Executive Summary:
The use of linear eddy-current brakes (ECBs) in rolling stock shortens the stopping distance and reduces the dependency of the actual braking capability on the wheel/rail adhesion properties. Other advantages are their no-wearing, no-smell, no fine-dust emission features, the reduction of maintenance cost for friction brakes, their potential independence from the catenary supply that makes them appropriate for emergency applications etc. To date, the general application of ECB in rolling stock gives rise to possible electromagnetic and thermo-mechanical incompatibilities between the braking system and the infrastructure. Firstly, some signalling systems such as axle counters are disturbed by the presence of ECBs. Secondly, the elevated rail head temperatures which introduce extra forces can lead to the buckling of the rail. ECUC (Eddy-Current Brake Compatibility) project's objective is to prove that ECB is a very effective and applicable solution for increasing the braking capacity of new high speed trains and solving the concerns raised by infrastructure managers by proposing concrete and realistic solutions to overcome its drawbacks.

In this manner, ECUC has clarified the interaction of ECB with track and trackside equipment by modelling...
In this manner, ECUC has clarified the interaction of ECB with track and trackside equipment by modelling and measuring critical electromagnetic and thermo-mechanical parameters.

Three EMC cases have been studied: Low frequency magnetic fields (Hz) emitted by the ECB when it is switched on as a DC source that moves as fast as 300 Km/h; the presence of a disconnected ECB passing by a wheel sensor, which can affect its readout by the presence of a metallic mass nearby; and high frequencies (KHz) magnetic fields radiated from the harmonics of the power supply emitted by the ECB when it is switched on. For each case EM simulation models have been developed for Knorr-Bremse´s ECBs and Frauscher´s axle counters. The results have been validated by comparison with extensive testruns of an ICE3 in the high speed line Munich – Nuremberg and in laboratory settings. The evaluation of the measured output signal of the axle counters and wheel sensors shows that, based on the high magnetic field emissions generated by each ECB-pole and the corresponding saturation of the rail, the curves of the output signals differ – in the influencing area of the ECB - from the typical shapes. But all investigated axle counters and wheel sensors work correctly. Furthermore, the testing provides no evidence that there is an interference mechanism from ECB affecting the track circuits beyond what is already known and used for compatibility requirements in TS50238-2 and EN50617 (for new development). Once the simulation models are verified, worst case conditions can be simulated without resorting to expensive testruns.

ECB-based track temperature increments have been obtained through simulation models carried out for UIC60 rail, which have been validated by comparing results with experimental measurements carried out in real situations. Simulation and measurement results show, with good agreement, the expected dependency of rail temperature from the ECB braking force and train frequency (trains per hour). With both models in place, a test setup and a test procedure for ECBs are described. ECUC also proposes a new generation ECB, new designs, engineering and operational guidelines for ECB and signalling equipment, and Project Technical Recommendations for future revisions of Technical Specifications for Interoperability.

Project Context and Objectives:
The project Eddy Current Brake Compatibility (ECUC) aims to prove that linear Eddy Current Brake (ECB) is a highly effective and applicable solution for increasing the braking capacity of new high-speed trains. While shortening the stopping distance, no wearing, no smell and no fine-dust are produced by ECB. Moreover, as it is independent of adhesion between wheel and rail, it leads to an improved safety. Its ability to perform most service brake applications without using the friction brake results in a reduction of maintenance costs. In addition, if the excitation power supply is independent of the catenary supply, ECB is a reliable safety device which can be used for emergency brake applications. Nevertheless, some issues have been detected. On one hand, some signalling systems such as axle counters are disturbed by ECBs. On the other hand, the derived elevated rail head temperatures can lead to the buckling of the rail. In this manner, ECUC has proposed recommendations to overcome these drawbacks and pave the way for future developments.

The following objectives have been achieved in ECUC project:
• Improvement of the understanding of the interaction between the eddy-current brake and the track and trackside signalling equipment.
• Design of a test setup and test site that contribute to the approval tests for ECBs.
• Definition of a test procedure according to representative worst-case conditions.
• Development of new design, engineering and operational guidelines for eddy-current brakes and trackside signalling equipment.
trackside signalling equipment.

- Improvement of the standardisation process of ECB.

The study has been performed in two domains: electromagnetic and thermo-mechanical. In its last stages ECUC has defined project technical recommendations for the correct interoperable functioning of the ECB in a complex railway system and input for revisions to Technical Specifications for Interoperability.

In order to ensure that the research and innovation objectives of ECUC project are achieved, the work program has been divided in five technical work packages and two work packages dedicated to management and dissemination. The results of WP2 contains the definition of the design parameters and requirements of ECB based on the analysis of all the actors involved in this project (ECB, rolling stock, track, trackside equipment). WP3 sets computer models for the interaction between ECB and the track and trackside equipment and describes a new generation ECB. WP4 defines the conditions that maximize the emitted interferences created by the ECB system. WP5 defines the test site, test procedure and test setup for the measurement of the ECB emissions and thermo-mechanical behaviour and carries out extensive testruns on track and laboratory measurements. They also served as validation purposes for the computer models set to predict worst case interoperability impact. WP6 defines the design, engineering and operational guidelines of the operational ECB, its installation, the tracks and the signalling systems.

Furthermore, it provides an input Project Technical Recommendations for the ECB and the infrastructure that is set in WP7.

Project Results:
WP2 Identification of the Performance Requirements, Design Parameters, and their Relationships
T2.1 Systematic collection and analysis of existing information regarding ECB
This task contains the collection and description of previous experiences and know-how of the partners of ECUC project concerning the design, the compatibility with the railway infrastructure and the operation of eddy current brakes (ECB).

DB, KB and SNCF contributed to the collection of existing information regarding problems between ECB and the infrastructure. CEIT reviewed the document. All existing information about ECB was collected. The previous know-how and the experiences of all ECUC partners led to a wide collection of information about ECB and its interaction with signaling systems, track and vehicle.

A common understanding and database concerning ECB has been established and shared between the different members (through the exchange of information between members). For this task, previous experiences and previous research know-how were systematically collected in a common knowledge database. The experience from DB and KB with installed ECBs were the basis of the task. All information was stored in different groups depending on the type of measurements:
- DB collected and analyzed existing information regarding ECB to establish a common knowledge database that describes all referenced problems of ECB.
- EM incompatibilities between ECB and signalling systems
- Temperature measured in the rail head
- Distortion or buckling of the rail
- KB created a collection of previous research activities with a historical overview of different kinds of Eddy Current Brakes, gave background information on calculation methods and test skills and described effective experience of KB with the Eddy Current Brake.

For SNCF this experience was mainly based on tests and also on the trackside experience acquired through the operation on the East HSL.

Each parameter was presented by a short description and, as far as possible, references on further
Each parameter was presented by a short description and - as far as possible - references on further documents with additional and/or more detailed information. Further information is given on the relevance of the parameter for the project.

- Brake force
- Dimensions for construction
- Electrical parameters for power supply, cabling, current flow in coils, max. temperature of coils, capability of coils
- Signalling systems
- Interaction with infrastructure, rail temperature, mechanical stress, mechanical contact, suction of metal parts
- Operating conditions, speed, brake cycle, infrastructure, country dependent conditions, maintenance
- Humidity, earth faults

The collection of actual information about the ECB, the experience of operation and maintenance and the development of signaling systems gave a good base of creation of the heuristic model. The collection of existing essays, reports, device descriptions etc. give an excellent overview about the interaction of the Eddy Current Brake with components of infrastructure (for instance rail, track systems, signalling devices) or components of train (for instance power supply, train control, bogie) and experience in service. Through the collecting of information and existing experience, it was established that hot box detectors (with inhibition systems when ECB is detected in the vicinity) and TVM are not influenced by ECB. Another group such as KVB, Eurobalise and track circuits can be influenced. Finally, axle counters are the most influenced signalling systems by ECB. Measurements of the compatibility of ECB with the aforementioned systems are particularly important since the absence of interference can help to the spreading out of the ECB technology (in Europe for instance with ERTMS). This argument needs to be taken into account. The characteristics of these systems in terms of mounting position and working frequency have been provided to help for the testing steps. Results concerning the interaction with rail temperature have also been gathered, with a specific law for ICE3 trains. This temperature increase has been used to define operational rules for capacity management, depending on the external temperature. Operational rules concerning the type of line used and also the speed range has been provided to describe the real conditions of use of ECB. In the deliverable D2.1 a good basis for the work in work package 3, 4 and 5 was achieved. Based on the collection of information and existing experience it was established that an enhancement of the advantages of ECB is possible based on its compatibility with the infrastructure and an easier implementation in rolling stock.

T2.2 Identification of the performance requirements of the ECB regarding the track, the rolling stock and the signalling systems

In this task a description of the different requirements to be complied with by a linear Eddy Current Brake (ECB) device in terms of functional and operational performances, vehicle integration, infrastructure, operation of trains, maintenance and signalling system influence was made. The relevant Standards were also identified.

- ALSTOM has analyzed the requirements located in the European documents (TSI and EN standards). Moreover, requirements from national organizations have also been analyzed.
Moreover, requirements from national organizations have also been analyzed.

- KB has supported ALSTOM in the standards and effective experience of homologation and operation in different countries. In the process of review, KB continuously reviewed report D2.2.

- DB has identified the performance requirements of the ECB regarding the track, the rolling stock and the signalling systems to establish the requirements of the ECB by means of the analysis of the interaction between ECB and the infrastructure (rail head, signalling systems) and rolling stock. For this all the requirements of the ECB were determined by analysing different factors:

- SNCF has fulfilled requirements from track circuits, ERTMS balises and from ballasted tracks.
- Moreover, the influencing factors on signalling systems with respect to EN 50238 have been analyzed by Frauscher.

- CEIT has analyzed the standards related to signalling systems.
- NRIL contributed to the delivery of Task 2.2 by identifying the procedure to control the critical rail temperature in UK in a dedicated report to the project. This input was incorporated in v.2.3 of the deliverable for task 2.2 and remained there for the final version of the report.

The analysis of force limitation of ECB showed inconsistent requirements between operation of magnetic track brake and ECB.

With this collection of various requirements from different sources (TSI, national rules from many European countries, operator guidelines) the possibility was given for a check of consistency and an overview of the main content of a new standard.

Moreover, the requirements regarding signalling systems have been determined:

- The relevant track circuits to be studied by the project have been listed. In addition, the characteristics of ERTMS balises are provided with the mounting characteristics and susceptibility requirements (for Balise and for Balise Transmission Module).
- Relevant frequency bands with maximum allowable magnetic field amplitudes have been isolated. These limits describe the currently allowable electromagnetic interference which may emitted without endangering the interoperability of locomotives and trackside sensing equipment.

Finally, requirements due to ballast tracks and slab tracks are detailed, with a heating effect on the rail and a cooling behaviour. Extensive design principle for the CWR stability have been given and also deterioration risk mitigation to derive precise requirements for ECB.

The improvement of requirements should respect the different properties (limits of force and rail heating) of balasted and unbalasted tracks and should also consider the long term experience in operation of magnetic track brakes in the European network.

T2.3 Identification of design parameters of ECB

The purpose of this task was to define the design parameters of a linear eddy-current brake system. The ECB as a wheel/rail independent brake system interacts in different ways with other railway systems. The functionalities, electric and mechanical properties of an ECB should be considered in relation to:

- installation into bogie and the train,
- influence on infrastructure and,
- operative aspects in service.

KB analysed the functional, mechanical and electrical aspects of using of an Eddy Current Brake in relationship to different perspectives. The perspectives mean the views of operator, infrastructure manager, car builder and brake system manufacturer. KB created a formal description of the properties of an Eddy Current Brake and the interfaces between the train (power supply, bogie etc.) and the infrastructure (track, signalling devices etc.).
DB identified parameters of ECB to establish the design parameters of ECB regarding their functionality. For instances, the number of poles, the current consumption, the material characteristics and the location in the train among others. This task was developed in parallel with T2.2. The outcome of both of them is the input of T2.4.

The report D2.3 shows the properties of Eddy current Brake in a formal description method independent of a special type of Eddy Current Brake. Also the ranges of typical design characteristics are described. T2.4 Identification of the relationships among the design parameters and the performance requirements.

With this task the qualitative relationship between requirements and design parameters should be described. The ECB as a wheel/rail independent brake system interacts in different ways with other railway systems. The functionalities and the electric and mechanical properties of an ECB should be considered with respect to

- overall design of the train and the integration of the ECB into it
- influence on infrastructure and
- operative aspects in service.

A typical high speed train is investigated. This train is based on the assembly of basic modules consisting of one motor car and one trailer car. The assumed technical data for such a module are oriented on the ICE 3 which is equipped with an ECB. However, the degree of distribution of power over more than one unit depends on the failure effect analysis and shall be considered in the brake calculation. The functionalities and the electrical and mechanical properties of an ECB were considered with respect to overall design of the train and the integration of the ECB into it, the influence on infrastructure and operative aspects in service.

Different studies have been carried out to highlight and quantify the link between design parameters and performance. Results are significant on the braking distance, temperature, braking effort and in ETCS operation.

KB described the qualitative relationship between requirements and design parameters for a typical high speed train while considering different train configurations. For example, in a typical high speed train, KB explained the influence of stopping distance requirements, maximum gradients of high speed lines and thermal limits of friction and Eddy Current Brake.

DB identified the relationships among the design parameters and the performance requirements to establish the qualitative relationship between the causes and the consequences that enables a common and thorough understanding of the physical phenomena and their effects on availability and safety. This task enables the understanding of the relationships between ECB design parameters (outcome of T2.3) and the requirements defined in T2.2.

WP3 Eddy Current Brake Compatibility Model design and Implementation

T3.1 Electromagnetic domain model design and implementation

KB, Frauscher and CEIT participated in this task. KB analysed the different forms (principles) of interaction between the Eddy Current Brake and signalling devices. KB explained the experience with the interaction of ECB and signaling devices. KB placed at the disposal of the consortium the model of three...
interaction of ECB and signalling devices. KB placed at the disposal of the consortium the model of three effects of interaction. The passive effect, the low frequency interaction with strong magnetic stray fields in frequency range from 0 up to 1000 Hz and the medium and high frequency interaction in the frequency range described in EN50238. This analysis provided the background for the decision to divide the forms of interaction in the three main categories. Following this, KB supported the partners in the simulation of the passive and high frequency interaction.

The main part of KB was the simulation of low frequency interaction with a 3D transient FEM model with a new, highly sophisticated, non-commercial software under consideration of different air gaps, speeds of train, variants of current/magnetisation and lateral positions of the Eddy Current Brake. The effort of calculation was significantly higher than expected. The use of a high performance computer with more than 70 clusters was necessary. This simulation was then expanded to wide stray field calculations and to validating by the existing Eddy Current Brake EWB154 R and laboratory stray field measurements. KB documented the results in report D3.1.

Frauscher completed a 3D model of the RSR180 and RSR123 wheel sensors for FEM simulations and verified with experimental measurements. This verification has been completed by Frauscher and both finalised 3D models were shared with CEIT for implementation in the holistic model and further analysis.

Apart from 3D models, spice schematics have also been developed to directly predict the wheel sensor signal. The 3D model is fully parameterized allowing simple integration with larger models. Based on these models, the complete simulation workflow including FEM simulation, extraction of results, import into Spice and analysis of results is operational. This workflow is based on CST, LTSpice and Matlab. The script has been regularly improved and updated. The version control is managed by SVN.

CEIT developed the interaction between ECB and axle counters in the passive case and high frequency emissions of ECB. On one hand, a 3D model of ECB has been implemented and it has been integrated with the model of RSR180 and RSR 123. The complete RSR 180 and RSR 123 electromagnetic models including ECB, wheel sensor, rail and wheel was first of all verified using experimental results from both the laboratory and track tests.

The interaction between axle counters and ECBs is the result of these simulations and they have been compared with the measurement campaigns from WP5 in order to validate them. Apart from ECB and axle counter, the rail has also been included in order to characterize the problem as well as possible. The model of ECB has been characterized by means of all the parts which compose the brake and the effect of each part has also been analyzed. The results contributed directly to several recommendations in D6.6.

On the other hand, CEIT has also analyzed high frequency emissions of ECB. The 3D model of ECB implemented for this task allows to calculate the saturation of the materials due to the effect of ECB. The saturation of materials is also included in the passive effect described before. Moreover, the rolling stock is also considered in this simulations and the measured parasitic capacitances and inductances of ICE3 cabling are implemented in the model. In this manner, a HF transfer function between ECB input current and output radiated emissions are obtained. The results have been compared with the measurement extracted from WP5 with very good agreement.

Task T3.1 (electromagnetic domain model design and implementation), within WP3 in ECUC project, is focused on creating a modelling technique that allows evaluating the Electromagnetic Compatibility of Eddy Currents Brakes (ECBs) and signalling devices. There are three issues related to EMC in this context. Based on the separation in different effects, they themselves could be more easily simulated. Also worst case conditions were easier to identify. The effects and their superposition can be tested in laboratory. A verification of functionality by consideration of worst case conditions is also possible.

Low frequency magnetic fields (Hz) are emitted by the ECB when it is switched on as a DC source that...
Low frequency magnetic fields (Hz) are emitted by the ECB when it is switched on as a DC source that moves as fast as 300 Km/h. This effect induces oscillating stray magnetic fields on the same spot where the signaling device is set. The model allows to anticipate the level of their intensity. There are two other effects for which a common electromagnetic commercial platform (CST Design Studio) has been employed: active high frequency radiation and passive interaction with signalling devices. In the same CST environment, an ECB is modelled starting from its building block definition: a pole. The proper definition of a pole in unsaturated and saturated at DC states will enable to address the aforementioned aspects of ECB EMC. Comparison are made with real laboratory measurements and the way in which input impedance and radiation coming from a pole with frequency variation are very well predicted both for unsaturated and saturated poles in DC.

The first effect modelled by CST is related to the presence of a disconnected ECB traversing a wheel sensor, which can affect its readout by the presence of a metallic mass nearby. This is translated in the so call “fingerprint” of the ECB. That is why Frauscher wheel sensors are also modelled in the same software before being validated and integrated with an ECB to study the interference. This is done gradually by characterizing the interference of a pole core alone as well as from a complete ECB pole (with coils). The typical deviation between simulations and measurements taken in laboratory is up to 4% and allows accurate prediction of the interference depending of the relative position ECB-signalling device (axle counter).

The second effect analyzed by CST is the high frequency (KHz) magnetic fields radiated from the harmonics of the power supply emitted by the ECB when it is switched on. No signalling devices are present here, but the comparison is done in terms of the signal captured by Magnetic Noise Receivers during on track ECUC running tests in October-November 2014. The complex model includes the whole ECB electrical installation, with its corresponding 4 magnets and filters, cables and parasitic capacitances. Due to the intrinsic difficulties to obtain certain parameter values during the measurement campaign, it was necessary to estimate some conditions. For example, this is the case for the lateral displacement of the bogie, the airgap between the ECB and the rail (approximately 5-7 mm and very difficult to determine) and the synchronization of the current signal on board a fast moving train with the output field on a static receiver situated by the track. With these limitations and the knowledge that the model is static while the real event is dynamic, worst case conditions are calculated. They allow higher radiation estimations to be set over real measurements.

Task 3.2 Thermo-mechanical domain model design and implementation

The objective of the thermo-mechanical model in Task 3.2 is to model the heat transfer within the track and estimate the lateral, vertical and longitudinal forces that might appear, with special emphasis in predicting the risk of lateral buckling of tracks.

The following progress has been done:
• A thermal model has been built to predict the temperature increases in the rail, through FEM-based heat transfer analysis. In three steps (pre-processing, FEM calculation and post-processing) it can calculate the temperature distribution in the cross section of the rail and its evolution with time. The input parameters of the model are: velocity of trains, braking force, train configuration (number of ECB-equipped bogies and its distribution in the train), presence/absence or wind cooling the rails, frequency of trains (traffic of trains braking at the same point)
• Knorr-Bremse has supported the task providing as many technical details of ECBs as were necessary to complete the model.
Complete the model

- This model has been validated by comparing the results to experimental measurements conducted in WP5.
- A structural model has been conceptually designed, based on Timoshenko beams. The model is prepared to run in a FEM-solver. Nevertheless, data to correctly model different types of track is missing (ballasted track, type of sleepers, etc). They should be obtained from measurements on the type of track and by adjusting discrete models that represent the behavior.
- The limitation of getting data to complete the structural model limits the usefulness of the structural model to determine whether temperature increases predicted with the thermal model will lead to lateral buckling of tracks. Furthermore, estimation of longitudinal, lateral and vertical forces is not possible at the moment.
- Nevertheless, the risk of not being able to predict the appearance of lateral buckling has been prevented by encouraging a procedure based on the maximum allowable temperature of tracks.
- Literature research has lead to previous work developed by the D202 committee (commissioned by EIRI and UIC) where safety criteria were established for lateral estability of Continuously Welded Rails. Concepts such as maximum critical temperature, allowable temperature of tracks, etc, were defined and were calculated for different type of tracks (taking into account the type of ballast and sleeper and also if they were passenger tracks or freight tracks) (see UIC720 leaflet).
- As infrastructure operators already know which are the allowable temperatures of their tracks, temperature increase estimation due to the use of ECBs is sufficient information to evaluate the risk of track estability and, thus, the objective of the task is reached although forces in the tracks could not be evaluated at the moment.

KB supported the partners with own modelling knowledge of thermal effects in case of rail heating and mechanical loads on the rail head (brake force, attractive force, lateral force). Additionally, important inputs regarding density of eddy currents in the rail head responsible for the rail heating as a result of the 3D transient magnetic field calculations in WP3.1 were given.

One of the aspects that modelling covers is the evaluation of the risk of lateral instability of tracks due to the heating of rails produced by the use of ECBs. Regarding structural stability, the main objective of the modelling effort has been focused in the prediction of temperature increases in rails, evaluating the influence of parameters such as: braking effort and deceleration of trains, frequency of trains run over the track, braking sequences, braking in similar kilometric points (i.e. accumulation of heat depending on traffic), velocity of trains and effect of wind/cooler air acting on the rails.

The thermo-mechanical model developed is a sequentially coupled heat transfer model: a heat transfer analysis is performed first, considering all thermal inputs due to the use of ECB, obtaining temperature fields in a rail section; a structural calculations could be conducted afterwards, having as an input the temperatures already calculated in the rails and other forces that might be relevant. The structural calculation allows determining the stress/strain fields in the rail and whether the track is at risk of lateral buckling due to the temperature increases in the rail. This second structural analysis might be skipped in case infrastructure operators know the allowable temperatures in their particular tracks, which is usually the case.

The heat transfer analysis is a 3D FE model, whose output is the temperature at each element. Conduction across the body, together with convection in the boundaries, due to the presence of cooler air surrounding the rails, is considered. Only a very short length is studied (10mm), thus representing a section of the rail. The thermal analysis considers a previous pre-processing and calculation of time-dependent heat fluxes acting as thermal loads. An excel application has been programmed that automatically gives the desired inputs for the FE model, as a function of train velocity, train configuration, braking forces and number of...
inputs for the FE model, as a function of train velocity, train configuration, braking forces and number of trains per hour.

The structural model is built via Timoshenko beam elements, as they include shear deformation and rotational inertia and are capable of reproducing lateral instabilities in the tracks. Only one rail of the track is studied. Non-linearities in the calculation appear when buckling occurs (high deformations) and they have to be carefully handled via the arc-length controlled method. Connections to the ground (specially representing ballasted track) are the most critical element of the model: the use of non-linear springs in the three directions (vertical, longitudinal and lateral), together with torsional springs is suggested. Validation of the thermal calculation has been conducted by comparing simulation results to measurements on track. Predictions are very satisfactory and match with accuracy measurement results, not only for the first test-run of each night, but also when consecutive test-runs are compared. The only uncertainty of the thermal model concerns the value of the film coefficient or heat transfer coefficient \( h \) that governs the convection process, as indications to estimate the value are very poor. Comparisons to measurements seem to confirm that absence of wind leads to a very low value of \( h \) (about 10 Watts/m\(^2\) K) and the presence of a low speed wind increases slightly that value. Nevertheless, this fact has not sufficiently been studied as to reach definite conclusions and further analysis would be needed.

The technique provides evolution of temperatures with time and along the cross section of the rail. An average temperature is also provided, a unique value that could be added to other contributions and compared to maximum allowable temperatures of particular tracks.

As for structural modelling, connections to ground have presented a higher complexity than expected. In order to obtain accurate results from the model, data of the type of ballast used, type of sleepers, etc, should be needed and experimental results conducted to fit the ballast model. This is a difficult path that most of times is not needed, as infrastructure operators already know which are the maximum allowable temperatures for their types of tracks.

Therefore the main achievements in this context are:

- A FEM-based thermal model has been built and validated to predict temperature increases in the cross-section of rails
- Validation of the model has been conducted, comparing simulations results with those coming from measurements. Temperatures at different points of the cross-section were compared at different braking forces, velocities of trains, etc
- The model allows evaluating temperature evolution with time as a function of the following parameters:
  o Velocity of trains
  o Braking force
  o Configuration of trains (number of ECBS, position in the train, etc)
  o Traffic: frequency of trains passing and braking at the same point
  o Influence of wind cooling the rails, although the worst case of no wind is always suggested
- The detailed simulation conducted leads to many results regarding temperature distribution in the cross-section of the rail and very accurate values of temperatures
- A routine to calculate the average temperature in the cross-section of the rail has been implemented, so that a unique value is obtained. This value is close to the temperature in the middle of the web, the weakest part from lateral resistance point of view
- A structural model is also available from conceptual point of view, that could be use in case the maximum temperature of a specific track was not known. Data from ballast type and presence of sleepers would be needed for the model to be accurate.

In this manner, the calculation of rail heating based on the local effective braking force of ECB is made...
In this manner, the calculation of rail heating based on the local effective braking force of ECB is made possible. The heat propagation leading to an average temperature of the rail could be also calculated. This is the basis of an enhanced operation of ECB for emergency and service brake application.

T3.3 Integration and verification of the different domain models into the ECUC holistic model

The risk of lateral buckling depends on the temperature increases that the use of ECB produces. They have to be seen as a further contribution to the heating of rail, as the rail could already be at temperatures over the stress-free temperature due to atmospheric conditions (sun radiation). It is highly interesting to be able to predict in advance the temperature increases in the rail due to the continuous use of ECBs.

The thermal model developed in task T3.2 allows obtaining the average temperature increases in rails due to the use of ECBs, as a function of train velocity, braking capacity (current ECB and air-gap), train composition and number of trains circulating per hour. Although the model provides temperature field in the section, average temperature seems to be the one that better reflects the possibility of buckling, as it is close to the temperature of the web (the weakest part of the rail concerning lateral stability).

Average temperature increases due to the use of ECBs should be added to other contributions and compared to the maximum allowable temperature of each particular track, a value known by the infrastructure operators and that could be tabulated (as it is in United Kingdom).

A particular track has been selected, with a known train circulation (4 trains per hour). Different scenarios have been simulated, varying the velocity of trains and the braking capacity. It should be noted, nevertheless, that some of the values simulated lead to braking forces above those of full service braking established by TSI.

At the same time, possible interference between ECBs and axle counters can produce false positive readings in the latter. In T3.1 an EM model has been defined to predict worst case interference conditions at high frequencies. By studying the results under same train speed and brake force as in the temperature analysis conclusions can be extracted in a comprehensive way which includes comparisons with the temperature model and highlight the bottle neck for worst case conditions: either temperature or emissions. Given that the corresponding models (thermal and electromagnetic) cannot be run on the same software tool (Abacus and CST respectively), it has been decided to perform the analysis separately under the same operating conditions.

In this task, simulations models were provided by CEIT. The main purpose of Frauscher was to analyse the simulated parameters generated by CEIT for test cases constructed in the model. These parameters were used in conjunction with an LTSpice model and post-processing in Matlab to calculate the wheel sensor currents which could then be used as a direct comparison with track test or laboratory data recorded in WP5. KB supported this task with numerous specific designs and simulation know-how of ECB.

A comprehensive approach to address worst case conditions is addressed. This comprehensive approach includes thermal and electromagnetic analysis for the same case studies. The case studies are described by speed of the train, braking force (current of the power supply to the ECB), air gap, number of trains per hour and train composition. The last two parameters only affect the thermal outcome on the rail. The first three also affect the electromagnetic interaction. High frequency AC radiation will be analyzed from this point of view. By comparing side by side the outcomes, for each case study, the most critical aspect could be selected.

The highest temperature increase is produced at 120km/h, at full braking capacity. A maximum temperature increase of 18°C is predicted, which is close to the maximum allowable temperature of the selected track (+25°C). If atmospheric conditions are such that there is already a rail temperature over the stress-free temperature, the track might be at serious risk of lateral buckling. Braking strategy should limit...
Stress-free temperature, the track might be at serious risk of lateral buckling. Braking strategy should limit the braking capacity as a solution, decreasing it to produce more reasonable temperature increases.

From the emissions point of view, even if a particular measurement can indicate tendencies when speed or braking force independently change, the extraction of the values that the model provide for worst cases does not signal any clear evidence about the change in impact on the axle counter that have been studied (ZP43, RSR 180, RSR 123): worst case conditions remain approximately constant with speed and braking force. However further analysis should be performed to extract more detailed recommendations.

Task 3.4 New generation ECB
Based on the compilation of information, requirements and enhanced properties of ECB, KB developed a concept for a new generation of ECB specifically with the focus on signaling compatibility. Specific design improvements were identified and implemented in concept studies of the mechanical system to reduce the specific mass and for magnetisation with a permanent magnetic system for more independence from the power supply of the train. The concept study on the topic of magnetisation identified the potential of a permanent magnetic Eddy Current Brake and analysed the electromagnetic interaction with the models created in WP3.1. The concept study of the brake mechanics analysed the potential of different designs of Eddy Current Brake frames with consideration of typical load cases and robustness in service.

A greater independence (lower safety requirements, continuous availability, different voltage levels etc.) from a power supply of the train is possible with a permanent magnetic Eddy Current Brake. The concept study on the topic of magnetisation identified the potential of a permanent magnetic Eddy Current Brake. The analysis of simulation results showed that small changes of one design parameter have a big influence on the functionality of Eddy Current Brake. In consequence, KB put significantly more effort into concept design and simulation to then also minimize the cost of manufacturing the prototypes and testing to reduce the development risk towards WP5.

The concept of a modularized structure of an ECB showed that an easier implementation of an ECB in different types of bogie is then possible. A reduction of the specific mass (ratio mass to performance) of the ECB was achieved. The expected magnetic stray fields were calculated by the usage of a new method of FEM modelling and solving. Also the improvement of lower electromagnetic interaction could be shown by 2 examples.

The localisation/position and the type of power supply plays an important role for easier integration of an ECB in rolling stock.

The first prototype for laboratory tests has been one of the main outcomes of this task for initial validation tests. The concept study on magnetization is in the phase of validation of significant parameters.

WP4: Definition of Representative Worst Case Conditions
Task 4.1: ECB operational conditions: definition of the worst case conditions regarding operational conditions of ECB
Investigations have been performed for the airgap measurement through the partnership with AEF (Agence d’Essais Ferroviaire). Realistic representative worst case conditions have been established, and they are the inputs for the requirements for the test site, test procedure and test setup, which is developed and executed in WP5.

The worst cases regarding operation result from the
- Operation cycle
- Environment
Regarding maintenance the worst case is if the air gap is not proper adjusted. KB supported with own experience of service, calculations and steps of improvement for ECBs. Based on the analysis of the functional, mechanical and electrical aspects of using an Eddy Current Brake, worst cases were simulated and described: one part in relation to the collection of loads for a test procedure of a fatigue test considering worst case conditions and others in relation to the infrastructure – split into track and EMC - and rolling stock –split into power supply and bogie interface - from the point of view of operational conditions of ECB.

Once of the main outcomes of this WP is the conclusion of avoiding ballasted tracks for tests. The identified worst cases led to a well-adapted test program. The collection of worst case condition builds an important basis of requirements, especially for calculation of safety margins and the verification by laboratory tests. They are very useful for the validation of functionality under nominal operation conditions.

Task 4.2 Signalling systems: definition of the worst case conditions for signalling systems.

The outcomes of this task are based on knowledge of known worst case situations and a thorough understanding of all possible situations by means of the information gleaned in WP2 as well as models and simulation results from WP3.

The worst cases for signalling systems are divided in the tree different cases:
- Influenced systems (axle counters, wheel sensors, speed detection)
- Non influenced systems
- Possibly influenced systems

A number of factors depend on ECB operating conditions and can significantly influence axle counters. This may include emitted magnetic fields within the working frequency range of the axle counter in question and also high intensity, low frequency fields which cause local magnetic saturation of the rail or ferromagnetic components of the axle counter. These effects may operate independently or together to corrupt the axle counter signal.

NRIL contributed to the definitions of the worst case scenarios signalling systems (T4.2) by identifying a potential issue with respect the malfunction of track circuits using insulated rail joints under activated ECB.

KB supported with own experience of service, calculations and steps of development of ECB for lower interferences with signaling devices.

A number of worst case situations could be identified:

High magnetic fields within the working frequency range of axle counters generated by:
- Noise present in the ECB power supply system
- Effects due to parasitic resonances of cabling or the bogie environment, e.g. ECB mounting position and separation
- High transient currents with significant duration
- Short distance between ECB and axle counter

Very high, low frequency magnetic fields which lead to saturation or change of the magnetic characteristics of the rail or components within the axle counter by:
- High operation current of ECB
- Short distance between ECB and axle counter

The additional interaction is relevant to large parts of the European infrastructure, so if resolved, it will help...
The additional interaction is relevant to large parts of the European infrastructure, so if resolved, it will help the roll-out of the new technology.

The collection of worst case conditions of interferences with signaling devices build an important basis for requirements and their verification by laboratory tests. They are very useful for the validation of functionality under nominal operation conditions and led to a well adapted test program.

Task 4.3 Rail head: definition of the worst case conditions for rail head

For the infrastructure worst cases regarding
- Track, Rail heating
- Forces on track/rail
- Gauge
- EMC
- Management of rail temperature
Have to be considered

For the worst cases regarding rail head it has to be considered:

- Modelled Conditions (Track temperature limits, Max. brake power / trainset, Succession of trains, Speed limit, material of rail, weather conditions)
- Track limitations (ballasted or non ballasted)
- Test requirements

A battery of simulations with the temperature model developed in Task 3.2 have been conducted in order to identify the parameters that are mainly affecting the temperature increase in the rails. Based on the report of design parameters of the Eddy current Brake, the maximum loads of brake and attractive forces which interact with the track were simulated and described. Based on the the analysis of the density of Eddy currents in the rail and the physical process of conversion from brake force into heat, worst case conditions of rail heating needed to be defined. It has been established that the worst case conditions are those at which braking forces are the highest and for intense traffic. Cooling of the rails is an important factor affecting the temperature increases in the rails: if the heat transfer coefficient is high (high speed wind) and time between trains is also high, the rails will cool and temperature increases will be very well under expected limits. Nevertheless, it is unlikely that high speed winds act on the rails as other aspects of stability of the vehicles would be affected, and, thus, the scenario of no wind/very low speed wind should always be adopted. Only the ambient temperature (cooler than that of the rails) affects the evacuation of heat. NRIL contributed to the definition of the worst case scenario for track by providing a report on how to best measure rail stress. In addition, NRIL provided the Operation’s guide to Verse – a non destructive method of SFT measurements. NRIL’s feedback as an infrastructure manager were taken into account and helped the project’s presentation of the model outputs in a more user friendly manner. NRIL was responsible for the report under T4.3 which captured all of the above. KB supported with the results of magnetic field calculation, especially the density of current in the rail and the magnetic saturation of railhead.

The identification of the main parameters for a precise model of thermal calculation of rail and the relevance of longitudinal stress of rail have been set.

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Relevance of longitudinal stress of rail have been set.

The identified worst cases led to a well adapted test program, see WP 5.
- Increasing braking force has a direct impact in the temperature increment that the rail will suffer. The braking force is also a function of speed of the train, following a curve that presents maximum braking forces at velocities around 120km/h. Therefore the maximum temperature increments occur at a velocity of 120km/h and decreases slightly till 300km/h.

- The second more influencing parameter in the temperature increments is the frequency of trains. As expected, if the frequency of trains is increased, the temperature of the rails also increases as time for cooling the rail decreases. Nevertheless it is not a linear relationship: the temperature increases very rapidly when the time interval between trains is less than 10 minutes (more than 6 trains per hour)

The air acting on the rail for cooling also influences the final temperature. If the speed of the wind is very low or still air is considered, the heat transfer coefficient adopts a small value (15 Watts/m2K, according to literature); if high speed air is to be considered, the heat transfer coefficient is an order of magnitude higher (100 Watts/m2K). Differences in temperature increases for different braking forces and traffic estimations are significant. Nevertheless, from the worst case point of view, the case of low speed wind/still air should be considered. Furthermore, it is very unlikely to find high speed winds acting on high-speed railway rails, as it could also affect the vehicle and its dynamic behaviour (circulation on track); tracks are almost always insulated against the action of winds.

NRIL steered the partners towards working together to resolve the outstanding concern regarding IRJs.

Task 4.4 Rolling stock: definition of the worst case conditions for rolling stock

The main objective of this task was to define the worst case conditions produced by an ECB regarding rolling stock. The definition of worst case conditions for rolling stock considered operational conditions and interactions with the infrastructure.

The worst cases of train/ECB result from the
- Speed
- Power supply/consumption
- Thermal limits
- Mechanical forces
- Consideration of the design of bogie and the brake control system.

Based on the output of the previous tasks (mainly tasks 2) a document was proposed by DB integrating all the conditions leading to the possible worst cases. This part has been reviewed by Alstom to complete this analysis from a system integrator’s point of view.

Based on the analysis of the functional, mechanical and electrical aspects of using of an Eddy Current Brake, worst cases were simulated and described.

The output of this tasks are keys for the definition of the engineering guidelines that are the inputs of the tasks of WP 6.

Based on the definition of worst case conditions a safety margin can be defined.

WP5: Test Site, Test procedure and Test Setup Design and Implementation

Task 5.1: Laboratory tests. Definition and implementation of the test site, test procedure and test setup for...
Task 5.1: Laboratory tests. Definition and implementation of the test site, test procedure and test setup for the performance of the ECB; realization of the tests.

KB supported the partners in preparing and carrying out laboratory tests. KB split the tests in electromagnetic and mechanical tests.

Based on the collection of information from WP2, WP3 and WP4 it was possible to create test procedures to identify proper function or malfunction of signalling device or subsystems of ECB.

For realization of the test procedures test sites were developed for electromagnetic and mechanical verification tests.

KB, CEIT and Frauscher have already participated in the signalling laboratory tests to validate simulation results with parts of existing types of Eddy Current Brakes and also the new generation of Eddy Current Brake.

Moreover KB, CEIT and Frauscher defined the description of laboratory tests for various signalling devices. The laboratory tests started with the existing ZP43 test bench on which the RSR123 and RSR180 were included in order to test the interaction between ECB and these types of axle counters. An important goal was the validation of simulation results of the EM model of the ECB developed in WP3. In order to do this, transfer functions from several ECB poles were measured in various configurations and compared with the simulated fields generated in the model. During active braking, the high magnetic fields cause saturation of parts of the ECB itself and the effect this has on the emitted radiation was also investigated.

Additionally, the reduction of interference between signalling devices and the magnet body of the existing Eddy Current Brake as well as the new Eddy Current Brake (passive effect) was measured. Based on the learnings, variants of prototypes of shield parts were designed and procured. By laboratory tests a systematic step by step optimization was carried out. The results of these laboratory tests showed a reduction of interference – passive interaction – by the full metal cover of the new Eddy Current Brake. And this reduction was shown to be applicable for both groups of wheel sensors and wheel flange sensors.

Additionally, a reduction of interferences (passive effect) was proven between the coils and wheel sensors. Another effect evaluated was the low frequency interaction with signaling devices. In laboratory the magnetic stray field density around the ECB was measured with different levels of magnetization. It was verified that by the simulation model developed it is possible to calculate the maximum of magnetic stray field depending on the speed and position of ECB in reference to the rail.

Based on the results of WP3.4 a concept prototype for a possible next generation Eddy Current Brake was developed and tested in laboratory. The ECB frame of this next generation of ECB is signed by modularization of main parts. For example, the new ECB magnet is built as a self-sustained body modularised by the main part of Integral-beam, angled screw couplings and an integrated support beam. Apart from the tests with signalling devices, KB defined the description of mechanical fatigue tests.

The significant achievements in this task have been:
- Impedance measurements of individual poles of the ECB
- The transfer function of single and multiple poles of the ECB have been determined in order to validate simulations
- The passive effect of current ECB types have been recorded for RSR180 and RSR123
- The passive effect of several shielding designs of a new ECB type has been measured
- The verification of FEM calculation of low-frequency magnetic fields was finished with a good correlation.

The possibility to carry out worst case conditions tests in laboratory was proven.

For EM test, three interactions are tested: passive (disconnected) ECB in the presence of a signalling device that could be detected as a false wheel, low frequency interference (Hz) due to a DC source on the
Device that could be detected as a false wheel, low frequency interference (Hz) due to a DC source on the move, and high frequency interference (KHz) due to harmonics coming from the power supply.

For the passive case, the analysed axle counters can be divided in 2 groups. RSR180 and RSR123 by Frauscher have the magnetic stray field at one side of the rail. They exhibit these common features:

- There is no observable difference between ECB 154 R L4 and ECB 154 R L5
- Changing the value of the impedance loads of a ECB has no effect on interference.
- The ground connection to the ECB magnet is irrelevant.
- The greatest interference appeals in the position of maximum negative latera displacement and the minimum of air gap.

ZP-43 is an example for the other group of sensors that have a magnetic stray field around the rail. In this case:

- The maximum of interference appears in the central position of rail of the ECB magnet.
- The impedance load has an important influence of the level of interference. The design of EWB L5 gives a higher immunity against changes of impedance loads and a greater secure signal-noise ratio.

The new ECB configuration 1-2-3-4 shows with all 3 types of analysed axle counters the lowest level of interference. A common consequence to all ECB is that it is possible to add massive metal bodies surrounding the ECBs to protect signalling devices against disturbing interferences.

For the low frequency interference the worst case conditions of maximum magnetic stray field density are divided in two areas below top of the rail or above top of rail. Based on the magnetic flux density it is possible to define a threshold in frequency range from static up to 500 Hz.

For the high frequency measurements, some conclusions can be extracted:

- The resonant frequencies of poles with iron core are lower than without iron core.
- The resonant frequencies of poles type /L4 (45.0 kHz) are lower than type /L5 (56.5 KHz).
- The peaks for maximum resistance (6 KΩ) and reactance (3 KΩ) are lower than their no-core counterparts by a factor of 6.
- The saturation of the core appears to have little effect on the magnetic stray field intensity from 10 KHz to 1 MHz. A small increase in field intensity with increasing saturation is perceptible and is typically < 2 dB.

As a consequence a threshold could be independent from brake force of ECB and could be verified easier. Fatigue test and attraction force characterization is also described. Based on test of components the concept of new ECB with a self-sustained magnet beam is feasible. As an overall conclusion, defined test sites, test set ups and test procedures can be the starting point to be considered by standardization bodies.

Task 5.2: Track Tests. Definition and implementation of the test site, test procedure and test setup for the performance of the ECB; realization of the tests

In this task the design, planning and implementation of the track tests have been completed. Numerous test runs with a modified ICE 3 train (equipped with different types of eddy current brakes) have been carried out on the high speed line Nuremberg-Ingolstadt. Measurements have been realized for different operation conditions of the ECB (e.g. current flow through the ECB, air gap between ECB and rail head) and the train (e.g. running speed). The train was instrumented by DB with 16 channels for measuring ECBs currents and voltages during normal operation. CEIT collaborated by corroborating that modelling and measurement were set in consistent ways. CEIT also measured parasitic capacitances of ICE3 train, an important piece to be embedded in the model for ulterior comparison.

On infrastructure side the magnetic field emissions of the ECB/train, the output signals of numerous axle
On infrastructure side the magnetic field emissions of the ECB/train, the output signals of numerous axle counters and wheel sensors mounted at the test track, the rail voltage of track circuits (isolated joints), the rail temperature and the rail stress as well as the influence on the LZB and PZB (national train control systems) were measured. DB and Frauscher mounted and recorded data for several different types of wheel sensors on both sides of the rail to measure the influence of the ECB on the specific sensor type. Additionally, Frauscher Magnetic Noise Receivers (MNR) were placed at typical mounting positions of wheel sensors, as defined in CLC/TS 50238-3, to record high frequency magnetic fields between 10 kHz and 1.3 MHz. The data was then collated, analysed and used in conjunction with measurements from D5.1 to test and verify the models and simulations and for the assessment of the influence of eddy current brakes on the infrastructure.

In this period of the project KB participated in design, planning, implementation and carrying out of running tests. In preparation of the running tests KB built 10 magnets of the electrically powered ECB Type EWB 154/L6 and 4 prototype magnet bodies of the new generation of ECB. Together with DB, KB equipped the test train with the ECB-magnets. These new generation magnets were only tested with respect to their passive effects. All magnets underwent a signalling series test with the signalling devices ZP43 and RSR123.

KB supported the partners by analysis of the measurements of rail temperature and the value of EMC. For instance the relation between the real test conditions for magnetisation and the effective brake force was a very important factor in the rail heating analysis.

Huge amount of data was postprocessed by DB, Frauscher and CEIT in order to set the right conditions for comparison with the model outcomes.

The significant achievements during the track tests are:
- The successful coordination and implementation of all test runs
- Wheel sensor data and MNR data collected and analysed
- Recorded data series dependent only on one variable, e.g. speed.
- The validation of the performance under nominal conditions could be finished. This showed that the design and simulation by FEM can be used as part of an easier and shorter process from the start of the development to the approval for EMC.

The evaluation of the output signal of the axle counters and wheel sensors shows that, based on the high magnetic field emissions generated by each ECB-pole and the corresponding saturation of the rail, the curves of the output signals differ – in the influencing area of the ECB - from the typical shapes. But for all that the investigated axle counters and wheel sensors work correct.

Single axle counters and wheel sensors (mainly working within band 1 of the frequency management defined in the interface document of the TSI CCS) show significant higher frequent influences. These influences correlate very well with distinctive magnetic field emissions occur within the frequency bands of the disturbed axle counters (magnetic field emissions near or partly - only for one axle counter type - above the limit levels defined in CLC/TS 50238-3). In the frequency range from 100 kHz up to 1.3 MHz the magnetic field emissions are far below the defined limit levels.

Changes in main parameters as e.g. ECB current or running speed seems to have no significant influence on the magnetic field emission of the ECB in the observed frequency range (in the frequency rang up to 100 kHz a slightly higher emission could be deviated at a ECB current of 50%).

Based on the very good correlation of the results of the magnetic field measurements with the evaluated axle counter output signals (higher frequency influences in the area of the working frequencies of the single axle counters) the assessment of the compatibility of a vehicle equipped with ECB with axle counters in future may can be done by:
WP6: Technical Recommendations and Design, Engineering and Operational Guidelines
Task 6.1: Development of the design, engineering and operational guidelines for eddy-current brakes

Based on the heuristic model and the collection of requirements including the worst case conditions an engineering guideline for ECB was created. A common way of description of the interfaces and the requirements was defined. The interfaces were defined to also respect the interaction between rolling stock and infrastructure. As a consequence of the high number of load cases, dependence on functional requirements, different worst case conditions and their combinations, the common requirements were based on nominal values. The overloads were defined to be considered by means of a safety margin. The value of the safety margin should be defined by both parties of the interface. In relation to the safety procedure, all requirements are described by a test case for verification and validation.

The analysis of interactions of signalling devices by the heuristic model of the three general effects (passive interaction, low-frequency and medium- and high-frequency) and their superposition gives the opportunity to complete and optimize the standards of EMC for signalling devices. Furthermore it allows to create thresholds for the design of the ECB itself.

The engineering guideline is oriented towards the structure of EN16207 for magnetic track brakes. The deliverable D6.1 contains requirements, for design, power supply, monitoring and diagnostics, performance and EMC and the description of interfaces of train and infrastructure. Type test and serial test procedures were explained for verification and validation in this document. Significant recommendations are:

- The design and definitions of interfaces should be carried out based on nominal values.
- The definitions of the forces of interfaces should respect tolerances of 15%.
- Worst Case conditions should be measured in laboratory as far as possible. Running tests should be applied to evaluate the functionality only at nominal conditions.
- Present evaluations by manufacturers of signaling devices should be prospectively integrated in European Standards and prospectively could build EMC requirements of design of ECB.
- From the other perspective: requirements resulting from the operation of an ECB (e.g. high magnetic fields in the lower frequency range) should be defined for the design of signaling equipment (e.g. axle counter).
- Expansion of the operational area for using ECB as service brake on ballasted tracks with simple temperature management.
- The national infrastructure registers should include information about ECB compatible tracks (signalling devices, type of track and additionally allowed increase of temperature by track brakes, track equipment)

The engineering guideline is oriented towards the structure of EN16207 for magnetic track brakes.
Task 6.2: Development of the design, engineering and operational guidelines for the installation of ECB in the vehicle

All the available information collected during the project has been compiled. Additional information has been provided by DB and KB.

It has been demonstrated that ECB Eddy current brake cannot be considered as a simple product which is easily installable in a train. In fact it is a complete system both at local vehicle level as it requires the combination of the ECB specific parts working together with traditional brake control and the traction systems, but at train level.

Design, engineering and operational guidelines have been developed that could support the implementation of such sophisticated system in trains designs different from ICE3. These guidelines are set to support the designer work for reminding the critical steps to be studied that involve the interfaces and the design of the main sub systems of the train: Overall system, traction, braking, TCMS 5 train control and monitoring system, and mechanical (bogie) design.

So far the only existing installation of Eddy Current brake systems has been made on the ICE3 trains of Deutsch Bahn. In order to investigate the compatibility issue of the ECB system, it has been felt that guidelines should be proposed to help the train designer teams to tackle the installation on other trains.

Eddy current brake cannot be considered as a product which is easily installable in a train. In fact it is a complete system both at local vehicle level as it requires the combination of the ECB specific parts working together with traditional brake control and the traction systems, but at train level, and especially when it is intended to use the ECB for service brake, a very sophisticated blending between the different available brakes (electro-dynamic brake, friction brake and eddy current brake) has to be implemented. Therefore it is, in fact, required the complete train brake system to become an eddy current brake system.

The availability of the eddy current brake is a key issue. Obviously this is first due to the availability of the ECB itself that could be impacted due to any failure (even with the best proven design, this can always happen in such a sophisticated system). But there are other reasons that could lead to prevent the use of the ECB:

- restriction due to the track capability to the ECB use,
- restriction due to potential overheating of the rails (due to ECB effect added to a high ambient temperature) that could create a risk of buckling of the track
- too much use leading to overheating of the device,

To cope for all these conditions (some of them being operating rules) the train brake management has to manage the blending between the different brakes to ensure the train braking capability. The dimensioning of the other brakes has to take into consideration additional duties in case of ECB unavailability. The transmission, in a reliable/safe way, of this train braking capability to the signalling (ETCS) system has to be ensured as well.

The proposed guidelines propose ideas to build to corresponding blending strategies.

Other guidelines in this task are described for approaching the physical interfaces with the other train subsystems, and working on the monitoring and diagnosis issues.

An easier implementation of ECB is a key issue in future.

Task 6.3: Development of the design, engineering and operational guidelines for signalling systems

Measurement data from the laboratory and track tests along with results from the ECBs and wheel sensors that have been modelled and simulated have been fused to generate a number of recommendations and guidelines. The interactions studied are specific to the ECBs and wheel sensors within the project and are...
guidelines. The interactions studied are specific to the ECBs and wheel sensors within the project and therefore specific to the technologies used. It is therefore difficult to make general extrapolations which are valid for all wheel sensors and ECBs on the market using other technologies. Recommendations have been made regarding magnetic field emissions at frequencies greater than 10 kHz with regard to both braking force and speed based on worst case scenarios. These recommendations focus on methods to reduce the interaction and influence of ECBs on wheel sensors. In addition, low frequency magnetic fields have been found to cause saturation of both rail and any ferromagnetic components found in the wheels sensors and hence there are recommendations advising against the use of such materials and also extended testing methods for wheel sensors. The link between original DB requirements for axle counters on routes which allowed the use of ECB and design change towards the use of non-ferrite coils is set.

A general overview of the emissions from the Eddy Current Brakes (ECBs) that potentially affect axle counter performance is shown. The transfer function between the AC current (harmonics) in the ECB circuit and the corresponding magnetic field intensity by the trackside is demonstrated to be virtually independent from the level of the magnetic saturation of the tracks and pole cores due to higher braking DC currents. Broadly speaking, the trend in the AC current amplitude is followed by the emissions regardless DC levels. It is observed that the level of emission is reduced with frequency. Therefore axle counters that should be compatible with ECBs are recommended to operate in the higher frequency band (300 KHz to 1.3 MHz). Dependency of emissions on braking force and speed are analyzed. The action of increasing brake current translates in higher emissions in the 100 KHz- 250 KHz band. Axle counters are recommended to be tested at maximum braking force that is applicable to the ECB, if they are to operate within this band. In similar terms, axle counters are recommended to be tested at 120 km/h and 160 Km/h if they operate within this band. Otherwise, the test conditions in braking force and speed are not relevant. Worst case lateral displacement of the ECB over the axle counter (-17.5 mm) introduces an estimated 5 dB increase of emissions when compared with common close to nominal lateral displacements. These results obtained by the model are set as reference in order to address the task of reducing them by ECB design (D6.5). A post-processing according to CLC/TS 50238-3 of the worst case leads to the following main conclusions:

• Broadband emissions with ECBs are always exceeded.
• The number of values exceeding the limit neither depends on the speed nor the braking force for the considered axle counters (out of 100 KHz-250 KHz band).
• Within the narrowband analysis, the axle counters allocated in the lower band (10 - 100 KHz) are found to be prone to exceeding the limits. The emissions limits for the higher band axle counters (100 KHz- 1.3 MHz) are not exceeded.
• Three groups of axle counters can be differentiated:
  o Those whose limits are not exceeded by the presence of ECBs (higher band)
  o Those whose limits are highly probable of being exceeded (lower band: ZP 30, ZP 43, ELS 93, ELS 95) ranging from 27 to 48 KHz.
  o Those whose limits are probably of being exceeded (Lower band, D39 X-component, WDD39 X-component, D50 X-component)

If the limits are exceeded, it does not necessarily follow that ECBs and axle counters cannot jointly operate. The aforementioned standard does not refer to ECB emissions and internal electronics of axle counters which filter unwanted signals in current designs. Conversely, phenomenon may occur in which limits are not exceeded but joint operation is not guaranteed (e.g. RSR 180).

In relation to axle counter design, magnetic parts in the internal setting of the systems are not recommended for compatibility with ECBs as they are saturated when the ECB is active and passing over...
recommended for compatibility with ECBs as they are saturated when the ECB is active and passing over the axle counter. An example of RSR 180 by Frauscher is shown. A distinction between ground dependant wheel sensors and wheel flange detection axle counters is made as the compatibility with ECBs strongly depends on this matter. In any case, compatible axle counters should be immune to an estimated 150 mT magnetic flux density \( B \) in the region where they are going to be installed.

The testing provides no evidence that there is an interference mechanism from ECB affecting the track circuits beyond what is already known and used for compatibility requirements in TS50238-2 and EN50617 (for new development).

Task 6.4: Development of the design, engineering and operational guidelines for tracks

Concerning track lateral stability, a collection of simulation results (temperature increase results) are provided, as a function of braking force and frequency of trains (time interval between consecutive trains braking at the same point). Those values are to be used as a guideline to define the braking strategy of ECB equipped trains from track safety point of view, especially to prevent lateral buckling.

Allowable temperature is defined as the temperature of rail which provides a margin of safety against a predicted likelihood of track buckling. It is a value already known by track operators for each particular track, dependent on its lateral resistance (type of ballast, sleeper, etc). All contributions to heat the rail above the stress-free temperature (the temperature at which there are no thermal stresses in the rail) increase temperature of rail, a temperature that has to be compared to the allowable temperature in order to be safe against lateral buckling of rails. These contributions have different origin: sun radiation (climatic conditions); maintenance of rails; and, of course, the use of Eddy Current Brakes. Rails are usually installed at their stress-free temperature, so that no initial compressive stresses are present. The procedure to define the use of ECBs proposes, firstly, to consider all temperature increases in rails due to other conditions but ECBs. Temperature increase due to the use of ECBs could not be over the gap left by the allowable temperature and the temperature of the rail after the rest of contributions are considered. Temperature increments obtained here are to be used to establish the braking strategy according to the temperature gap described above. They are function of braking force (of whole train) and frequency of trains (traffic). On one hand, for a desired particular traffic situation the limit in the braking force of ECBs could be estimated. On the other hand, the frequency of trains could be determined for a desired particular braking force of ECBs.

Other braking systems have not been included in the study and, therefore, the temperature increases are considered as if the train only had a braking system based on ECBs. That is, temperature increases reported here do not take into account the influence of other braking systems applied in the train. They should be considered apart from ECB braking system and their influence in temperature increase calculated separately and considered as an extra temperature increase of the rail (as climatic conditions would be). Significant achievements are:

- A procedure has been suggested to evaluate the risk of lateral buckling. The procedure suggests to substract from the allowable temperature of a particular track temperature increases due to other contributions, not ECB (such as temperature increments due to climatic conditions, maintenance works, other braking systems, etc). The value obtained would be the gap that ECBs could fullfill; that is, the maximum temperature increased allowed due to the use of ECBs.

- Temperature increments as a function of braking force and frequency of trains have been calculated form the model. These results, given in tabular and graphical form, are useful information for infrastructure operators in order to define braking strategies of ECB-equipped bogie.

In this way, lateral stability of tracks will be guaranteed.
In this way, lateral stability of tracks will be guaranteed. Several easy formulae are also provided in order to interpolate/extrapolate the results to values not in the tables.

Braking strategies should be adopted according to these results:

- If allowable temperature is overtaken either the braking force or the frequency of trains should be reduced.
- For a desired frequency of trains, braking force should accordingly be reduced, although train operators should be that another braking system should be incorporated.
- For a desired braking force, the number of trains per hour allowed to brake using ECBs should be reduced, in order to give more time to the rail to evacuate the heat and cool.

Task 6.5: Development of the Technical Recommendation regarding ECB new requirements and the test procedure of ECB in the vehicle.

Based on deliverable D6.1 type and serial test procedures were extracted. The recommendations were separated in a way that is relevant to the TSI and to EN-standards. Furthermore, once worst case ECB emissions were estimated in D6.3 the present task presents ways to reduce the emissions by ECB design. Computations for the emissions in the new hypothetical cases are carried out with the aid of the model defined in D3.1 and improved in D6.3. They are compared with the worst case defined in D6.3. Just the study of a new filtering procedure of the output of the power supply and the ECB-circuit comprises 8 proposals.

In relation to the safety procedure all requirements were described by a test case for verification and validation. The type test and the series test procedures, that allow to verify several requirements in the laboratory, were described.

Also the technical recommendations related to signalling devices contain detailed proposals to supplement the Standards of EN50238, CLS/TS50238-3 and EN50617-2.

The analysis of all deliverables provided the valuable input for the modification and supplementation of TSI requirements and for the filling in of open points in the TSI.

Additional aspects were described which expand the opportunity for operation of ECB on conventional lines with ballasted tracks and equipped with ETCS.

The recommendations and the test procedures were oriented towards the structure of EN16207 for magnetic track brakes.

ECB general recommendations are presented below:

- The design and definitions of interfaces should be carried out based on nominal values.
- The definitions of interfaces should respect tolerances of 15%.
- The functionality at nominal conditions should be evaluated and worst case conditions should be measured in laboratory.
- Present evaluations by manufactures of signaling devices should be prospectively integrated in European Standards and could help define EMC requirements in ECB design.
- In the future the standardization group should determine an optimized geometry and position of measurement antenna for low frequency magnetic fields.
- The content of this engineering guideline is oriented towards the structure of EN16207 for magnetic track brakes.

It is also observed that the following techniques can be applied to reduce emissions:

- Improvement of the filter strategy, either by redistributing current filtering on critical points or by adding extra coils (e.g. like the ones corresponding to the actual magnet).
- Extending the cable length that goes from the traction container to the first magnet at each side by e.g. 4...
Extending the cable length that goes from the traction container to the first magnet at each side by, e.g. 4 times.
- Decreasing the parasitic capacitance of the first pair of poles of the first magnet connected to the traction container (e.g. by decreasing the height of the poles).
- Feeding in parallel the aforementioned pair of poles.
- Shielding them by a metallic sheet.

Estimates of the reduction in emissions are presented in each case. For the most significant techniques, computations of the new estimative limits according to CLC/TS 50238-3 are added and the number of times in which limits are exceeded is compared to the previous worst case. Not all proposals are currently practical when addressing implementation, but they set a trend and several guidelines for future developments.

Enhanced recommendations for TSI, CLC/TS50238-3, prEN50592 and prEN50617 part 1 and part 2 are also included in this task.

Task 6.6: Development of Project Technical Recommendations for Interoperability for the rest of the systems disturbed by ECB.

It was the aim of the ECUC project to gain an extensive knowledge on the interaction of the ECB with the infrastructure and the physical effects behind and to deviate – based on this knowledge and understanding – inputs for the design and the use of ECB as well as for components installed at infrastructure side and to define first requirements for an interoperable authorisation of vehicles equipped with an ECB.

Therefore within the ECUC project numerous simulations and measurements - in the laboratory, on the train and on the tracks - have been carried out. The measurement results could successfully be used for the validation of the realized simulation models and for the assessment of the influence of eddy current brakes on the infrastructure.

One significant point is the influence of the ECB on track side installed signalling systems like axle counters and wheel sensors. In the frequency range from 100 kHz up to 1.3 MHz the magnetic field emissions are far below the defined limit levels. Single axle counters and wheel sensors (mainly working within band 1 (27 kHz – 52 kHz) of the frequency management defined in the interface document of the TSI CCS) show higher frequent influences (noise). These influences correlate very well with distinctive magnetic field emissions occur within the frequency bands of the disturbed axle counters (magnetic field emissions near or partly - only for one axle counter type - above the limit levels defined in CLC/TS 50238-3 [3]).

Changes in main parameters as e.g. ECB current or running speed does not have a very significant influence on the magnetic field emission of the ECB in the observed frequency ranges.

The evaluation of the output signal of the axle counters and wheel sensors shows that, based on the high magnetic field emissions generated by each ECB-pole and the corresponding saturation of the rail, the curves of the output signals differ – in the influencing area of the ECB - from the typical shapes. But all investigated axle counters and wheel sensors work correctly.

It is observed that the level of emissions is reduced with frequency. For ECB compatibility it could therefore be easier for axle counters to operate at higher frequencies as e.g. above 300 kHz. It was also shown in D6.3 and D5.4 that CLC/TS 50238-3 limits are prone to be exceeded in the lower band axle counters (10 KHz – 100 KHz). However, if the limits are not complied with, it does not necessarily follows that, in these cases, ECBs and axle counters cannot jointly operate as the aforementioned standard does not refer to ECB emissions and internal electronics of axle counters filters undesired signals in current designs. The converse phenomenon (limits fulfilled but incompatibility in practise) also occurs in cases that
designs. The converse phenomenon (limits fulfilled but incompatibility in practise) also occurs in cases that are already known (e.g. RSR 180). Therefore internal technology of axle counters is a factor that should be taken into consideration along with limits study, since the latter as a stand-alone criterion is insufficient to define compatibility.

Dependency of emissions on braking force and speed were also analyzed in D6.3. The action of increasing brake current translates in higher emissions in the 100 kHz- 250 kHz band. Axle counters are recommended to be tested at maximum braking force that is applicable to the ECB, if they are to operate within this band. Additionally, axle counters are recommended to be tested at 120 km/h and 160 Km/h if they operate within this band. Otherwise, the test conditions in braking force and speed are not relevant. Based on the very good correlation of the results of the magnetic field emissions with the evaluated axle counter output signals (higher frequency influences in the area of the working frequencies of the single axle counters, lower frequency influences generated by ECB-poles) the assessment of the compatibility of a vehicle equipped with ECB with axle counters in future can be done by:

a) measurement and evaluation of the low-frequency magnetic field emissions, generated by the very high DC magnetic field of each of the single ECB-pole with the running train;

For the evaluation limit levels, the maximum low frequency magnetic field emission have to be defined by axle counter manufacturers, considering the saturation effect of the rail. The fixed limit levels should be included in the EN 50617-2 (specification of axle counters) as well as in a future comparable standard for the (type) specification of ECB (leading to maximum allowed emission of ECB).

b) measurement and evaluation of the middle/higher frequency magnetic field emissions according the frequency management defined in the TSI CCS interface document respectively the future standard prEN 50592 and – for single axle counter types - in the CLC/TS 50238-3 [3] or national rules (e.g. in Germany Regelung EMV 05).

c) measurement and evaluation of the passive effect primary at laboratory in combination with a magnetic field source, generating magnetic fields (frequency sweep) within the working frequency ranges of axle counters (ranges as defined in the frequency management of the TSI CCS [4]) and the full installation of the ECB power supply system; For the evaluation limit levels for the damping of the ECB housing and the resonant coupling (e.g. Q-factor) between the field source (axle counter) and e.g. the coils of the ECB (including their parasitic capacitances) have to be defined by axle counter and ECB manufacturers. These limit levels should be included in a future standard for (type) specification of ECB (see also a).

The definition of the influence of the rail saturation on the interaction with axle counters and wheel sensors as well as the definitions on the passive effect may be the major standardization work which has to be done.

Also in this document, insights into the main factors that influence Eddy Current Brakes (ECBs) EM interaction with axle counters are defined. In D6.3 it was shown that the level of magnetic saturation of the rail due to higher levels of DC current of the ECB does not significantly affect the level of emissions in AC up to 1.3 MHz. The influence of the input DC current of the ECB (and therefore its braking force) is reflected in the level of saturation of the rail by decreasing its relative permeability. As the axle counter is calibrated to a relative permeability corresponding to the unsaturated state, the decreasing of this parameter is the main EMC issue. An estimate of the levels of rail saturation is done by two means in this document:

- By calculating the minimum incremental relative permeability of the rail and ECB pole core when high levels of DC currents are introduced in the ECB in a magnetostatic computation.
- By adjusting the relative permeability of the rail and pole core when comparing the output of RSR 123.
By adjusting the relative permeability of the rail and pole core when comparing the output of RSR 123 axle counter readouts in running test when the ECB was active. Both cases indicate that a relative permeability of 1 (100% saturation) of the rail and pole cores are representatives of worst case conditions for maximum input DC current. The extra damping of the aforementioned axle counter that could lead to a misreading is calculated as 6% from the unsaturated value and given as a coefficient (Saturation Interference Coefficient SIC). This value is representative of saturation when performing passive unsaturated measurements in the laboratory. Even if the value of 6% is only applicable to RSR 123, the general concept can be extrapolated to any axle counter. Based on computation, a non-magnetic material, such as aluminium, is recommended to be used as test-bench material for the rail in axle counter fingerprints measurements in the laboratory in active ECB state (magnetic saturation). The higher conductivity of aluminium when compared to rail steel compensates the effect of employing unsaturated pole cores in the experiment when mimicking saturated tests for RSR 123. Instead of using an aluminium solid block for the rail, a thin foil of approximately 0.2 mm thickness could be used due to the reduced penetration of the field into the rail at the axle counter operation frequencies. The recommendations given in this paragraph have not been experimentally demonstrated but there is enough evidence to support the improvement of the ECB-axle counter test benches over these lines.

A critical aspect concerning Continuously Welded Rails (CWR) safety is the temperature to which tracks are subjected. According to UIC720 the stress-free temperature (Tn) is the temperature at which there are no thermal stresses in the rails. When the rail temperature rises from the stress-free temperature high compressive stresses will occur. As the CWR (continuously welded rail) is not allowed to expand in the longitudinal direction, any irregularity in the track, a small lateral force, etc., may trigger the lateral buckling. The use of Eddy-current brakes raises rail temperature further, a rail already heated due to ambient temperature and sunlight radiation. Lateral stability of the track can be seriously affected and the probability of buckling and derailment increases.

ECB-based temperature increments reported in this document have been obtained through simulations carried out with a thermal model of a UIC60 rail, which has been validated by comparing results with experimental measurements carried out in real situations. Simulation and measurement results show the expected dependency of rail temperature from the ECB braking force and train frequency (trains per hour). While for a braking force of 45 kN and a train frequency of 10 trains/hour the rail temperature increases between 7.6 and 8.4 °C, the temperature rises between 30.2 and 33.5 °C by a braking force of 180 kN and the same number of trains per hour.

Relating on the rail temperature considerations have been made to allow - for a line section – the use of an ECB with different braking force levels, depending on the environmental temperature and the knowledge of the application of the ECB by previous trains in this line section.

Potential Impact:
Socio Economic Impact
The goal of ECUC project was, among others, to address concerns raised by infrastructure managers regarding the interoperability between linear eddy current brakes and the infrastructure. The recommendations presented pave the way for approved acceptance of this brake type by highlighting an understanding of the origin of these concerns and by proposing methods for infrastructure manager, brake manufacturer and wheel sensor manufacturer to overcome, or at least diminish, their effects. The first economic impact is based on the infrastructure capacity, which can be a consequence of the spread of the ECB’s use: the capacity of railway infrastructure is directly linked to the braking performances of the rolling stock which allows to shorten the stopping sequences and therefore to bring
performances of the rolling stock which allows to shorten the stopping sequences and therefore to bring
the trains closer. One advantage of a ECB magnet system is to have its performance decoupled from the
wheel/rail adhesion. Difficult conditions (humidity, leaf deposition...) reduce travelling speeds of trains
which culminate in delays. These instances could be greatly reduced by ECB usage. As a consequence,
track efficiency and train punctuality for paying customers will be highly improved. Therefore, ECB brings
braking performances over the level allowed by wheel contact braking systems.
The enhanced operation of ECB as a service brake on conventional tracks and ballasted high speed lines
can help to reduce the effort of maintenance for conventional friction-based systems. In this manner, there
are also benefits regarding the rolling stock operation because the ECB magnet system is wearless and
costs due to friction pads are very high in the whole life of a train.
The extension of the usage of ECUs that ECUC results promote will translate into higher quality standards
of travelling by train: the fact that the ECB generates no noise, no dust and no smell in operation will
enhance the quality of experience of the passenger.
Another advantage is to have a high constant brake power for a wide range of speeds, including an
additional braking force at both high speeds and during emergency braking. Again, safety is increased
while travelling at higher speeds. The high brake performance of ECB allows to accept higher gradients in
new lines, which in turn would reduce high costs of infrastructure. The advantages of increased safety,
reduced travel times and trains arriving at their destinations punctually would increase the popularity of
travelling by rail thereby increasing passenger numbers. Shorter travel time and reduced costs are key
issues for improvement of rail mobility.
The insights and knowledge gained from ECUC project will be implemented in the development of new
generations of ECUs and wheel sensors immune to ECUs thereby securing jobs within Europe and the rail
sector. Once these sensors have an established position within the market, ECUs can be broadly
introduced to the infrastructure therefore strengthening the position of ECB manufacturers and once again
securing jobs in their region. At the same time, providing information about rail temperature increase due
to ECB performance will help infrastructure managers to set a comprehensive strategy for the definition of
ECB-compatible lines.
An easier recycling of the product at the end of its lifetime based on the concept of modularisation of the
new generation ECB is another advantage. Hence the ECB fulfils the aspects of a “green” product to a
high degree. Business opportunities are open up by paving the way for future ECB developments,
contributing to European leadership in the railway sector.

The Wider Societal Implication of the Project
If introducing ECUs into more railway sectors increases the number of passengers travelling, then there is
not just a direct impact on the manufacturers of both ECUs and compliant signalling systems to supply
these systems, but also on the railway operator, railway stations and an indirect impact on services and
transport systems to and from railway stations.
Furthermore, potentially introducing a new all electric rolling stock brakes will make the railway transport
system more affordable as additional systems to overcome poor adhesion are ruled as unnecessary.
Besides, the decision for developing very high speed railway projects (those whose speed can reach more
than 300 km/h) remains at high political level. The balance to be hit is the combination of the overall growth
of European activity that is achieved and the required investment on a better transportation capacities in
large territories, which should overcome interoperability issues. ECUC results are geared to pave the way
of the interoperability between a high end brake system at one end, and signalling devices and
infrastructure at the other.
List of Websites:
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