Part 1: SAFETRAIN Project Results and Rail Passive Safety Harmonisation

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A methodology for improved passive safety, which includes the specification, design, testing and validation procedures for crashworthy rail vehicles has been developed within the EU project SAFETRAIN. This presentation does not result from an individual work but it summarises the output of the research done by the whole Consortium. It gives the final conclusions of the SAFETRAIN project and the recommendations made for the specification and validation of crashworthy rail vehicle designs. SAFETRAIN was selected by the Panel Presidents of the Descartes Prize to go forward for the final examination of the Descartes Grand Jury on 26th November.

1. COLLISION SCENARIOS

Two types of scenario were considered:

- **The reference collision scenarios:** scenarios identified within the UIC/ERRI B205.1 accident analysis, statistic analysis and risk assessment report as representative for collision accidents in Europe.
- **The design collision scenarios:** scenarios of collision accidents characterised for crashworthy design requirement purposes.

2. METHODOLOGY FOR DEVELOPMENT OF PASSIVE SAFETY IN RAILWAYS

The SAFETRAIN project used the reference collision scenarios from the study carried out in the B205.1 ERRI working group reflecting the accident situation in Europe during the period 1991-1995. The study was general to Europe involving a wide range of train operations and train configurations. As a result of this study and taking into account practicable energy absorption limits for the trains considered within the SAFETRAIN project and economic constraints it was decided to adopt the following three design collision scenarios:

- **Scenario 1:** Collision between identical trains at 55km/h.
- **Scenario 2:** Collision of a train with an 80 ton buffered vehicle at 36 km/h.
- **Scenario 3:** Collision of a train with a road vehicle (simulated by a 16.5 ton rigid block) at level crossings at 100 km/h.

Scenario 1 was chosen since head-on collisions between trains result in the highest number of serious injuries.

Scenario 2 was chosen to represent current classical trains prone to overriding and buffer-stop collisions.

Scenario 3 was chosen because it is less likely that this type of accident could be fully prevented through active safety.

These design collision scenarios were considered to cover a wide range of:
• Train operations e.g. high speed, intercity, mainline and regional trains.
• Train configurations e.g. loco hauled, motor coach trains and multiple units.

The design requirements for crashworthiness have been developed in the project SAFETRAIN to enable trains to withstand the collision conditions as identified in the selected design collision scenarios and to avoid occurrence of aggravating factors, such as overriding and derailment resulting from collisions.

The design requirements were validated by means of specific methods, combining tests and numerical simulations.

**Recommendations for development of passive safety:**
A three-step approach should be used in the development of passive safety:

a) Definition of design collision scenarios. This may require a review and statistical analysis of past accidents to determine likely future accidents and/or carrying out a risk analysis to support the definition of appropriate design collision scenarios.

b) Development of design requirements for structural crashworthiness and vehicle interior solutions to enable trains to withstand the design collision scenarios identified in step a) and effectively reduce the severity of occupant injuries (drivers and passengers) to acceptable levels.

c) Validation of the design requirements.

For a new crashworthy train design, a suitable risk assessment should be undertaken to determine appropriate reference collision scenarios.

The risk assessment should consider parameters such as:

• Active safety systems.
• Type of traffic.
• Operating speed.
• Brake system requirements.
• Level crossings.
• Level of prevention of track obstruction.

In the absence of suitable accident data, the following scenarios can be considered adequate for design purposes for general mixed traffic lines carrying a wide variety of train types:

1. Head-on collision between two identical trains (symmetric collision).
2. Collision at buffer stop or with a buffered vehicle.
3. Collision with a road vehicle at level crossing.
3. DESIGN METHODOLOGY

SAFETRAIN identified that two of the principal causes of occupant injuries in train accidents are loss of survival space through crushing and secondary impacts. The objective of any improved crashworthy requirements therefore is to minimise injuries due to these two causes. The avoidance of aggravating factors, such as overriding and derailment, should also be targeted.

3.1. First Design Objective: Minimisation of Loss of Survival Space

Loss of survival space is a major cause of casualties in accidents. Therefore, the first objective of passive safety is to protect occupants from space reduction, hence avoiding significant plastic deformations or structural crushing of the carbody in the driver and passenger’s areas.

The term deformation needs to be clearly defined. Within SAFETRAIN, three types of deformation have been considered:

- **elastic deformation**, below the material’s yield point, recoverable, not damaging the structure.
- **plastic deformation**, permanent but small, usually associated with local buckling of components.
- **crushing**, corresponding to large deformations and involving severe reduction of volume.

**Recommendations for minimisation of loss of survival space:**

Minimising loss of survival space is best achieved by:

a) Ensuring that crushing does not occur in areas occupied by passengers or crew for the design collision scenarios. For collisions at speeds above the design collision scenario speed, crushing of occupied areas of the train should be minimised.

b) Fitting appropriate anti-climbing devices.

4.1.1 Train energy management

Of all the trains types considered, SAFETRAIN identified a 129 ton three car multiple unit (see Task 2 summary) as having difficult energy management requirements for the identified scenarios.

From the lumped mass models results it was concluded that:

- Scenario 1 generated 2.3 MJ to be absorbed at the train front end and 1.4 MJ at the inter-trailer zone.
- Scenario 3 generated 4.6 MJ to be absorbed at the front end and 0.6 MJ at the inter-trailer.

These energies were derived from 1-D lumped mass models in which each vehicle was simulated using a single mass and was constrained to a 5g maximum acceleration level.

These characteristics were then taken forward to the detailed vehicle design.
Recommendations concerning train energy management:

Based on:

- the design scenarios,
- the train characteristics (masses, number of vehicles, number of bogies, coupler types and characteristics, etc.),
- the vehicles’ extremities characteristics (crushing length, space available) and
- the safety objectives (crushing length of the unoccupied designated areas and acceleration levels),

lumped mass models should be used to provide the crashworthy characteristics of the extremities and of the vehicle structure. Parameters to be specified or considered for lumped mass models are:

- Masses of vehicles
- Coupler type
- Available crushing length
- Maximum force levels
- Force-Displacement characteristics
- Energy distribution along the train set
- Acceleration level

4.1.2 Vehicle design

In SAFETRAIN two different types of energy-absorption structural arrangements were identified and designed to meet the design collision scenarios.

The following crashworthiness design requirements were specified:

- **High energy (HE) extremities at the train front.**
  - Specified progressive force-displacement crushing characteristics with a total energy absorption of 4.6MJ
  - Progressive deformation from the impact point to the rear of extremities with a maximum stroke of 1.8 m.
  - Energy absorbing coupler, shear-off mechanism and coupler trap, this to avoid falling to the track and risk of derailment.
  - Obstacle deflector.
  - Anticlimbing devices, geometrically compatible with classical buffer arrangements, withstanding 150 kN vertical forces and allowing engagement with a 100 mm vertical offset.
  - The 0.75 m survival space for the driver was achieved by a sliding driver’s desk and seat.

- **Low energy (LE) extremities at inter-trailer**
  - Specified progressive force-displacement crushing characteristics with a total energy absorption of 1.4 MJ.
— Progressive deformation from the impact point to the rear of extremities with a maximum stroke of 660 mm.
— Energy absorbing coupler, shear-off mechanism and coupler trap, this to avoid falling to the track and risk of derailment
— Engagement of the anti-climbers as soon as possible taking into account minimum track curvature.

The design of modern vehicle energy absorbing structures relies heavily on numerical solutions. Throughout the design process carried out within the SAFETRAIN project, many important lessons were learned and recommendations for validation of design, using such numerical simulations, are provided in Annex C (Recommendations for finite element analysis).

**Recommendations for vehicle design:**

Specific recommendations for individual designs cannot be made, however, the following should apply to all train vehicles:

- Deformation must be controlled in order to absorb the maximum energy, be progressive and occur only in the designated collapse zones
- A minimum of 0.75 m driver’s survival space must be maintained. The emergency egress should be maintained after collision.
- Detachment of structural pieces or equipment should be avoided to limit risk of derailments
- During the crush process, peak forces will usually exist. Forces lasting less than 5 ms can be considered non-significant.
- It is clear that the occupant’s area of the carbody must keep its integrity during the full crush process, even in the presence of significant peak-forces - integrity being understood as the absence of significant plastic deformations and general buckling of carbody occupant’s areas. Local plastic deformation and local buckling will be accepted if it is demonstrated that they are sufficiently limited, so as not to significantly reduce the passenger and driver space.
- Anti-climbing devices shall be fitted; coupler must allow the anti-climbers to engage as soon as possible during the crash. Anti-climbing devices must resist a vertical force of 150 kN, must be designed to function with a vertical offset of 100mm between impacting vehicles, must be designed taking into account the compatibility with other rail vehicles (buffered vehicles, vehicles fitted with coupler, …)
- Obstacle deflector: must not disturb the crushing scenario, must be placed as much in front the driver’s cabin as possible.
- Where appropriate and for reasons of compatibility, the current UIC static proof loads’ requirements must not be violated by any specified crashworthiness requirements.
4.2 Second Design Objective: Minimisation Of Severity Of Occupant Injuries Resulting From Secondary Impacts

In the SAFETRAIN project several vehicles and cabs throughout Europe were reviewed in order to determine current best practices. Additionally, means of specifying requirements for vehicle’s interior crashworthiness were investigated.

Current practices within other transport industries is to specify a longitudinal acceleration pulse which characterises the occupant acceleration environment during a collision. SAFETRAIN used the same approach to specify an appropriate acceleration pulse for train collisions. This pulse was derived from a number of instrumented train collision tests and also took into account the collision scenarios developed within SAFETRAIN.

Recommendations for minimisation of severity of occupant injuries:
1. For the purpose of determining passenger secondary impact injuries when contacting interior fixtures and fittings, a longitudinal acceleration pulse is defined which should lie within the upper and lower limits shown below. The vehicle speed change associated with the pulse should be 30 km/h.

2. For cab occupants, the collision pulse is dependent on the design of crushable structure and no acceleration pulse is recommended.

3. During the secondary collision the passengers and cab occupants will impact their surroundings when subject to the acceleration pulse. Where appropriate, the severity of the impact can be measured either by test or mathematical modelling. Under such conditions, the following injury criteria should not be exceeded.
Head  
A HIC of 500  
A 80g peak resultant head acceleration for no more than 3ms

Neck  
A peak flexion bending moment of 190 Nm  
A peak extension bending moment of 57 Nm  
An axial compressive force not exceeding 1100N for more than 30ms  
An axial tensile force not exceeding 2900 N for more than 35ms  
A fore/aft shear force not exceeding 1100 N for more than 45ms

Thorax  
A peak thorax compression of 50 mm – fore/aft direction  
A peak viscous compression (V*C) of 1.0 m/s – fore/aft direction

Legs  
A femur compression force not exceeding 7.58 kN  
A peak tibia compression force of 8 kN  
A peak tibia index of 1.0 at either end of the tibia  
A peak knee sliding joint displacement of 15 mm

5 VALIDATION METHODS

One of the most important issues in demonstrating vehicle crashworthy design is validation of the design.

SAFETRAIN has shown that combining numerical simulation and tests is the most suitable method, at present, for the evaluation of the vehicle crashworthiness.

Budget limitations have not allowed the SAFETRAIN project to carry out the validation of a complete vehicle. Nevertheless, the tools used in the SAFETRAIN project are to be used also for the full carbody validation.

Within the SAFETRAIN project, quasi-static and dynamic tests were carried out as part of the validation process. Dynamic tests of individual components and sub-assemblies were also undertaken and the results were used to calibrate the original model. Quasi-static and dynamic test results exhibit a good agreement with the numerical simulations and provide evidence that the proposed recommendations are acceptable and justified.

Consequently, within SAFETRAIN a carefully selected sequence of numerical simulations and static and dynamic tests was implemented to validate the designs. The full applicability of this sequence depends on the innovation, newness and complexity of the crashworthy design.

Recommendations for validation of carbody crashworthy designs

The following method (followed and proved within SAFETRAIN) is recommended for new designs:
<table>
<thead>
<tr>
<th>Step 1</th>
<th>Components’ dynamic tests. Components are tested and validated separately.</th>
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<tbody>
<tr>
<td>Step 2</td>
<td>Simulation of the component tests and calibration of the numerical model, It is recommended to simulate the component tests and to calibrate the subassembly models.</td>
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<tr>
<td>Step 3</td>
<td>Simulation of the extremity full scale test (at least energy absorption component and the driver cabin) Numerical simulation is to be carried out before the test to prepare it and to evaluate the robustness of the model</td>
</tr>
<tr>
<td>Step 4</td>
<td>Dynamic or quasi-static full scale test of the extremity Measurements carried out during the tests must allow the numerical models to be calibrated. <strong>Remark:</strong> As the test conditions are not representative of the design collision scenarios, complementary simulations have to be carried out to finalise the design validation.</td>
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<tr>
<td>Step 5</td>
<td>Calibration of the numerical models and simulation of the test using the test results.</td>
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In **Step 5, only the vehicle extremities are validated.** The complete vehicle structure behaviour has to be evaluated to demonstrate that the safety level required is achieved (eg. no significant plastic deformation in the passengers area). It must be proved that the **vehicle carbody is able to withstand** the loads generated by the collision design scenarios and transmitted during the crushing of the extremities.

SAFETRAIN would recommend carrying out the following steps in order to complete the validation of a crashworthy vehicle:

<table>
<thead>
<tr>
<th>Step 6</th>
<th>Modelling of the carbody shell of the vehicle</th>
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<tr>
<td>Step 7</td>
<td>Simulation of one of the proof tests of the carbody shell of the vehicle (underframe proof load test, vertical load, coupling test, …)</td>
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<td>Step 8</td>
<td>Calibration of the finite element model of the vehicle carbody</td>
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<td>Step 9</td>
<td>As a final step the simulations of the design scenarios may be carried out</td>
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In cases where the design of crashworthy vehicle is very similar to one previously tested and the corresponding numerical model calibrated, numerical simulation can be used as a validation method in lieu of testing.

The experimental tests and numerical simulation tasks should be carried out by experienced users using certified software and recognised facilities.

With respect to the relative merits of quasi-static and dynamic testing, each method has its advantages and disadvantages and the validation method to be adopted in the individual cases should be determined according to cost, design method, design materials, design novelty, amount of energy absorption specified, etc.

Recommendations for the minimum requirements for each testing and numerical simulation methods were also given in Safetrain.
Safetrain - 4.6 MJ Front Cabin - Quasi-static crush test vs. modeling
Safetrain – 4.6 MJ Front Cabin – Dynamic crash test (red) vs. modeling (blue)