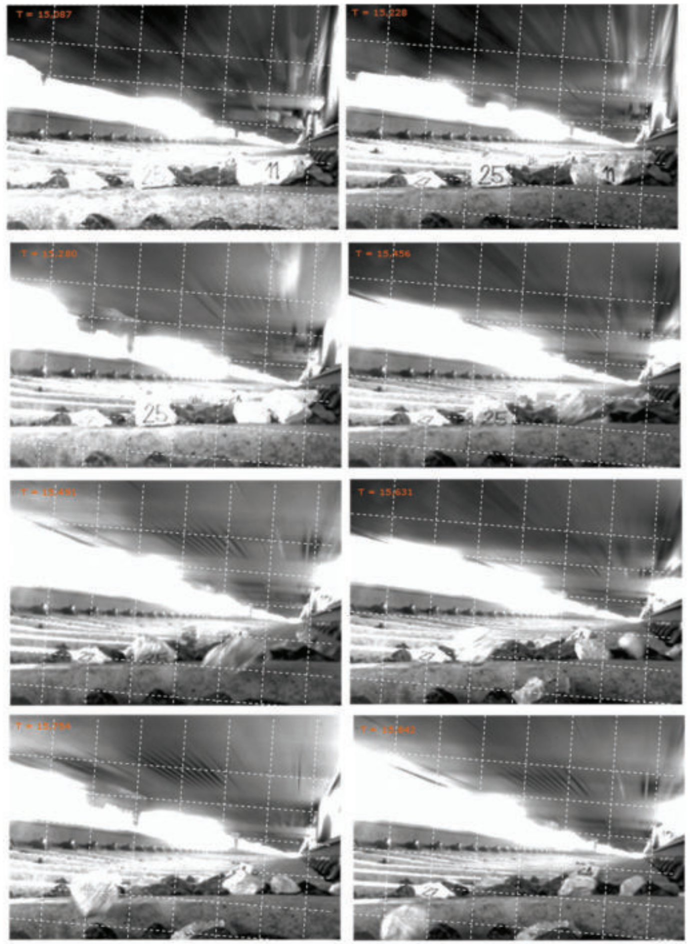
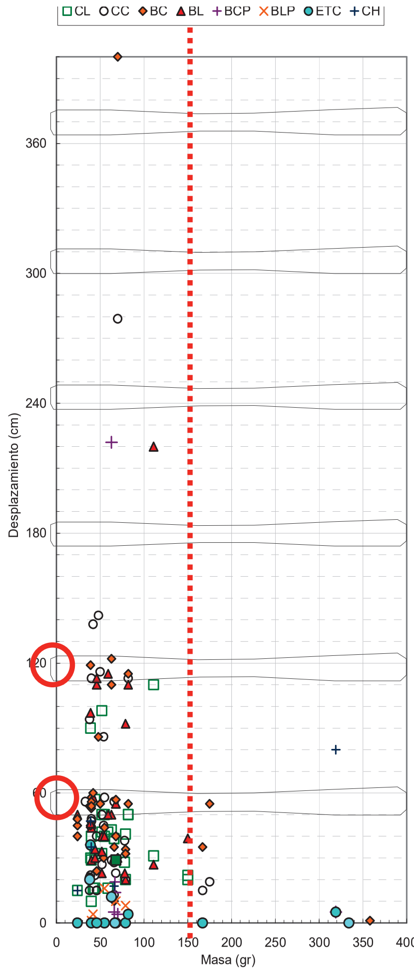
EXPERIMENTAL TESTS ON TRACK

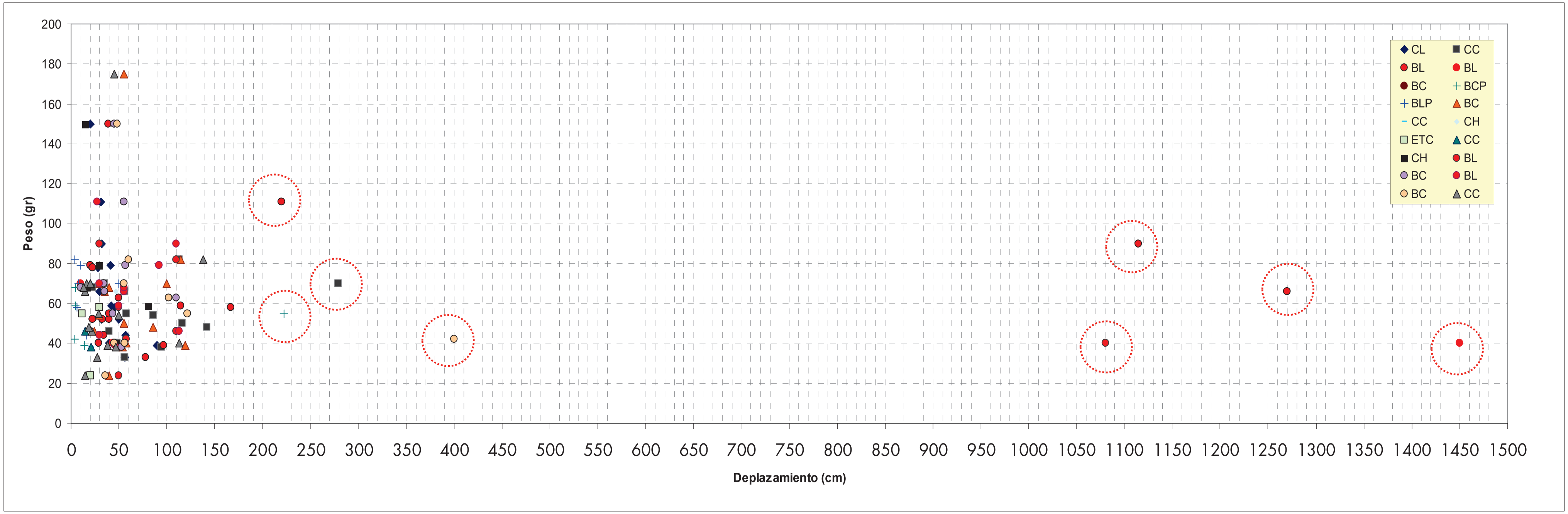




Identification of High-Speed Rail Ballast Flight Risk Factors and Risk Mitigation Strategies

Results In situ test with painted ballast particles

Mass Versus Displacement



Ballast on top of the sleeper between rails position is the worst case

Results In situ test with painted ballast particles

Estimated Number of Exposed Ballast Particles

Over 100 km of track: **≈ 76.000.000 particles**

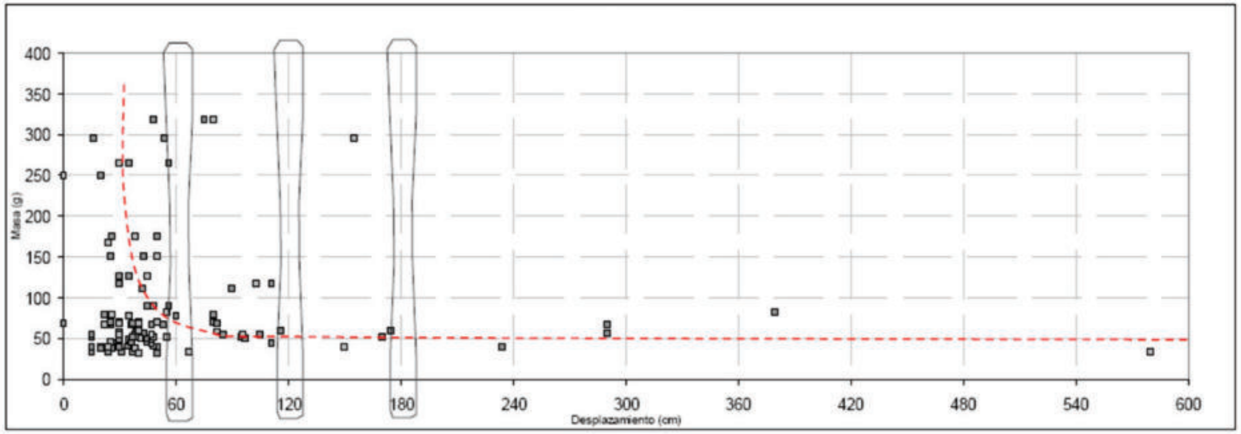
For HSL Madrid – Barcelona

471.960.000 particles (aprox.)

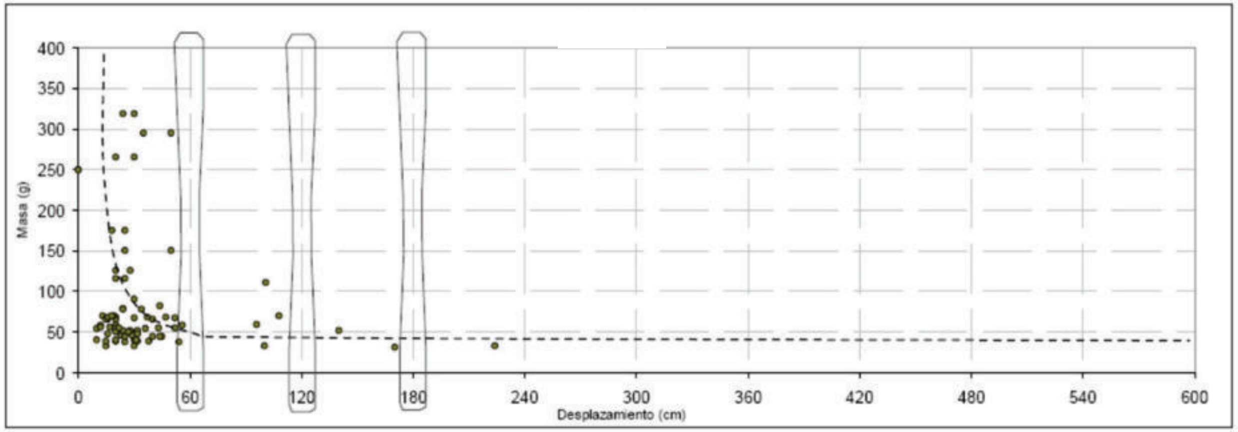
DEFINITION OF THE PROBLEM AND EXPERIMENTAL TESTS ON TRACK

Results of experimental test running 2 different types of high speed trains at 300 kph

Train 1



Train 2



Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

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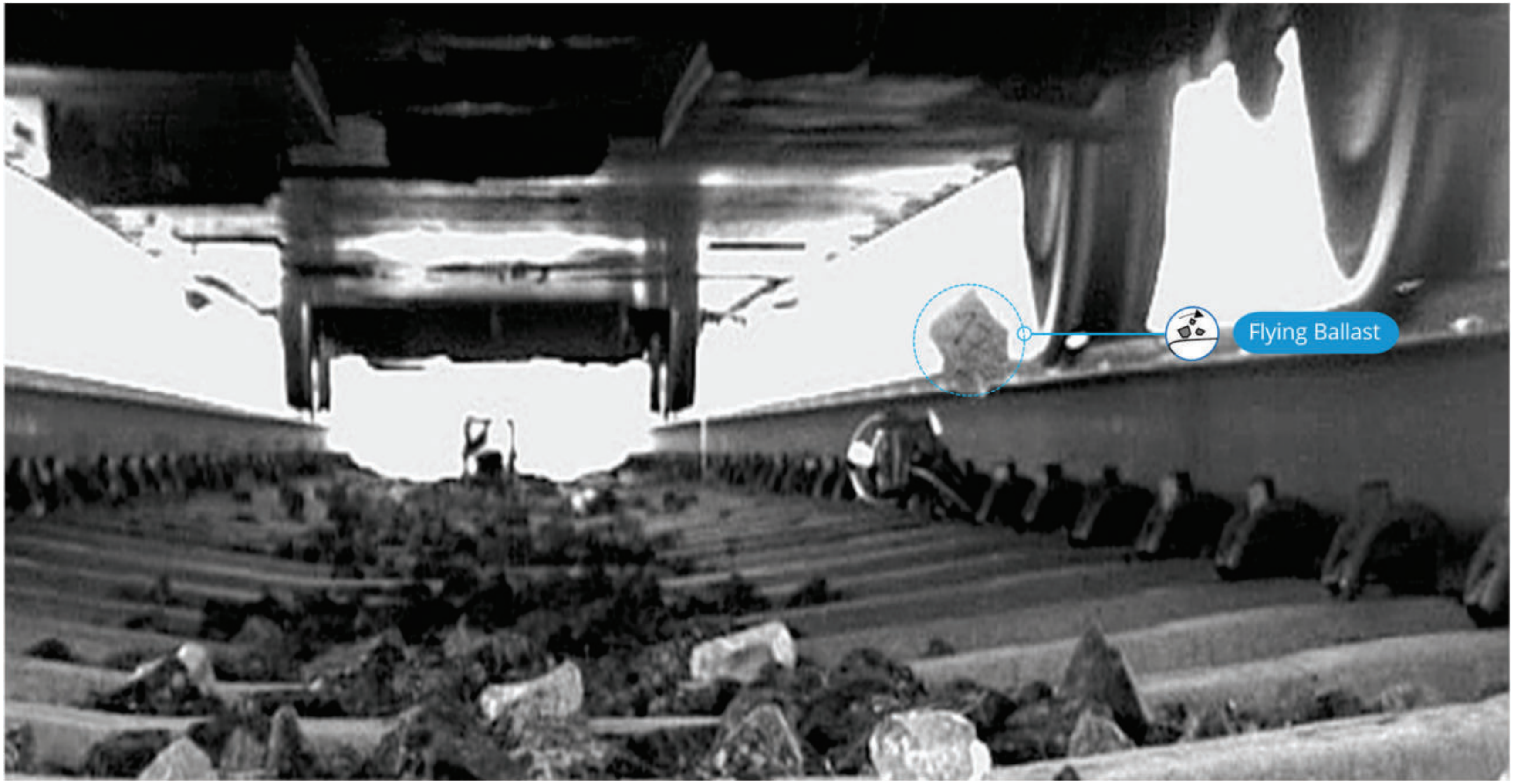

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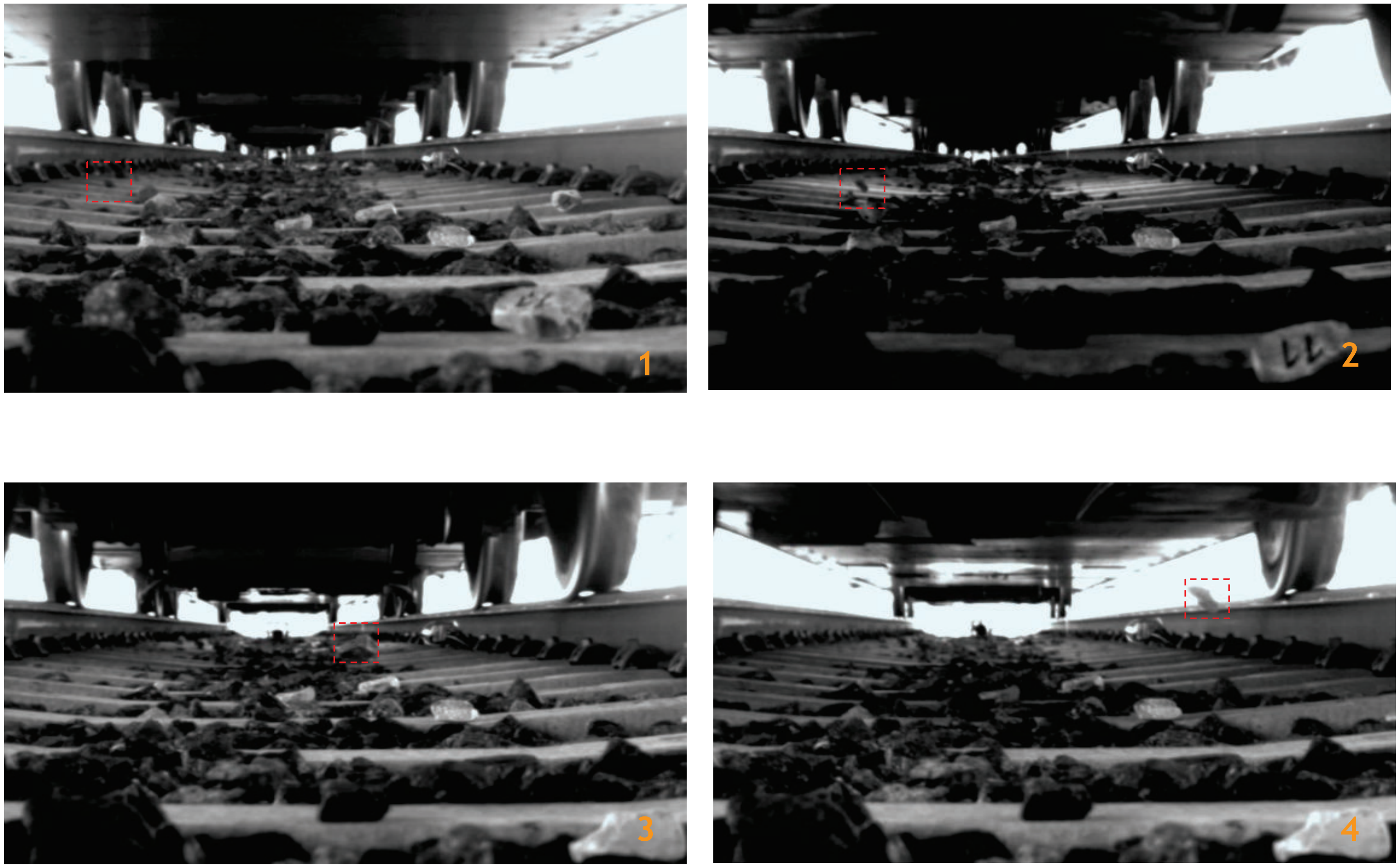

INDICE

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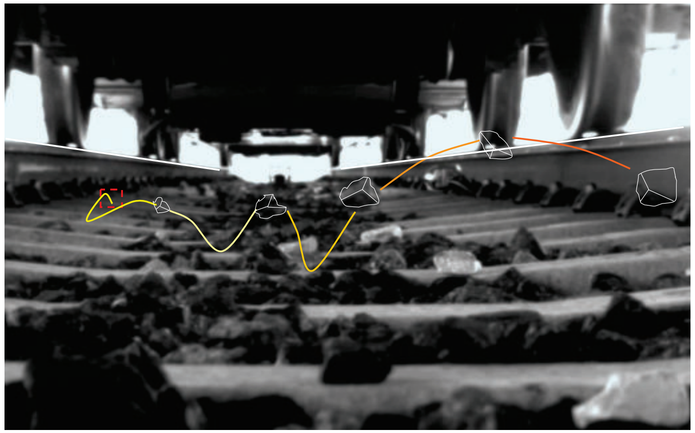
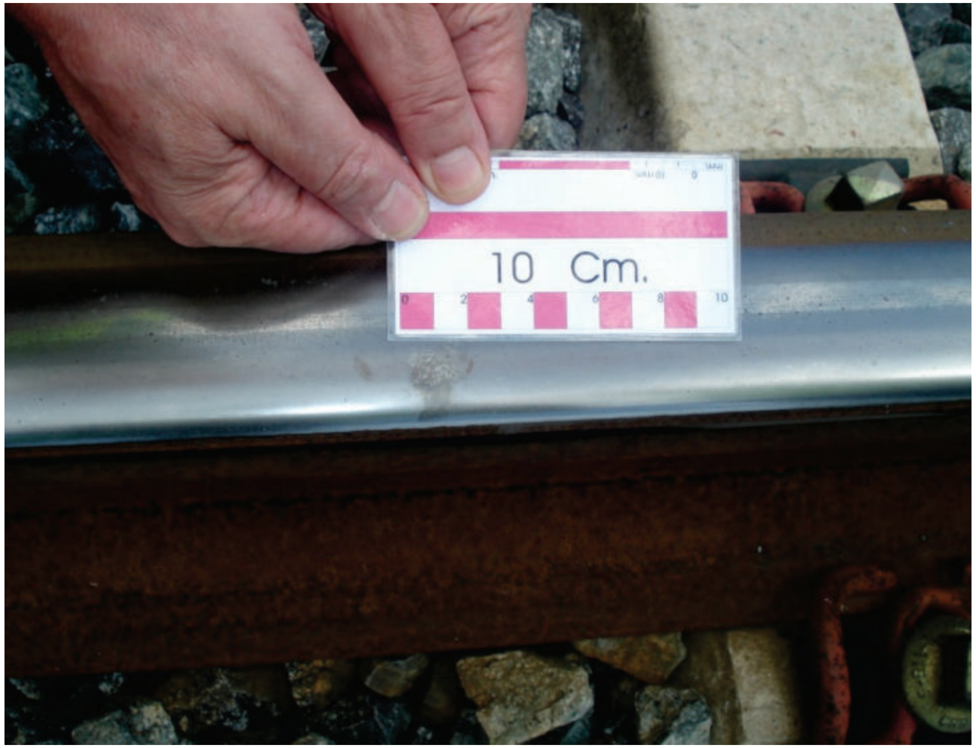


200 m ≈ 2.4 seg
400 m ≈4.8 seg

RAIL DEFECTS CAUSED BY FLYING BALLAST PHENOMENON



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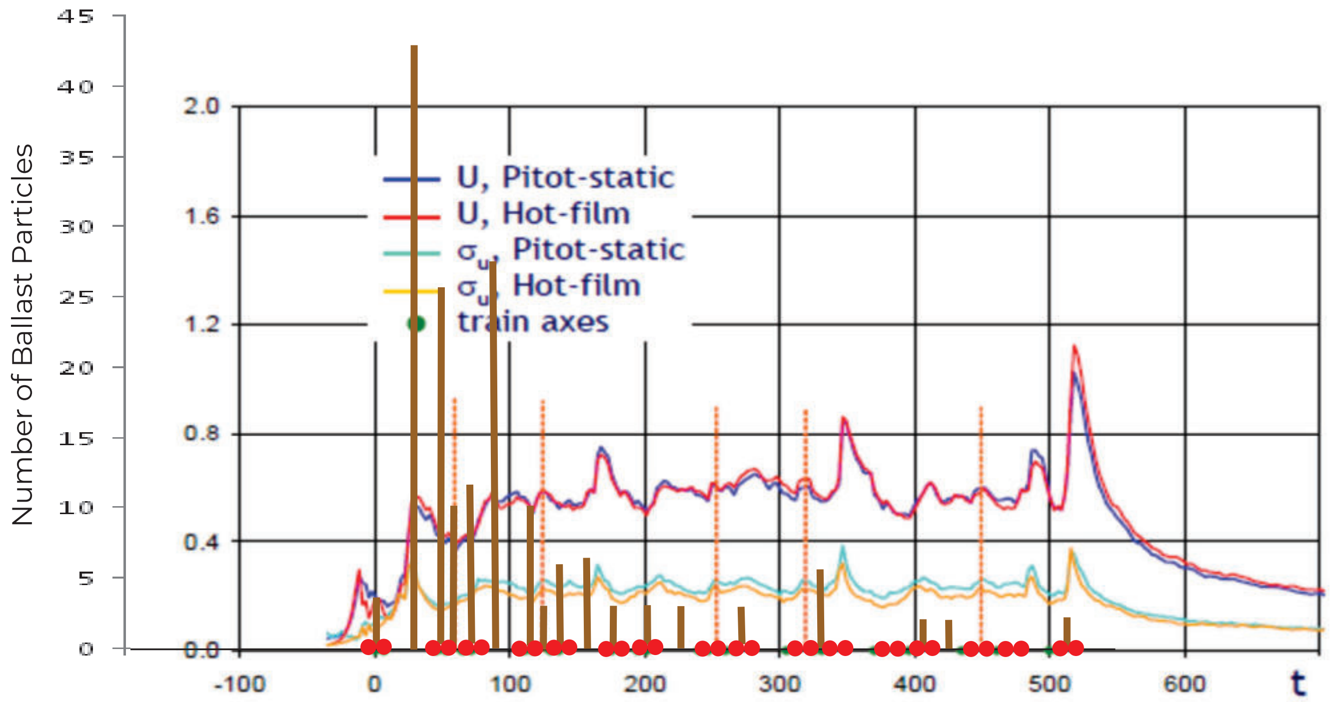


Phase-averaged anemometry close to the ballast bed ($y-y_{BB}=0.21$)

Test Trains objetive

Counting the number of ballast's impacts on a high speed train Talgo S-112 in double composition.

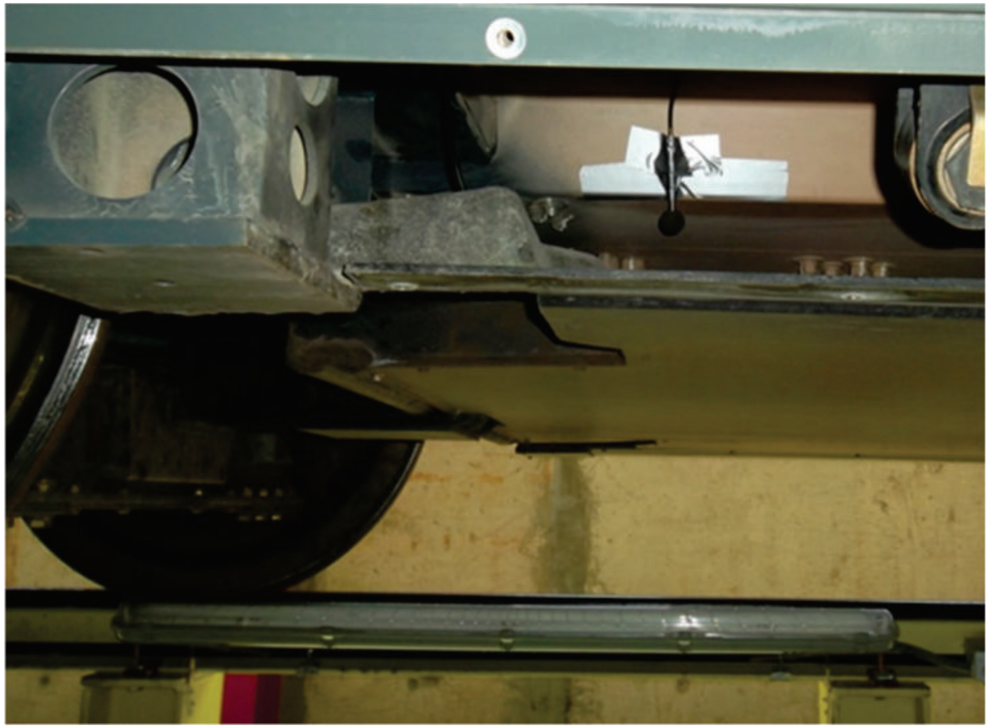
Test sites are the HSL Madrid-Barcelona and Madrid-Valencia.

Train speed: 315 km/h and 330 km/h (195 mph and 205 mph)

Hypothesis:

Every microphone gives us an idea of the impacts on the surrounding environment.

Uncontrolled chain reaction is only considered as one impact



Test sites

HSL Madrid-Barcelona (until Lérida).

420 km (260 miles)

HSL Madrid-Valencia (until Siete Aguas).

298 km (185 miles)

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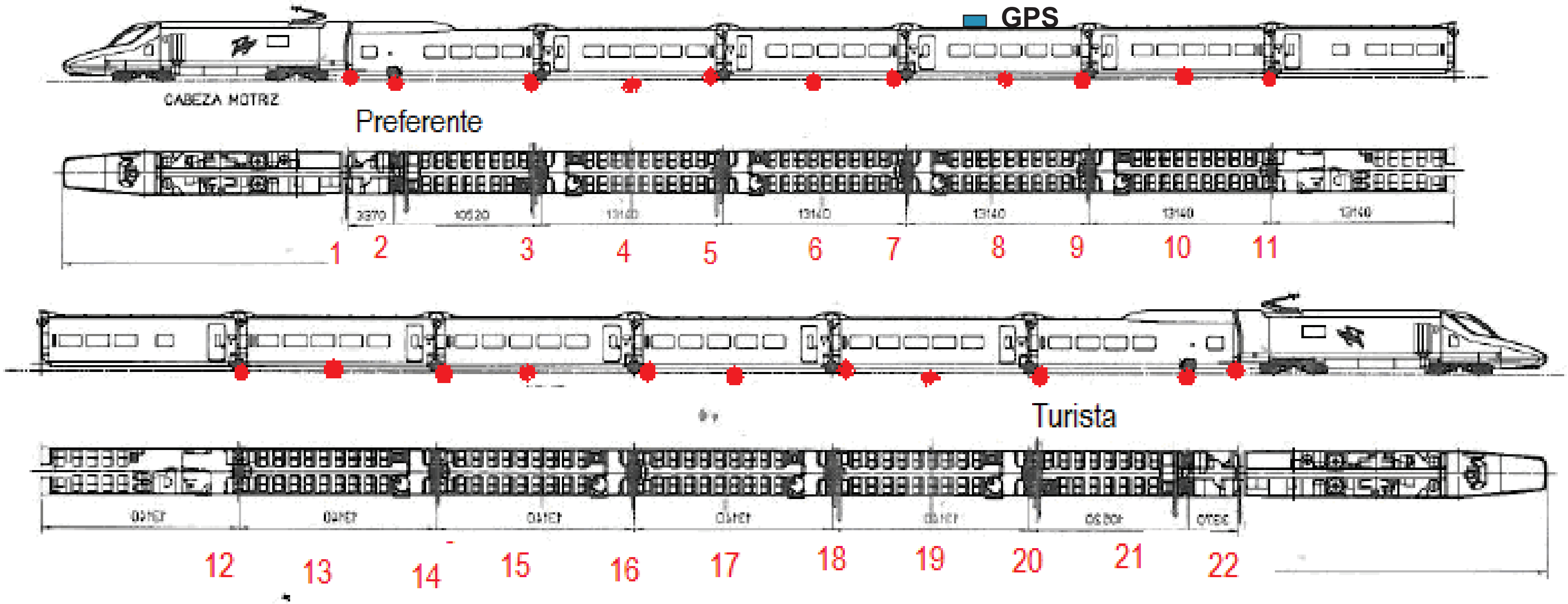
DEFINITION OF THE PROBLEM AND EXPERIMENTAL TESTS ON TRACK

Instrumentation

22 microphones + 1 GPS



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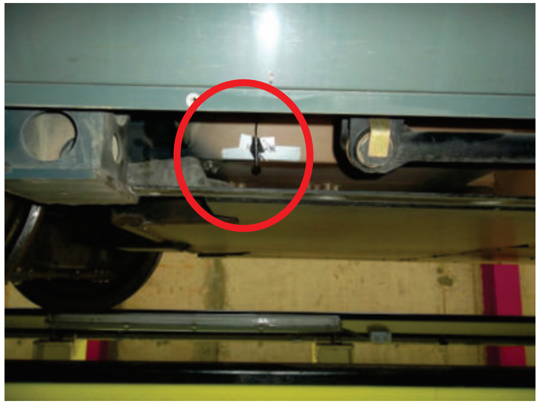
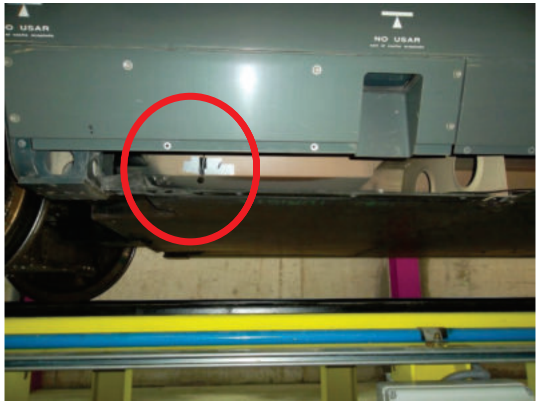
Microphones





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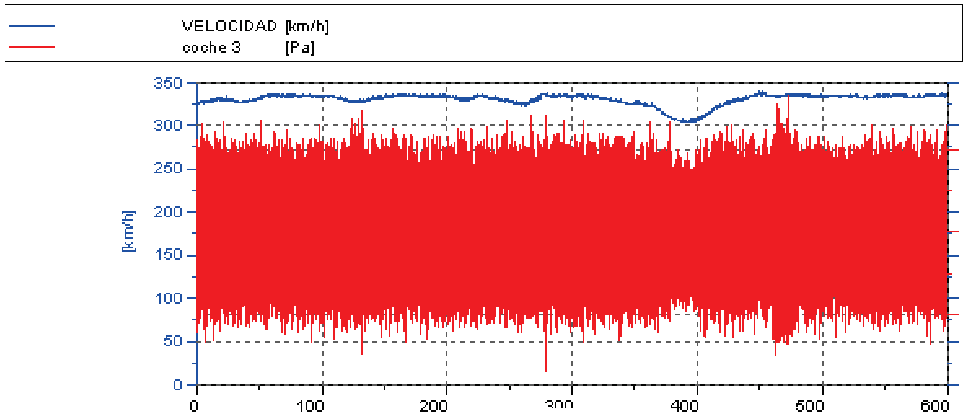
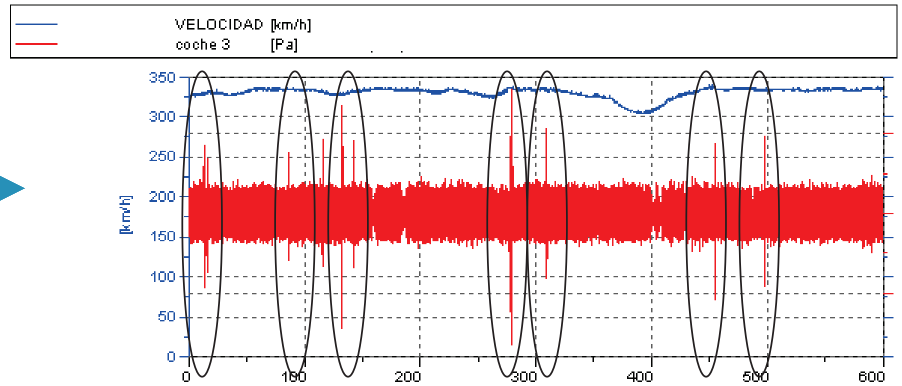
Data processing

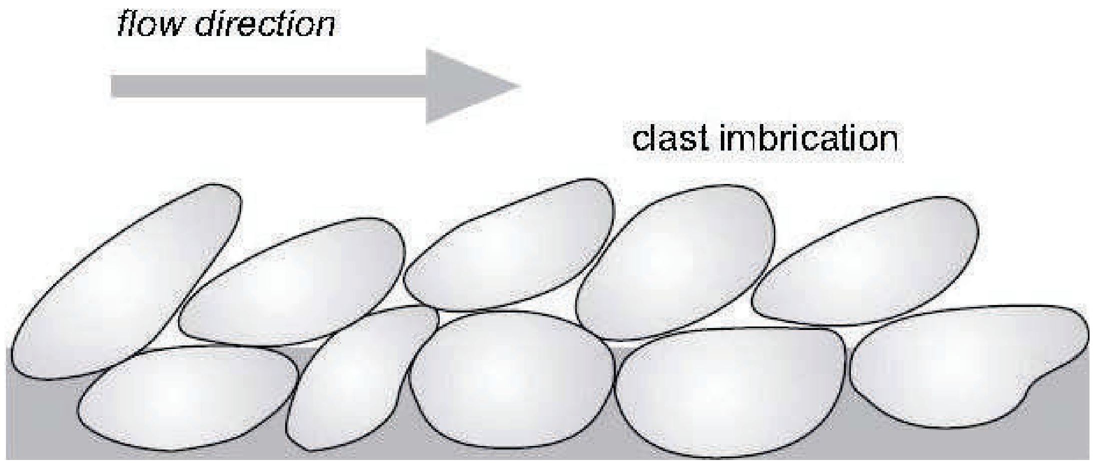


Filtering

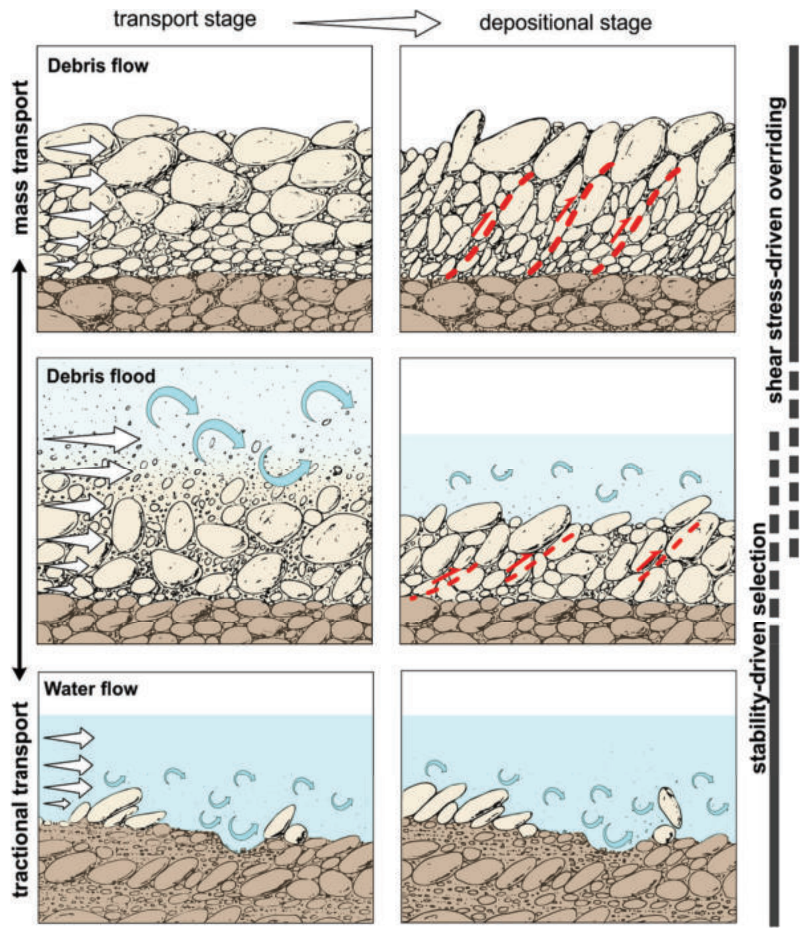


Interpretation

Clast imbrication



Ballast particles tend to reorient themselves into more aerodynamically favorable positions as trains pass over them



The probability of a single ballast particle causing an impact

Probability per particle: 0.00001316%

This means there is 1 impact per approximately 7,6 M particles.

The event is extremely rare.

A ballast impact is **nearly twice as likely** as winning the lottery!

however

DEFINITION OF THE PROBLEM AND EXPERIMENTAL TESTS ON TRACK

A train travels approximately 450,000 km per year.

Assuming that 25% of this distance is travelled in dual mode, we will have to:

Estimated ballast particle impacts in double traction operation over time:

10 years: 112,500 impacts
20 years: 225,000 impacts
30 years: 337,500 impacts

CHARACTERIZATION OF THE TRAIN-GROUND FLOW FIELD

INDICE

Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

CHARACTERIZATION OF THE TRAIN-GROUND FLOW FIELD

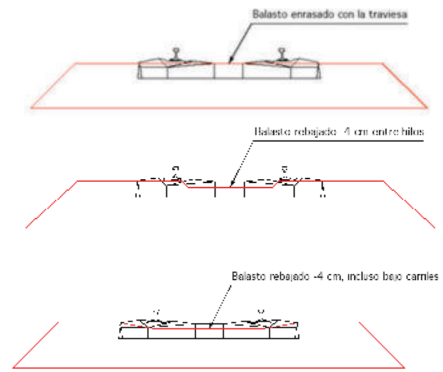
Three sections have been prepared:

One of them in track number 1 and the other two section in track number 2.

Track number 2 allow running trains at maximum speed of 395 km/h with track reserve during the night from 24:00 to 5:00.

- Section 1A 400 m – track 1. Ballast surface at the top of the sleepers.
- Section 2A 400 m – track 2. Ballast surface 3-4cm under the top of the sleepers
- Section 2B 400 m – track 2. Ballast surface 3-4cm under the top of the sleepers, even below the rail.

Different ballast configurations



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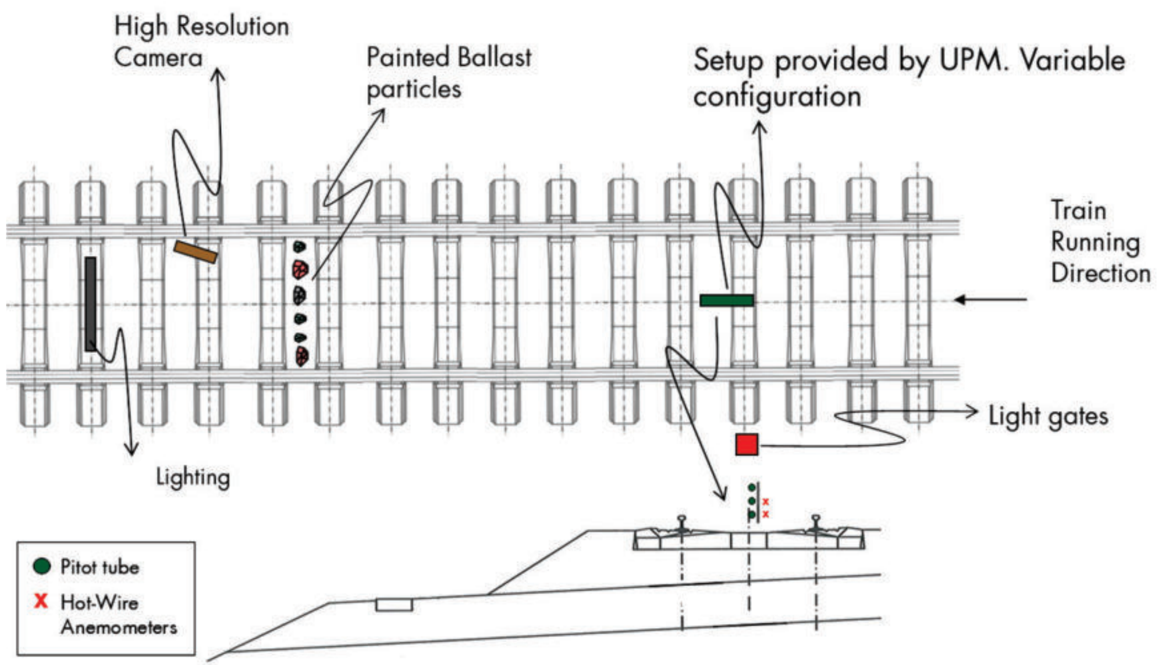
CHARACTERIZATION OF THE TRAIN-GROUND FLOW FIELD

TEST SET UP



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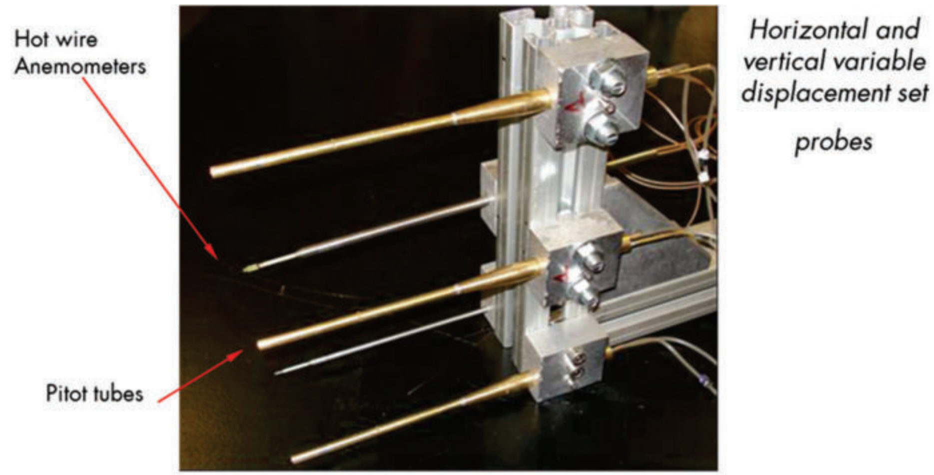
CHARACTERIZATION OF THE TRAIN-GROUND FLOW FIELD

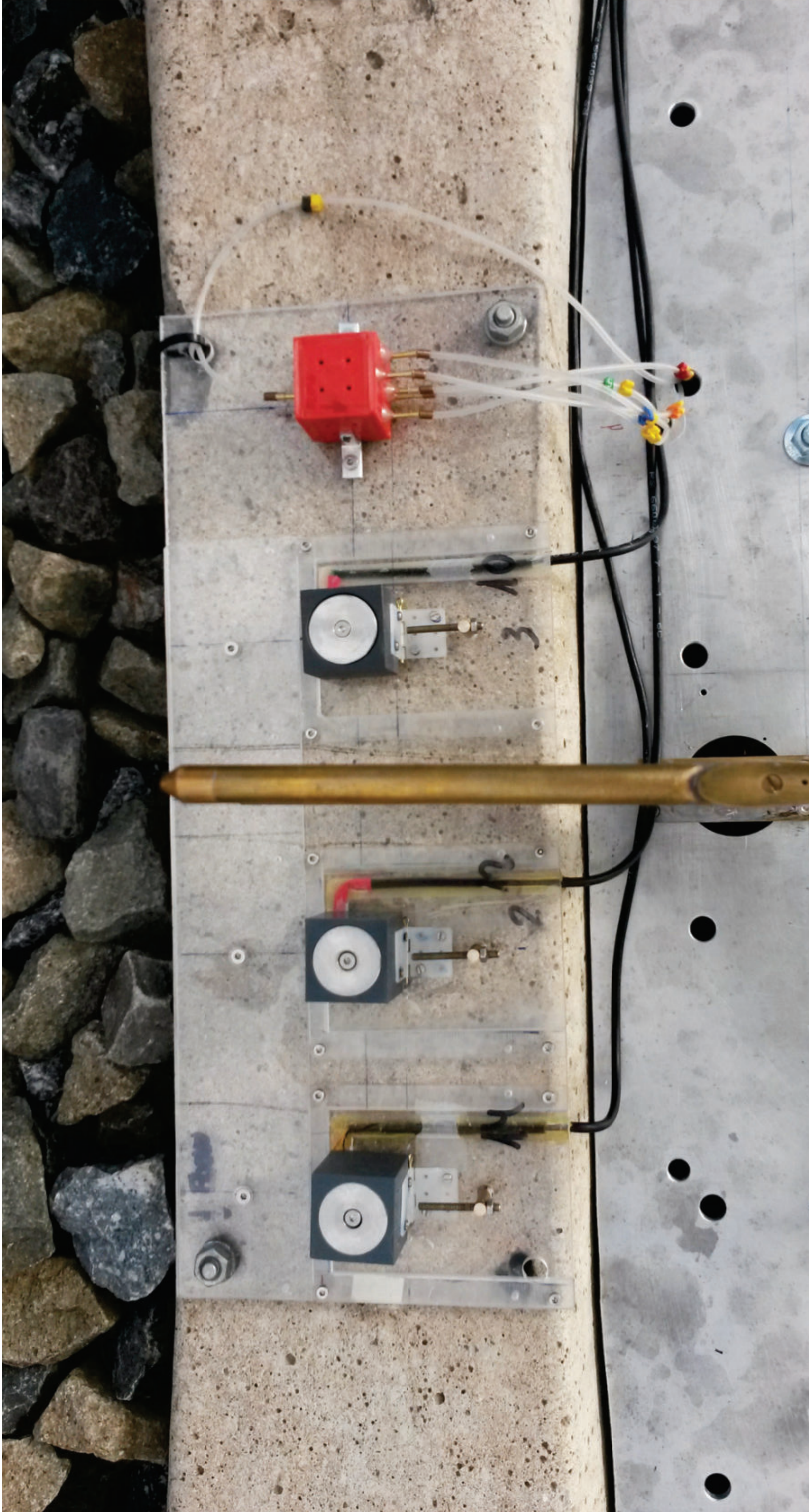
- Characterization of the train-ground flow field.
- Use of Prandtl and hot-wire probes to measure velocity field (mean and fluctuations).

  Prantdl probes have been used to obtain the mean velocity field and to serve as dynamic calibration to the hot-wire probes (wake measurements).

  The hot-wire probes have been used to obtain components of the Reynolds stress tensor.

- In-situ hot-wire calibration procedure based on the train wake flow has been developed. Hot-wire probes individually calibrated for each train passage.
- Test campaings completed using three different trains and three different ballast configurations.





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CHARACTERIZATION OF THE TRAIN-GROUND FLOW FIELD

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CHARACTERIZATION OF THE TRAIN-GROUND FLOW FIELD

High Speed trains were tested in double composition and at different speeds up to 300 km/h

EMU RENFE S/102-112
Sección: 9,5 m²

$V_{máx}$ 330 km/h

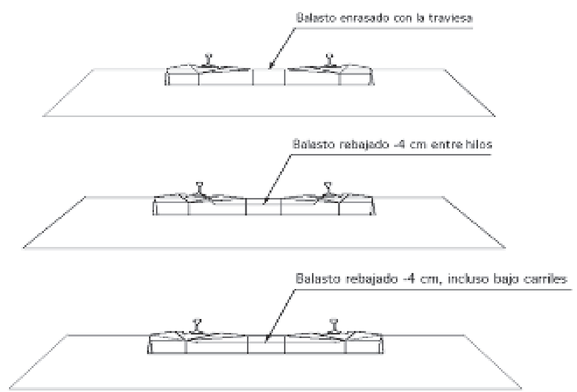
EMU RENFE S/103
Sección: 9,8 m²

$V_{máx}$ 345 km/h

EMU SNCF TGV DUPLEX
Sección: 10,94 m²

$V_{máx}$ 320 km/h

Trenes AV. [S100, S102 y S103] Acoplados.



400 m track sections

CHARACTERIZATION OF THE TRAIN-GROUND FLOW FIELD

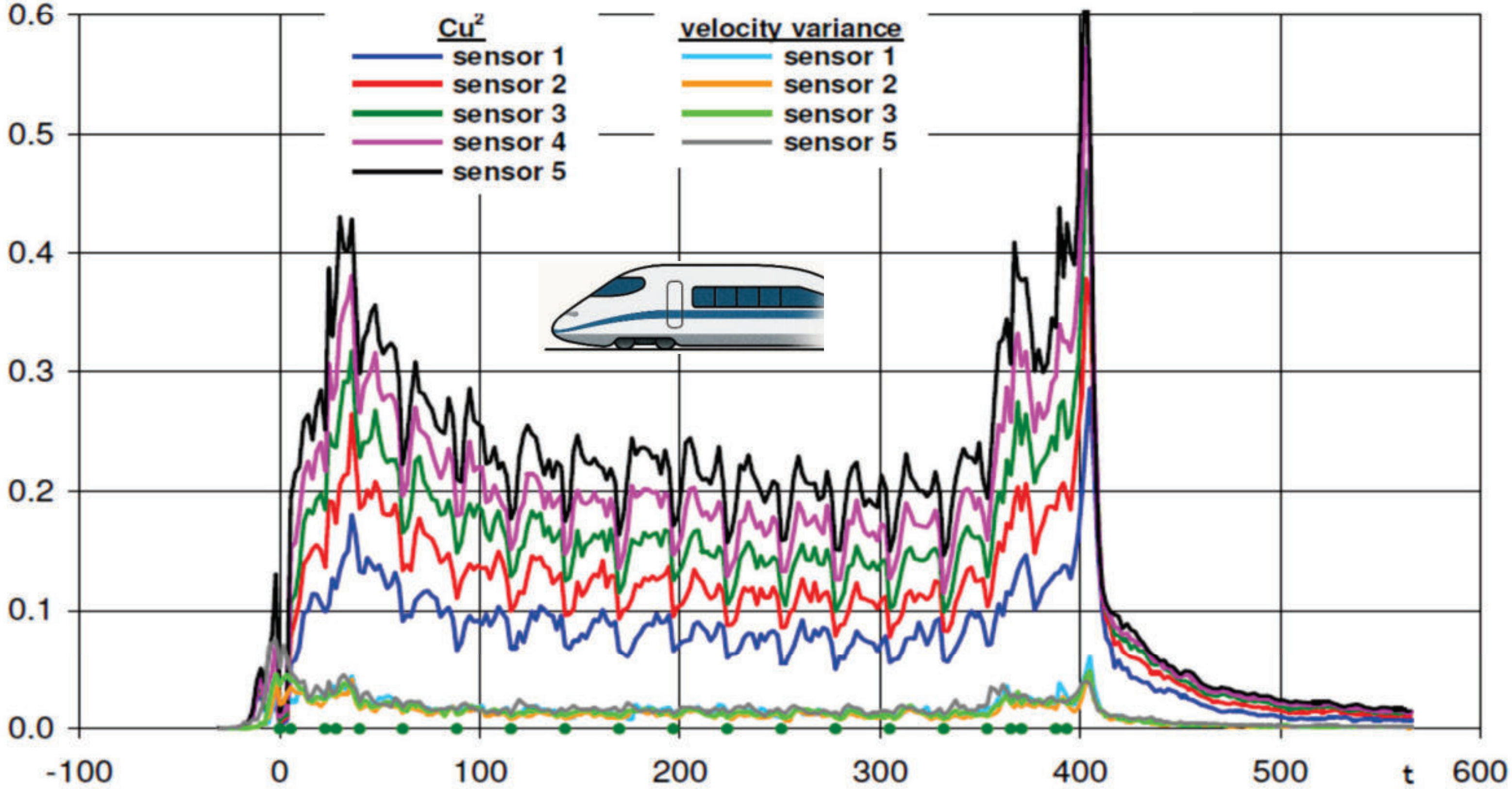


Figure 24: Phase-ensemble temporal evolution of the mean squared (cu^2) and variance ($\overline{u'^2}$) velocity measured at sensor locations 1 to 5 ($0.006 < z < 0.377$) and station B (mid-plane between sleepers), S-102 train

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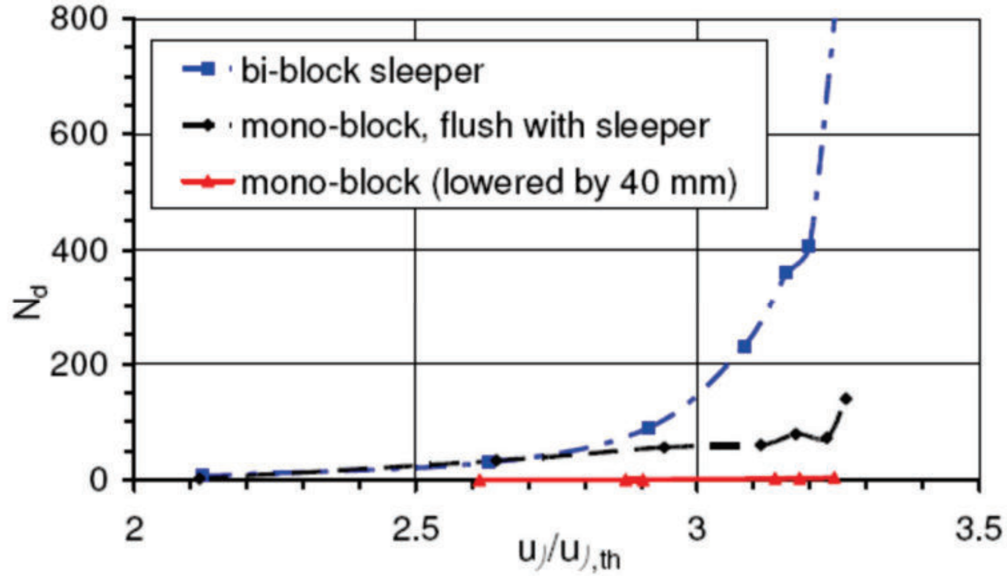
CHARACTERIZATION OF THE TRAIN-GROUND FLOW FIELD

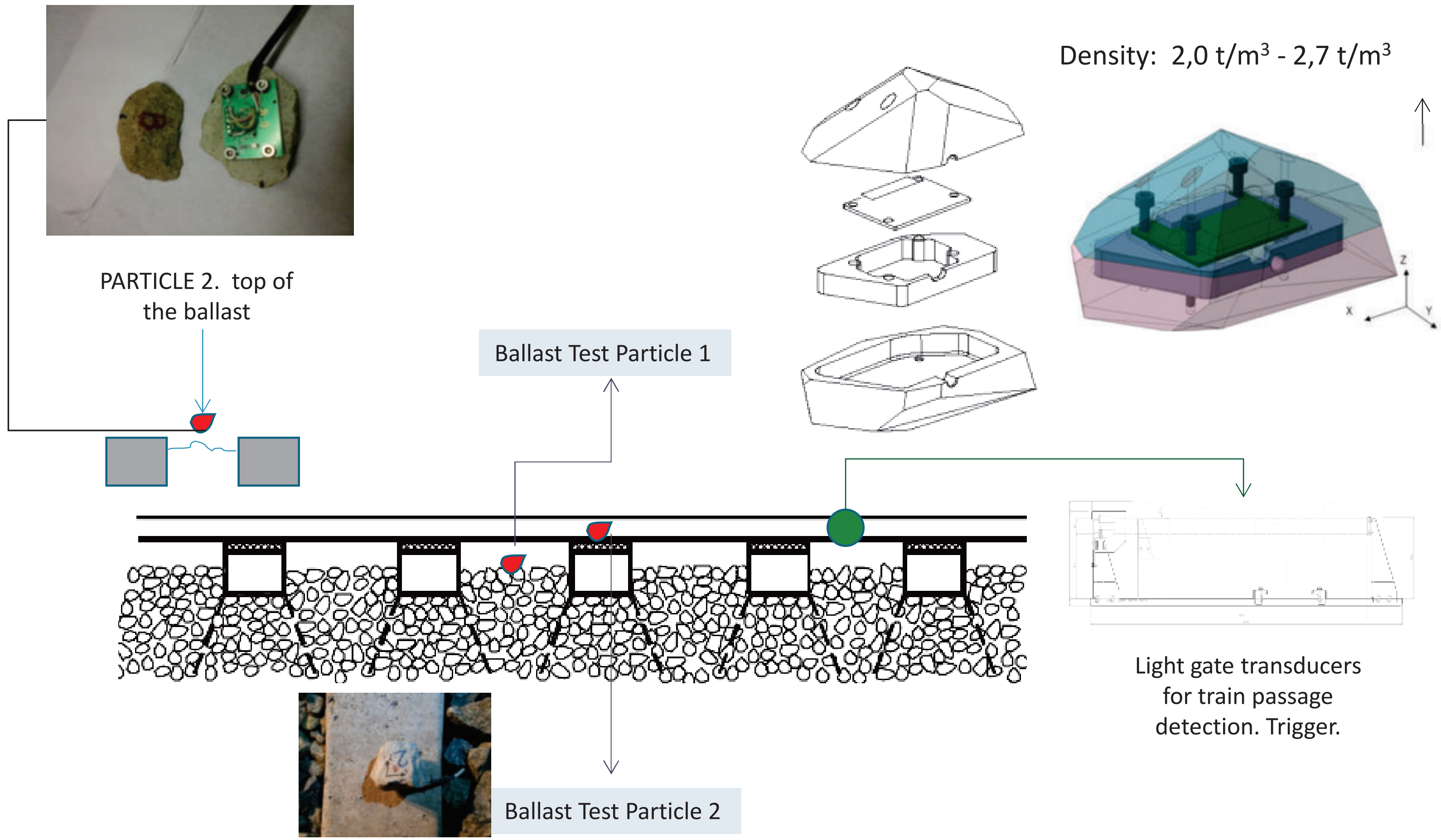
Number of dislodged particles versus normalized friction speed $u_\tau / u_{\tau,th}$ (measured ahead of the test section) for three trackbed types.



Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

CHARACTERIZATION OF THE TRAIN-GROUND FLOW FIELD

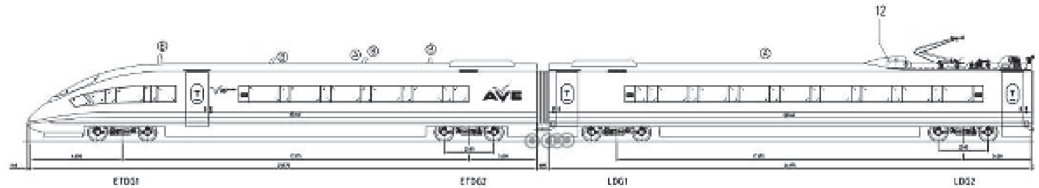
Studies on ballast accelerations under the passages of HST

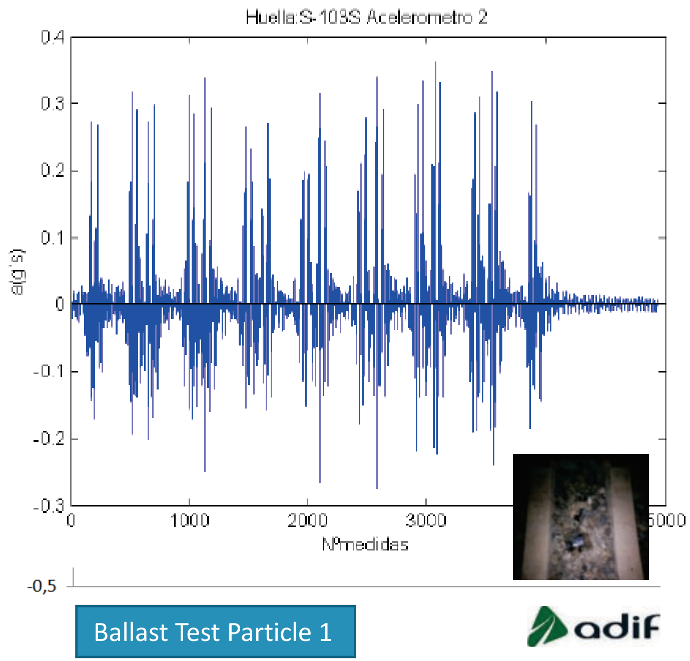


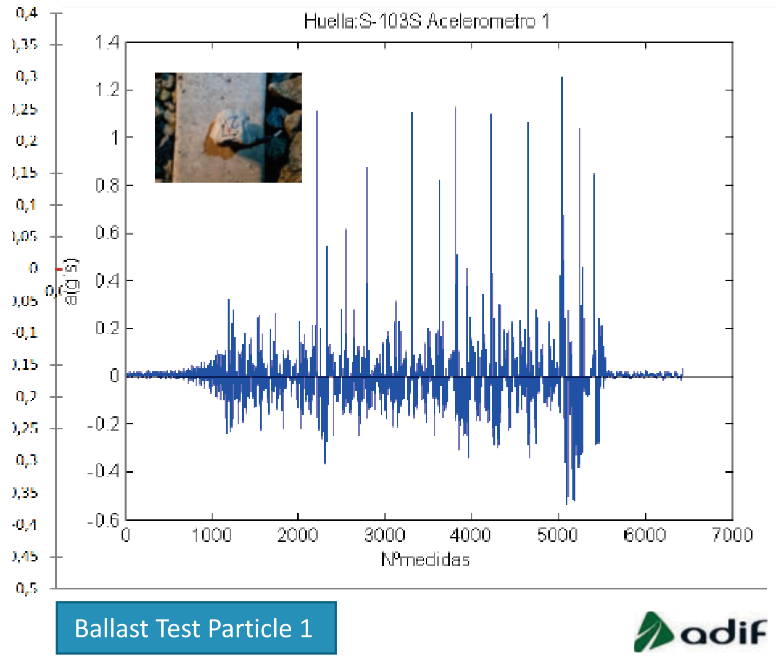
Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

CHARACTERIZATION OF THE TRAIN-GROUND FLOW FIELD

TRAIN: S-103. Siemens Velaro 350
Speed: 298 kph
Single unit







MITIGATION MEASUREMENTS. NOVEL SLEPPER

Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

MITIGATION MEASUREMENTS. NOVEL SLEPPER FLOW FIELD

Mitigation Strategies

To reduce the aerodinamic load over the particles of ballast

To reduce the flying ballast phenomenon on High Speed Lines

MITIGATION MEASUREMENTS. NOVEL SLEPPER FLOW FIELD

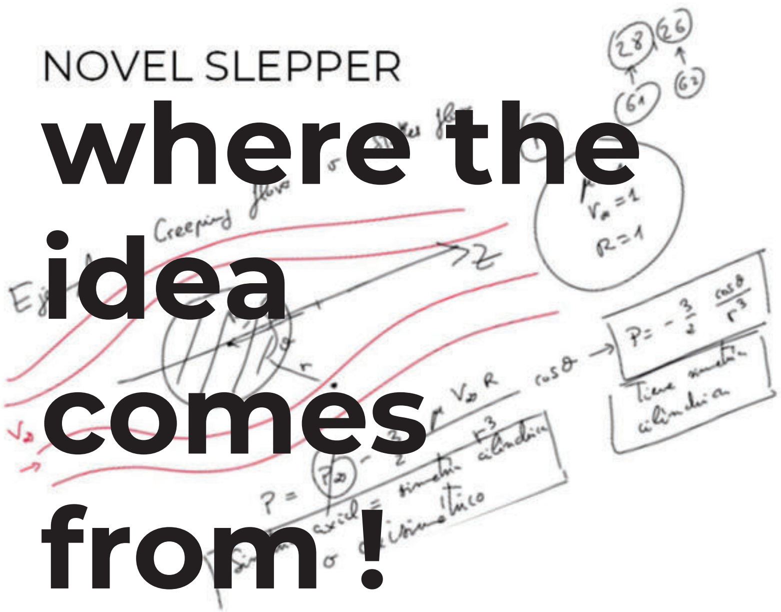
- **Ballast lowered 3-4 cm** below the top of the mono-block sleepers between rails. No affection to the lateral stability of the track.

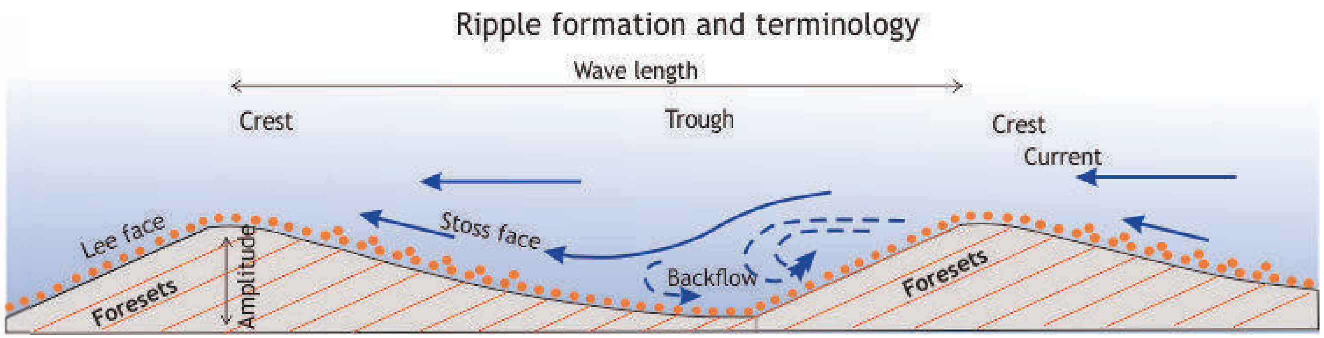
Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

MITIGATION MEASUREMENTS. NOVEL SLEPPER FLOW FIELD

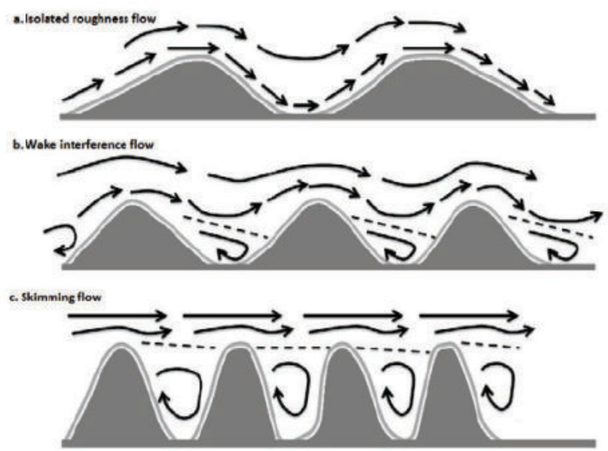
NOVEL SLEPPER

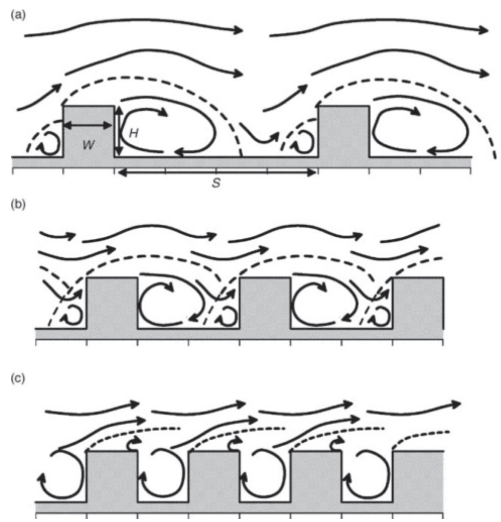
where the idea comes from !





The current moves sand grains up the stoss slope. At the crest of the ripple the grains enter a region of low velocity backflow where gravity takes over and the grains tumble or avalanche down the lee face. In this fashion the ripple moves down-stream with the current.





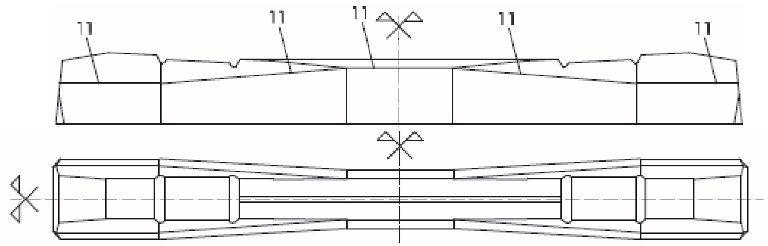
Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

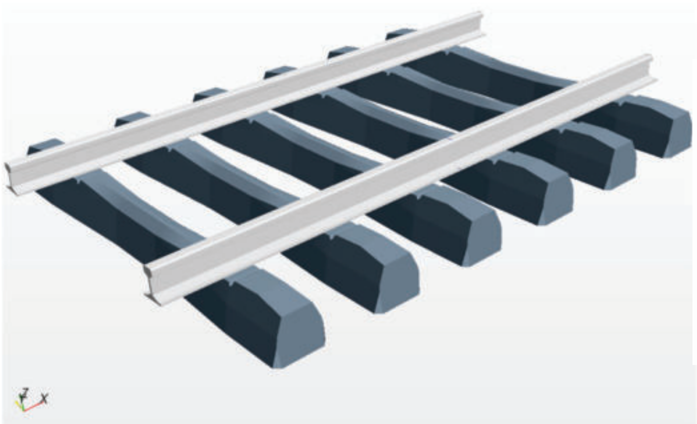
MITIGATION MEASUREMENTS. NOVEL SLEPPER FLOW FIELD

AERODYNAMIC SLEEPER. Results.

Improvements over the actual sleepers

- Reduction of the aerodinamic load over the particles of ballast
- Reduction of the number of particles over the sleepers.





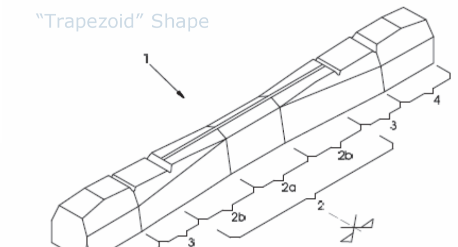


FIG. 1

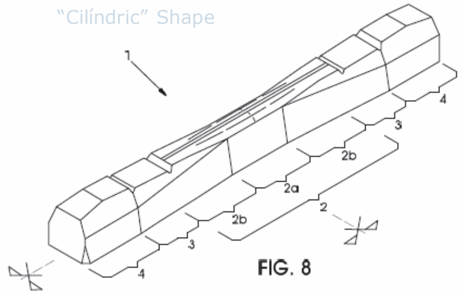
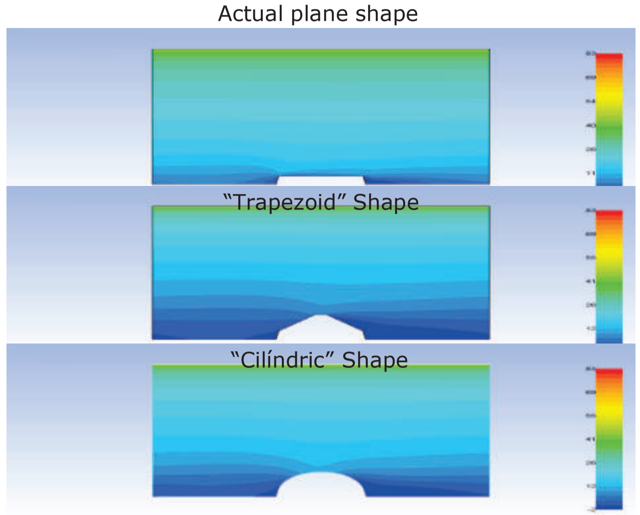
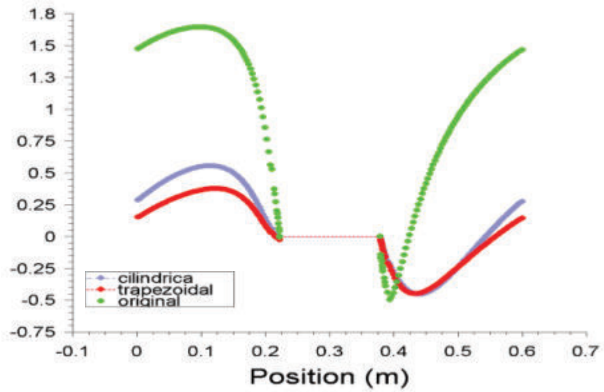


FIG. 8

Patent **P201230248**





Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

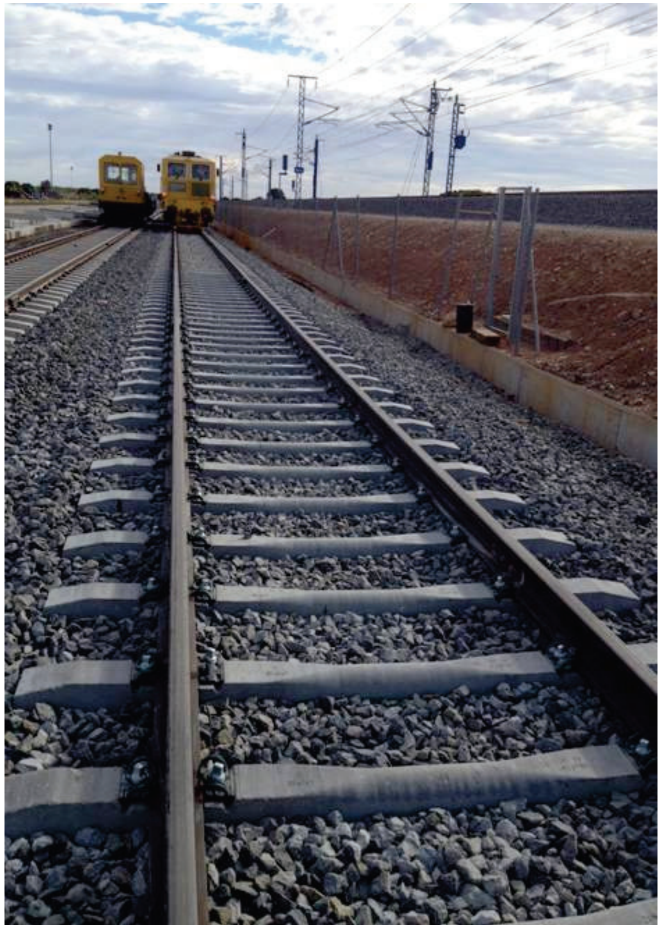
MITIGATION MEASUREMENTS. NOVEL SLEPPER FLOW FIELD

AERODYNAMIC SLEEPER. TESTS

Validation of behaviour in maintenance tasks.

Reduction of the aerodinamic load over the particles of ballast

AERODYNAMIC SLEEPER
Results. Maintenance tasks tests



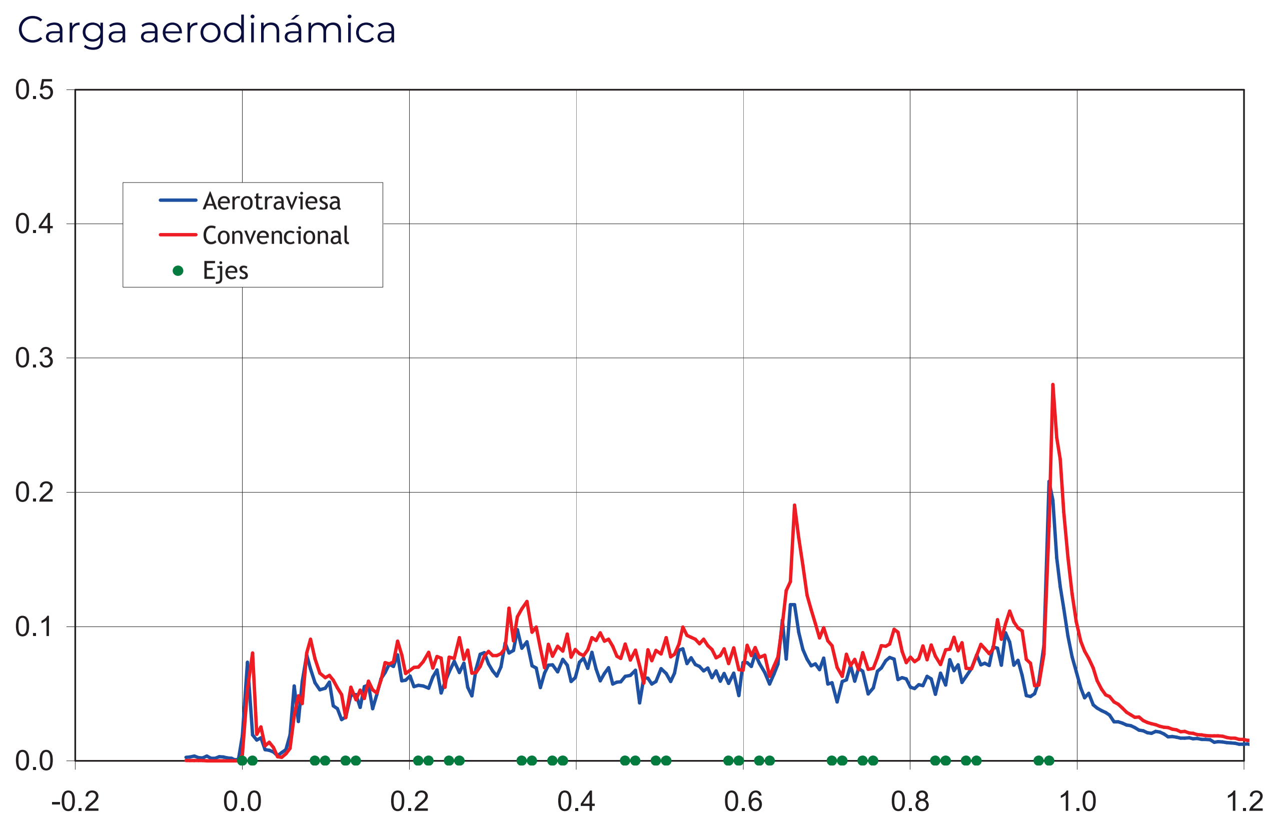
Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

MITIGATION MEASUREMENTS. NOVEL SLEPPER FLOW FIELD

AERODYNAMIC SLEEPER
Aerodynamic Load Test

Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

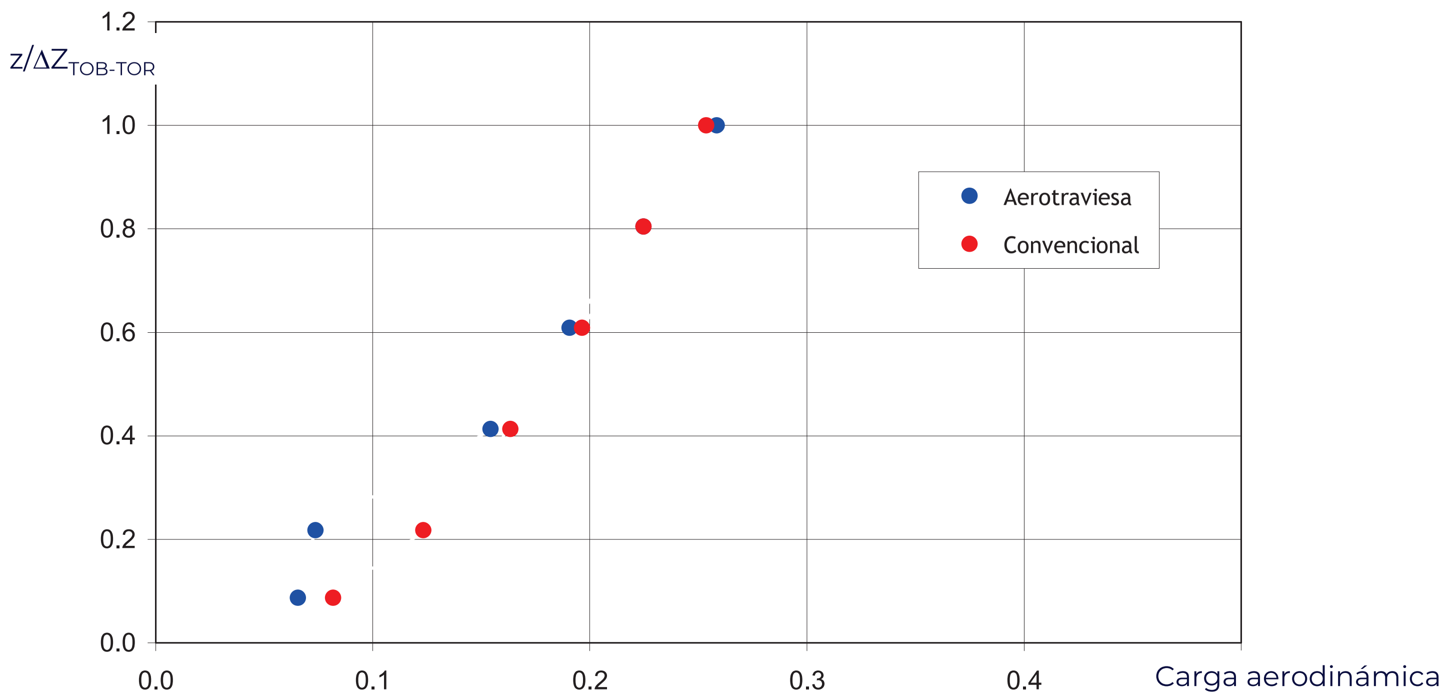
MITIGATION MEASUREMENTS. NOVEL SLEPPER FLOW FIELD



Carga aerodinámica a 0.02 m del lecho de balasto

Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

MITIGATION MEASUREMENTS. NOVEL SLEPPER FLOW FIELD

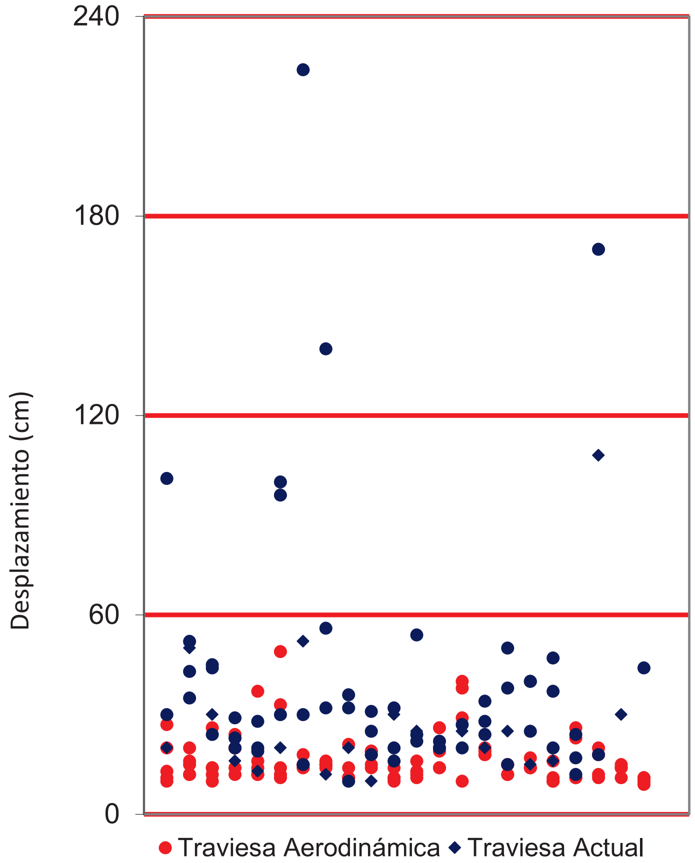


Perfil vertical de carga aerodinámica promediada en el paso del tren

Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

AEROTRAVIESA
Desplazamiento de partículas

Disminución del desplazamiento de las partículas situadas sobre la traviesa



Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

MITIGATION MEASUREMENTS. NOVEL SLEPPER FLOW FIELD

Reduction of Aerodynamic Load:

The aerotraviesa reduces the aerodynamic load on the ballast bed by up to 21%,

Optimized Geometric Design:

Its shape modifies the airflow between sleepers, reducing the velocity gradients on the ballast. Minimization of ballast particle position at the top the sleeper

Increased Operational Speed without Additional Risk:

The design allows trains to operate at higher speeds (up to 370 km/h) with the same aerodynamic impact as conventional sleepers at 330 km/h, thus improving performance without compromising safety.

Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

MITIGATION MEASUREMENTS. NOVEL SLEPPER FLOW FIELD

Aerosleeper in production for the HSL Murcia - Almeria

Línea Alta Velocidad
Murcia - Almería

PROCEDURE TO DETERMINE THE RISK OF BALLAST IMPACT ON HIGH SPEED TRAINS

Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

PROCEDURE TO DETERMINE THE RISK OF BALLAST IMPACT ON HIGH SPEED TRAINS

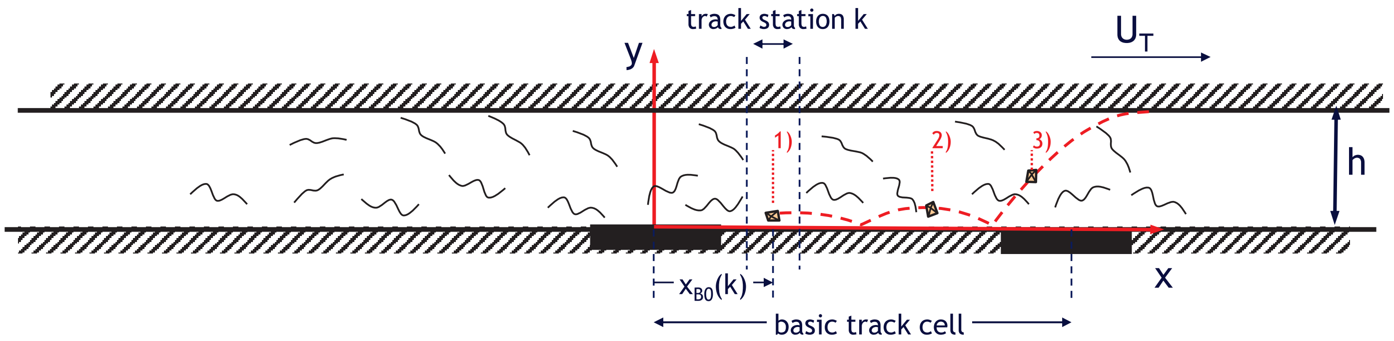
The guideline establishes a procedure to determine the risk of ballast impact on high speed trains. The input needed is the aerodynamic load established near the track surface by the passage of the rolling stock, using a standard defined, plated track. The output is an estimate of the impact risk as a function of the train velocity that would take place in a reference track.

The application of the guideline implies two well defined steps:

- Determination of the surface aerodynamic load created by the high-speed train. The norm describes how to perform this test in a standard, plated track. This determination can be achieved by performing the test with the full scale rolling stock.
- Calculation of the impact risk curve as a function of the train velocity, using a well documented procedure that requires simple algebraic manipulation of the surface aerodynamic load data.

Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

PROCEDURE TO DETERMINE THE RISK OF BALLAST IMPACT ON HIGH SPEED TRAINS



Ballast bed is divided in N_B stations characterized by similar ballast projection risk. Characteristic x-location of ballast bed station “k”: $x_{B0}(k)$. Number of particles per unit length of track in ballast bed station “k”: $n_B(k)$.

For each ballast bed station, the ballast projection event sequence becomes:

1)Induction

2)Ballast bed transport

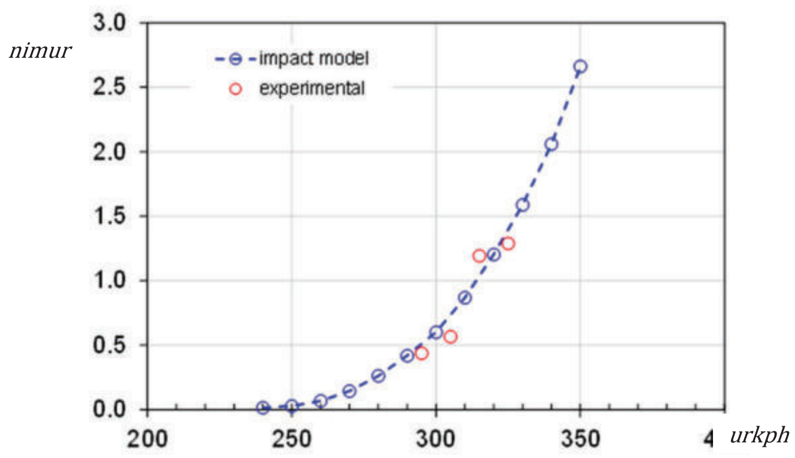
3)Flight and impact

Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

PROCEDURE TO DETERMINE THE RISK OF BALLAST IMPACT ON HIGH SPEED TRAINS

Validation of the ballast impact risk determination procedure

The surface aerodynamic load test and ballast impact risk procedure has been validated against full scale impact data gathered with microphone probes in a dedicated experimental campaign performed using a double composition train.



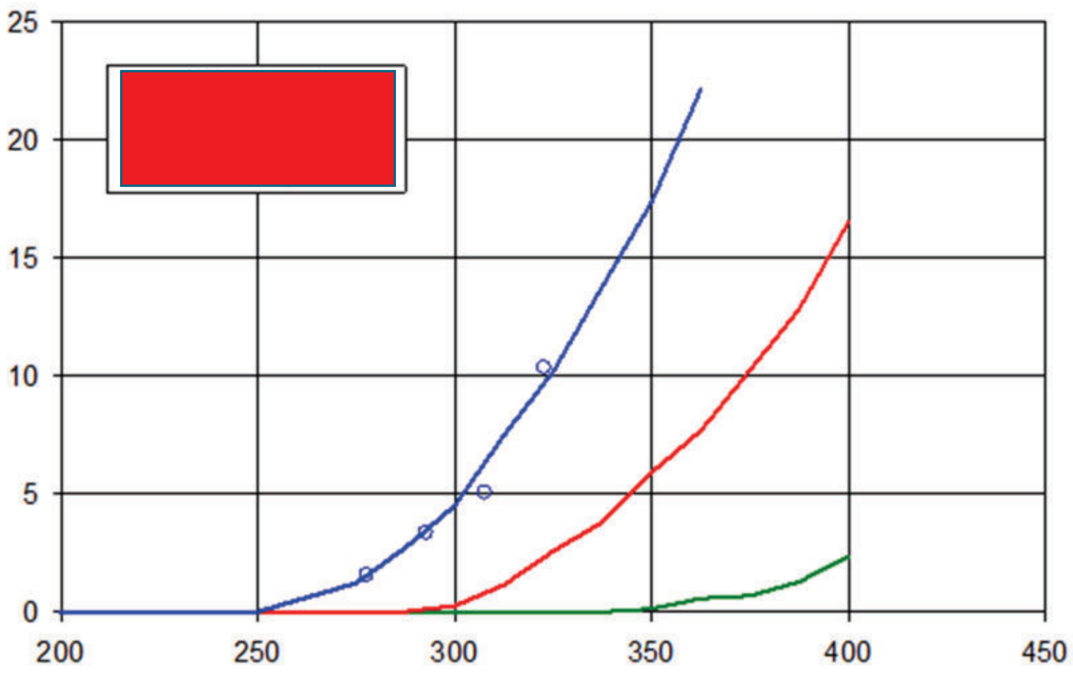
Validation of the impact risk evaluation procedure against full-scale impact data in a double composition train.

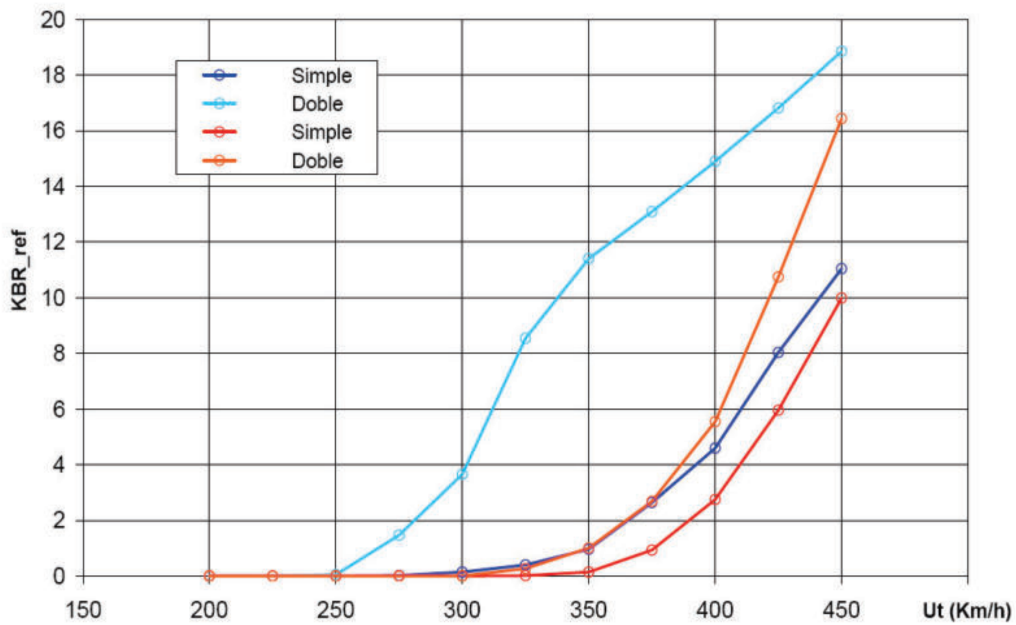
Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

PROCEDURE TO DETERMINE THE RISK OF BALLAST IMPACT ON HIGH SPEED TRAINS

Resultados obtenidos

Modelo de evaluación riesgo de impacto



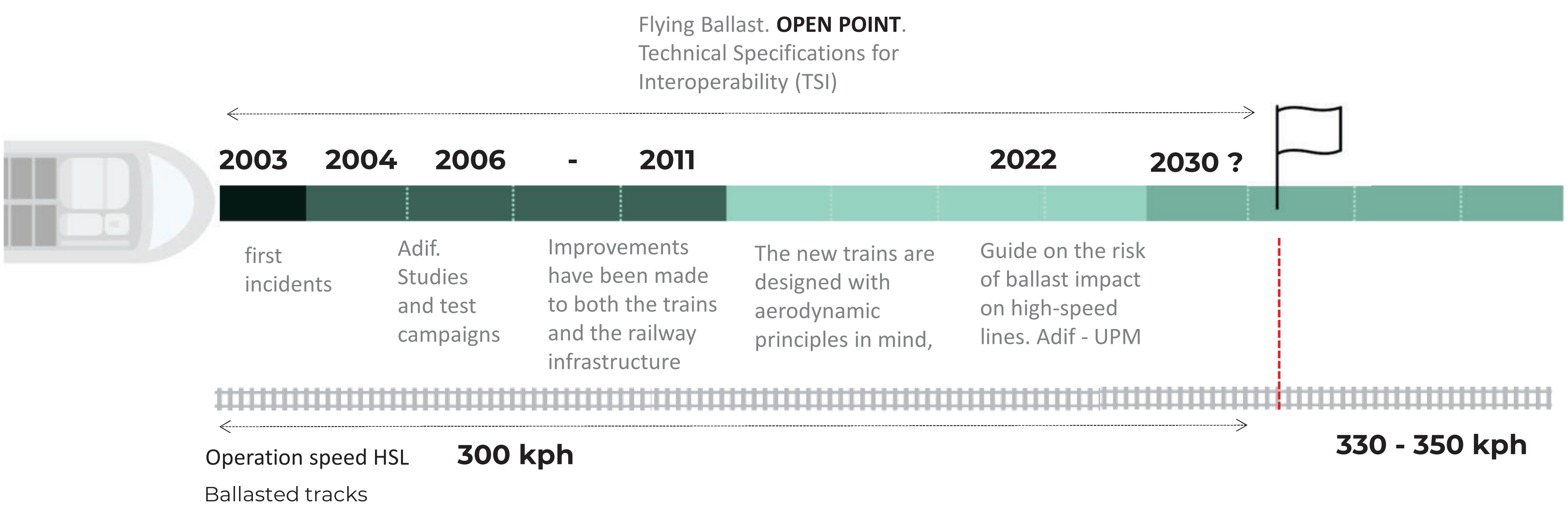


Gráfica con el kbr_ref (riesgo de impacto ponderado con la energía cinética de las piedras y referenciado a un tren en configuración doble circulando a una velocidad de 350 Km/h)

CONCLUSIONS

Flying Ballast in High-Speed Railway: Mechanisms, Risks, and Mitigation

PROCEDURE TO DETERMINE THE RISK OF BALLAST IMPACT ON HIGH SPEED TRAINS



Thank you

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mrodriguez@adif.es