CHAPTER 1

Technical consolidation report on all validation results (Executive summary and Chapter 1)

Written by

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PROJECT CO-ORDINATOR

Dynamics, Structures & Systems International

D2S BE

Société des Transports Intercommunaux de Bruxelles

STIB BE

Alstom Transport Systems

ALSTOM FR

Bremen Strassenbahn AG

BSAG DE

Composite Damping Materials

CDM BE

Die Ingenieurswerkstatt

DI DE

Institut für Agrar- und Stadttökologische Projekte an der Humboldt Universität zu Berlin

ASP DE

Tecnologia e Investigacion Ferriaria

INECO-TIFSA ES

Institut National de Recherche sur les Transports & leur Sécurité

INRETS FR

Institut National des Sciences Appliquées de Lyon

INSA-CNRS FR

Ferrocarriles Andaluces

FA-DGT ES

Alfa Products & Technologies

APT BE

Autre Porte Technique Global

GLOBAL PH

Politecnico di Milano

POLIMI IT

Régie Autonome des Transports Parisiens

RATP FR

Studiengesellschaft für Unterdirdische Verkehrsanlagen

STUVA DE

Stellenbosch University

SU ZA

Ferrocarril Metropolita de Barcelona

TMB ES

Transport Technology Consult Karlsruhe

TTK DE

Université Catholique de Louvain

UCL BE

Universiteit Hasselt

UHASSELT BE

International Association of Public Transport

UITP BE

Union of European Railway Industries

UNIFE BE

Verkehrsbetriebe Karlsruhe

VBK DE

Fritsch Chiari & Partner

FCP AT

Metro de Madrid

MDM ES

Frateur de Pourcq

FDP BE
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0. EXECUTIVE SUMMARY

Urban Track is a so-called “Integrated Project”, that is a large scale Research and Development project (18 Million €) partially funded by the European Commission (~50%), gathering 38 partners, which has been developed from September 2006 to September 2010 as part of the Sixth Framework Program of the European Union, under priority 1.6 “Sustainable Surface Transport” (Project nºFP6-031312).

This four-year research project aimed at developing, testing and validating a series of innovative products that can be categorised in three classes:

- innovative new products and solutions: prefabricated track modules, green tram tracks, embedded metro tracks, alternative low-cost tracks for floating slab in tunnels and on gradients
- innovative new methods: innovative track installation methods, automated track installation, fast renewal and refurbishment methods, cost/benefit analysis method for infrastructure works, preventive and predictive maintenance methods, techniques for reducing wear in curves and turnouts

The products have been integrated into a family of solutions categorised in function of the track type (metro, tram shared, tram segregated) and in function of the network’s specific needs. Validation has been carried out in ten networks (each validating another type of infrastructure or solution). The evaluation has been based on criteria such as operational availability and cost.

0.1. OBJECTIVE OF THE DELIVERABLE

The current deliverable consolidates in one set of documents the various reports which have been produced as outcomes of the project.

It is structured according to the various sub-projects which had been defined in the original description of works, except the sub-project 6 (SP6) on Consolidation & Dissemination, according to which the current final consolidated report is produced:

Chapter 1. SP1 – Low cost modular new track systems & fast installation methods
Chapter 2. SP2 – Cost effective track maintenance, renewal & refurbishment methods
Chapter 3. SP3 – Design & implementation of solutions at test sites
Chapter 4. SP4 – Life Cycle Cost (LCC) calculation
Chapter 5. SP5 – Functional requirements

Each chapter is a separate document, due to the huge size of some chapters as electronic files.

0.2. PROBLEMS ENCOUNTERED

This report was produced later than planned because the deliverables on the basis of which it must be produced were themselves delayed. The European Commission accepted to give UITP 6 extra weeks to produce this deliverable (during the EC Review meeting in June 2010).
0.3. **PARTNERS INVOLVED AND THEIR CONTRIBUTION**

UITP prepared this report on the basis of the contribution of all partners.

0.4. **CONCLUSIONS**

The main project results presented in this final report were also summarised during URBAN TRACK final conference organised in Prague on 24-25 June 2010 which was attended by more than 70 track specialists.

Some outcomes (e.g. review of existing track related European standards) are used as input for future standardisation works. The project itself is mentioned in a mandate given by the European Commission to the European Standardisation Organisations (CEN-CENELEC-ETSI) which targets the standardisation of Urban Rail systems excluded from the scope of the Interoperability Directive 2008/57/EC by application of Article 1.3 (a) and (b) of this directive.

0.5. **RELATION WITH THE OTHER DELIVERABLES (INPUT/OUTPUT/TIMING)**

This deliverable is linked to D0601 “Technical consolidation report on conceptual designs and selected methods” that was produced at M18 (one year and a half after the beginning of the project).

It is also linked to all produced Deliverables in URBAN TRACK as it consolidates all public results.
1. **LOW COST MODULAR NEW TRACK SYSTEMS & FAST INSTALLATION METHODS (SP1)**

The following chapter 1 is presenting Sub-project (SP) 1 targeting new tracks. It revolves around the following new products/solutions: prefabricated track modules, green LRT/tram tracks, embedded metro tracks, alternative low cost tracks for floating slab in tunnels and on gradients, and maintenance-free interface between rail and street pavement for embedded tracks.

SP1 was made of three sub-packages:

1. **Design of modular low cost new integrated track systems (WP1.1);** the sub-package is itself divided into two chapters addressing two different topics:

   - **Chapter 1.1:** Design of modular low cost new integrated track systems: **removable embedded metro systems** (WP1.1, developed by CDM). The validation site was Madrid, Spain, see chapter 3.1.

   - **Chapter 1.2:** Design of modular low cost new integrated track systems: **Damping models for metro and urban rail systems** (WP1.1, developed by SU). The validation site was Madrid, Spain, see chapter 3.1.

2. **Design of ecological tracks (WP1.2);** the sub-package is itself divided into seven chapters, covering three topics (four chapters are presenting the third topic “Different alternatives of floating slabs”):

   - **Chapter 1.3:** Design of ecological tracks: **green tram tracks** (WP1.2.1, developed by ASP). The validation site was Brussels, Belgium, see chapter 3.2.

   - **Chapter 1.4:** Design of interface between rail and street pavement (WP1.2.2, developed by D2S). The validation site was Seville, Spain, see chapter 3.4.

   - **Chapter 1.5:** Alternatives for floating slabs: Design of load redistribution slab for tram track at grade (WP1.2.3, Part A, developed by APT). The validation site was Brussels, Belgium, see chapter 3.6.

   - **Chapter 1.6:** Alternatives for floating slabs: Review of existing damping systems (WP1.2.3, Part B1, developed by ALSTOM). The validation site was planned to be Singapore but eventually changed for Valenciennes, France, see chapter 3.11.

   - **Chapter 1.7:** Alternatives for floating slabs in tunnels: Sleeper feasibility (WP1.2.3, Part B2, developed by ALSTOM). As for chapter 1.6, the validation site was planned to be Singapore but eventually changed for Valenciennes, France, see chapter 3.11.

   - **Chapter 1.8:** Alternatives for floating slabs in tunnels: Design of ecological tracks (WP1.2.3, Part C, developed by CDM). The validation site were Brussels, Belgium, see chapter 3.7, and Barcelona, Spain, see chapter 3.8.
3. **Development of innovative track installation methods (WP1.3)**; the sub-package is itself divided into two chapters addressing two different topics:

   o **Chapter 1.9: Development of innovative track installation methods: Installation of modular track systems** (WP1.3.1, developed by CDM and VBK). The validation site was Karlsruhe, Germany, see chapter 3.9.

   o **Chapter 1.10: Development of innovative track installation methods: Automatic installation of direct fixation fastener** (WP1.3.2, developed by ALSTOM). Although the focus was on metro, the validation site was a light rail equipped French city, Reims, France, see chapter 3.13.
1.1. **DESIGN OF MODULAR LOW COST NEW INTEGRATED TRACK SYSTEMS (WP1.1, DEVELOPED BY CDM)**

1.1.1. **Introduction**

New projects for metro in tunnels have to specifically take in consideration safety aspects as well as the comfort for the passengers and the environment. The European Union emphasizes those requirements for all future public transportation through tunnels.

This has as a consequence that tunnels will be equipped with a track infrastructure allowing multimodal use (rolling stock, emergency vehicles,...) and an easy evacuation by passengers in case of an emergency.

![Figure 1.1.1: Evolution towards embedded track in tunnels](image1)

In response to this trend rolling stock manufacturers come up with modular vehicles having multiple exits on the sides and sometimes also emergency exits at the front and the back of the vehicle.

![Figure 1.1.2: Metro vehicle with front emergency exit](image2)

Track infrastructure manufacturers have developed track superstructures with elastically embedded rails which are continuously supported, use no mechanical fixations and are integrated in a concrete slab allowing:

- easy and fast installation and reduction of the installation costs of the total infrastructure
- multi-modal use and easy evacuation in case of emergency
- attenuation of noise & vibrations
Figure 1.1.3: Example of continuously supported fastenerless embedded rail system

At the moment, the operators and permanent metro way owners are however still concerned about the replacement possibilities of such embedded rail systems.

In WP1.1 of the Urban track project a low cost **Removable Embedded Metro System (REMS)** has been developed. The test and homologation of small prototypes allowed in WP 3.1 to implement and validate REMS in the Metro Madrid end user network (see chapter 3.1).

The current chapter retraces for WP1.1 of the Urban track project the work performed and the results obtained as to the development of a ‘new low cost embedded rail system’ for use in metro which has as main new feature its **easy replacement capability**.
1.1.2. REMS Development (REMS: Removable Embedded Metro System)

The development process of a concept for REMS was subdivided in the following phases:

1.1.2.1. Analysis of the state of the art

Common track systems in tunnels

For reasons of ease of maintenance and rail replacement most existing metro tracks are based on discretely supported rail. Slab track with discrete fixations and track with booted sleepers are most common. Three stiffness classes for the rail fixation are frequently used:

- standard stiffness
- lower stiffness for vibration isolation
- comfort solution with very low stiffness

![Figure 1.1.4: Slab track with discrete fixations and track with booted sleepers in tunnel](image)

The following table shows an overview of the installation cost evaluation of the common metro track systems.

<table>
<thead>
<tr>
<th>Typical metro systems for 15T/axle load and approx. 750 - 900 mm distance between fastenings</th>
<th>[ kN/mm ]</th>
<th>[ Hz ]</th>
<th>Cost evaluation Euro/ln (ex rail and concrete)</th>
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<td>c. Low stiffness solution</td>
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<td>10</td>
</tr>
<tr>
<td>Booted sleepers (500 kg)</td>
<td>a. Standard stiffness</td>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td>CDM2/ES, Stedef, Taco Elastico</td>
<td>b. Vibration isolation</td>
<td>15</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 1.1.1: Comparison table of installation costs of common metro track systems

The installation cost target for the removable embedded metro system development ranges between 300 - 400 Euro/ln depending of support stiffness. The total life cycle cost of the new system should be 25 % lower than that of the existing track systems.
Removable continuously supported embedded rail

Seven systems regarding removable continuously supported embedded rail were found and are described below.

- **Embedded Nikex Rail.** A special low rail profile is positioned on a rubber strip within a metal omega shaped metal gutter and kept in place by two lateral rubber profiles. The low bending stiffness of the Nikex rail profile has proven to cause wave propagation problems along the rail limiting the success of this development.

  ![Figure 1.1.5: Schematic view of the Nikex rail system](image)

- **Embedded removable Balfour Beatty rail.** A block like rail profile is positioned in a concrete gutter by means of a polymer shell, pad and seal system. The railhead is however not really flush with the surface of the concrete slab and possibilities for noise vibration attenuation are rather limited for this rather uncommon rail type.

  ![Figure 1.1.6: Schematic view of Balfour Beatty rail system](image)

- **Hermann Ortwein Patent DE4427237.** Concrete block no. 7 is kept in place by bolt no. 8 and keeps the assembly 1, 3, 4 and 5 in position. The railhead is however not really flush with the surface of the concrete slab and the extruded rubber encapsulation is costly.

  ![Figure 1.1.7: Schematic view of Ortwein rail system](image)
US patent application 2004/0221532 by Sheridan Ross PC. The rail 14 is encapsulated in a rubber boot 18 which can be reversibly installed or removed in the grooves of a concrete slab. The resilient boot is temporally compressed and also lubricated on its outside to allow installation or removal.

This concept raises questions as to:

- the gauge stability since the boot has internal apertures to allow compression during installation/extraction;
- the possibilities to attenuate vibrations which seem rather limited since the bottom part of the boot is thin;
- the cost of the boot which is most probably made of extruded virgin rubber;
- the required tooling for installation/extraction.

Patent DE2045274 by Beton & Monierbau AG. The rails are received in a concrete recesses 14 provided with a resilient lining 15, 16 and may be anchored in a pre-stressed state by e.g. wedges 17. Attenuation of vibration seems limited and global track assembly complicated by the numerous different components.
➢ **ReRail track system.** This system allows the removal and replacement of just the worn down part of the rail. The used U-shaped railhead shell can be taken off and replaced by a new one which snaps on tightly. Lengthwise there is a mechanical locking.

![Figure 1.1.10: Schematic view of the ReRail track system](image)

The mechanical stability, fatigue resistance, realization of welds and required tooling affect the feasibility of this concept, which is still under development.

➢ **ALH Tensor TM system.** This removable embedded rail system uses pre-moulded elastomer boot elements (brown and green) fitted to the rail and a closure piece (beige). The noise and vibration capabilities of the system seem however limited because of the rather thin boot components and because the rail web is not fully encapsulated.

![Figure 1.1.11: view 3D of ALH Tensor TM system](image)

### 1.1.2.2. The gathering of requirements.

In collaboration with STIB, MDM, Alstom and TTK the following technical and functional requirements have been defined.

The project requirements for REMS are:

- Rail flush with tunnel invert
- Initial installation in a minimum of time (target: - 25% compared to classical techniques)
- Minimum tunnel invert section (target: reduce height of rail infrastructure by 200 mm)
- Three rail stiffness classes:
  - 30 – 40 MN/m/lm-rail
  - 15 - 20 MN/m/lm-rail
  - < 10 MN/m/lm-rail
- Electric isolation meeting the present standard EN13481
- Integrated safety lighting
- 18 m single track renovation in 4 hours night time window
1.1.2.3. **Brainstorming.**

Using the case study and the state of the art and project requirements as input, the generation of a new REMS concept started by finding ideas through a brainstorming process. The following possibilities have been considered:

**A. Use a chainsaw** to cut up the recycled rubber encapsulation in order to take out the rail. This operation is not fast and causes a lot of dust presenting a potential explosion hazard in tunnels. The fixation of the new rail requires the pouring of fast curing resilient material in between the rail and concrete.

**B. Don’t use an ‘old fashioned I-shaped rail profile’** which was initially developed for use on discontinuous support but allow **‘new U-shaped low rail profiles’** which can be better adapted to the requirements of continuously supported embedded rail. The U-shaped low profile rail (LR55 for example) can be bolted on a metal beam for fixation and obtaining of sufficient bending stiffness. The rail can then be encapsulated in a recycled rubber boot. In case of wear the rail is unbolted, taken out of the boot and replaced. The railway world is however rather conservative and does not like...
uncommon rail profiles. Fatigue failure of the bolts fixing the rail on the steel profile is also a new ‘hazard’ to consider.

C. Encapsulate the rail in recycled rubber jackets which do not adhere to the surrounding concrete and which are kept in position by distinct metal fixations. Dismounting the fixations allow the encapsulated rail to be easily taken out of the concrete for replacement. The effective absorption of the potential rail uplift forces by the discrete jacket fixations is however doubtful.

D. Use a key-like system to lock the rail with recycled rubber web chamber blocks (2) in a recycled rubber gutter (1) which is embedded in the concrete slab.
After presentation and comparison of the four different technical options, concept D was finally retained for further development and validation in the Metro de Madrid network.

The different encapsulation elements of concept D can be pre-mounted on the rail and kept in place by u-shaped metal clips.

![Figure 1.1.16: Pre-mounting of rubber encapsulation elements on rail](image)

During phase 1 of the installation in the tunnel, rails are positioned with special gauges. During phase 2 concrete is poured and the gauges are taken out.

![Figure 1.1.17: Installation of REMS rail system in tunnel](image)

To enable the cutting and welding operation of the rails a reservation is foreseen in the ground every 18 m. Those reservations are filled with specific rubber jackets.
Reservation of 600x600 mm.
Length of 18m for an easy and fast manageability.
Objective = replacement of up to 18 lm rail/night

Figure 1.1.18: Cutting and welding reservations in slab
1.1.2.4. Prototype development.

The next step in the development consisted of the realization of small prototypes. Many aspects like materials, manufacturing, pre-compression, insertion, extraction, securing, possible gauge adaptation, tolerances, aging, fatigue, special tooling and costs had to be cleared.

Prototype version 1

To check and tests the practical viability of the key concept the two different options were realized. Finally the most promising solution was to be withheld for further testing and development.

A. Prototype with elliptical key for self locking concept.

The hard key has to be forced in to position and keeps the components of the rail encapsulation in place. The prototype depicted below allowed getting to know more about the practical issues like key insertion forces, rail displacement under load etc.

![Elliptical key prototype](image)

Figure 1.1.19: Elliptical key prototype

B. Flat keys for articulated locking concept.

A second prototype with recycled rubber encapsulation and elastically articulated locking elements was constructed and features an easy insertion and removal of the keys. The flat keys were made of rather stiff recycled rubber.

![Flat key concept with elastically articulated locking elements](image)

Figure 1.1.20: Flat key concept with elastically articulated locking elements

Using two keys also created an assembly allowing adjustments (e.g. left & right key of different thickness) of the track gauge if required.

The practical design for the flat key prototype used 7 parts (see figure 1.1.21) which are easy to manufacture using the regular cost effective resin bonded recycled rubber moulding process.
Flat keys with securing bulge and covered with plastic film

Elastically articulated locking elements

Figure 1.1.21: Flat key prototype with elastically articulated locking elements

The flat hard rubber keys were covered with thermal shrink films before gluing them in position during the pre-mounting of the REMS components on the rail which was put upside down.

Figure 1.1.22: Application of shrink film envelope by means of a heat gun.

The pre-assembled parts were kept together by a U-shaped metal clip to allow the rail system to be turned around and embedded in concrete.

Figure 1.1.23: Pre-assembly with U shaped clip of REMS components on rail turned upside down.

When replacing the embedded rail the cutting of the shrink film envelope allows the easy removal of the keys since there is no adherence between the key, the concrete and the rubber locking element. Simple thin pliers can be used to grasp the keys and initiate their extraction. The locking elements can then be easily bended aside allowing the removal of the rail with its two blocks.

When installing the new rail the two rubber blocks, which are in direct contact whit the rail, should be reused to prevent possible trouble with tolerances. The elastically articulated locking elements are blocked once the keys are pressed in their slots again.

To get an indication of the deflection as well as the static and dynamic stiffness, tests on a lab press have been conducted for the two V1 REMS prototypes.
The detailed results of the stiffness tests are shown in enclosure 1.1.4. Comparing those results to a similar standard embedded rail block reveals that the prototypes do not show a big difference in vertical stiffness. The inclined tests give however results which show stiffness which are a bit lower compared to those of the reference rail block. This can be explained by the slight amount of slack which exists in between the jacket components.

<table>
<thead>
<tr>
<th>Deflection at F = 20 kN</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elliptical key proto</td>
<td>1.04 mm</td>
<td>1.81 mm</td>
<td>1.43 mm</td>
<td>0.88 mm</td>
</tr>
<tr>
<td>2 flat keys proto</td>
<td>1.03 mm</td>
<td>1.53 mm</td>
<td>2.02 mm</td>
<td>0.99 mm</td>
</tr>
</tbody>
</table>

Figure 1.1.25 shows rail deflection data for the two different prototypes. The critical deflections in column 1 and 2 of the table are within a reasonable range. The polytechnic University of Milano also performed a 2D finite element analysis on the concepts using their Abacus software. The flat keys concept performed best as is shown in the figure 1.1.26 below.
Stresses under inclined load

Figure 1.1.26: Stresses and lateral stiffness of prototypes under a 26° inclined load.

Finally a practical rail replacement test was conducted for both prototype test blocks. Figure 1.1.27 shows the operation for the elliptical key prototype. The replacement operation was not successful since the extraction and insertion of the elliptical wooden key could not be realized in a vertical way.

Figure 1.1.27: Rail replacement with elliptical key prototype.

Figure 1.28 shows the same operation for the flat keys prototype. After cutting the plastic envelope the keys were easily taken out with a pair of pliers. The rail could be taken out easily while keeping the
locking lips bent open with some improvised equipment. Inserting the rail and keys was easy and successful as well.

Finally it was decided to drop further development work on the elliptical key prototype because of the difficulties with the key insertion and extraction.

In the vertical rail push out test the prototype with flat keys showed a 3 cm displacement at 7000 N. The lateral locking elements proved to be too thin.

Figure 1.1.28: Rail replacement with the flat keys prototype.

Figure 1.1.29: Vertical rail push out test set up for prototype with flat keys.
Prototype version 2

The next development step consisted in the redesign of the flat keys v1 prototype keeping in mind to realize:

- 3 different stiffness classes
- a larger clearance space for the wheel
- vertically stiffer rubber locking brackets
- an improved securing of the keys
- keys with a shape allowing the proper application of a shrink film envelope
- an improved assembly accuracy of the different components
- a lower rubber requirement
- production by molding of bonded rubber granules
- a minimization of the number of different components

Version 2 of the prototype is shown in the figure below. The difference in stiffness class is obtained by adapting the thickness and material of the resilient strip under the rail foot. The keys are mechanically secured and easily enveloped in shrink film thanks to their angular shape. The number of different components per stiffness class is 5. The strip and locking brackets assemble more accurately thanks to their respective interpenetrating shapes.

![Prototype design version 2](image)

30 – 40 MN/m/Im-rail (compact) 15 - 20 MN/m/Im-rail (classic) < 10 MN/m/Im-rail (comfort)

Figure 1.1.30: Prototype design version 2.

All components can easily be moulded and have a length of 1.2 meter. The removal operation of the rail is shown in figure 1.1.31. After removal of the keys by cutting up the shrink film envelope and taking out the keys with some pliers, wedges are forced in to bent open the locking brackets. This allows the easy vertical removal of the rail together with the filler blocks. Only the rail is replaced. To avoid tolerance problems all rubber parts are put in their original location again.
Since rail cutting and aluminothermic welding operations require much free space around the rail a reservation of about 60 cm x 60 cm x 30 cm is foreseen at every 18 m of rail. These reservations have to be easily filled up and opened but should not change the rail support stiffness. The figure below shows the laterally removable jackets and removable prefab concrete blocks (shrink film coated).

For installation the REMS components are premounted on the rail using metal U-shaped brackets. See figure below.

Finally the rails with REMS components are accurately positioned on the track location by means of gauge frames. Rails are welded and a first layer of concrete is poured. Before the pouring of the concrete finishing layer the gauge frames are removed. See figure 1.34 below.
Figure 1.1.34: Installation of REMS on the track construction site.

The rail replacement operation starts by taking out the concrete blocks, jackets and strips to clear the space of the welding zone reservations. The rail can then be cut. Once the keys have been taken out and the wedges inserted the rail can be taken out and replaced. See figure 1.1.35. All rubber elements are reused in their original locations to prevent possible tolerance problems.

Figure 1.1.35: Rail removal operation of REMS.
Meanwhile a 2D FEM analysis was performed by Polimi showing the behavior of the REMS system under load. The figure below show stresses under vertical load.

![Visualization of stresses under vertical load for the three stiffness classes (2D FEM analysis by Polimi).](image)

Under inclined load the analysis shows the appearance of a noticeable opening on the inside of the rail between the filler block and locking bracket for the comfort REMS.

![Visualization of stresses under inclined load for the comfort stiffness class (2D FEM analysis by Polimi).](image)

**Prototype version 3**

Feedback from Polimi and Metro de Madrid on version 2 showed the need for:

- an increased wheel clearance taking the maximal allowed wear of the railhead into account
- an opening in the rubber allowing a cable passage along rail
- maximum rubber support on the outside of the rail to prevent the appearance of an opening under inclined load
- the possibility to apply pre-compression after installation of the REMS components by inserting metal strips between the rubber keys and concrete to overcome the appearance of a possible opening of the REMS under inclined load

![REMS version 3 design](image)

These new requirements forced the increase of the number of different components of the REMS solution and lead to the design shown in the figure above. Meanwhile Polimi realized new FEM calculations showing stresses and displacements for the three different stiffness classes under vertical and inclined load.
load (see for applied modeling parameters enclosure 1.1.4.8). The application of 10% pre-compression (key is 10% thicker than slot) can suppress the appearance of an opening between the rubber components on the inside of the rail.

Figure 1.1.39: FEM analysis of REMS compact version 3 design without and with 10% pre-compression

- **Vertical stiffness:** 56.423 MN/m/m
- **Lateral stiffness:** 7.867 MN/m/m
- **Rail extraction stiffness:** 3.432 MN/m/m

Figure 1.1.40: FEM analysis of REMS classic version 3 design without and with 10% pre-compression

- **Vertical stiffness:** 56.201 MN/m/m
- **Lateral stiffness:** 8.724 MN/m/m
- **Rail extraction stiffness:** 14.500 MN/m/m

Vertical stiffness: 36.882 MN/m/m

- **Lateral stiffness:** 6.723 MN/m/m
- **Rail extraction stiffness:** 3.524 MN/m/m

Vertical stiffness: 38.319 MN/m/m

- **Lateral stiffness:** 7.854 MN/m/m
- **Rail extraction stiffness:** 14.846 MN/m/m
Figure 1.1.41: FEM analysis of REMS comfort version 3 design without and with 10% precompression

To allow the modeling of the longitudinal rail stiffness, Polimi also made a 3D FEM model.

Figure 1.1.42: Visualization of 3D FEM model of Compact, Classic and Comfort REMS

The graph below shows the longitudinal rail stiffness as function of REMS type and pre-compression.
The longitudinal rail stiffness is important when considering acceleration and deceleration forces produced by the rolling stock.

The previous results were promising enough to start the realization of moulds for full size prototype realization. The figure below shows the moulds used for the rubber crumb/PU moulding process.

Figure 1.1.43: Longitudinal rail systems and pre-compression

Figure 1.1.44: 3D images of the moulds for manufacturing of version 3 prototypes.
Six new test blocks for prototype testing were produced (see figure 1.1.45 below)

The rail removal and replacement test proved successful using wooden wedges to open the locking brackets.

For future installation purposes at the validation site a new GSF fixation interface and jacket pre-assembly clip were designed. The new GSF design allows the accurate setting of the gauge distance by pressing the railhead on to an accurately positioned gauge reference notch with help of a screw device.
Figure 1.1.47: New GSF and clip design for installation of REMS.

Screw device pushing rail against notch to guarantee accurate gauge tolerance
1.1.2.5. Testing

The main REMS parameters to check with help of the prototypes are:

- vertical rail stiffness (static and dynamic) of the track system
- rail stiffness (static and dynamic) of the track system under inclined load (26°)
- longitudinal behavior of rail (take up of braking forces)
- rail gauge stability in curves (inclined load)
- resistance to rail uplift
- fatigue of track system
- initial track installation method and speed
- rail replacement method and speed

**Tests at CDM**

In the CDM lab three test blocks were tested under vertical and inclined loads (26°). Enclosure 6.4 shows the detailed system performance results under vertical load. A summary of the results is shown in table 1.1.2.

<table>
<thead>
<tr>
<th></th>
<th>Compact</th>
<th>Classic</th>
<th>Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. deflection</td>
<td>1,22</td>
<td>1,58</td>
<td>2,99</td>
</tr>
<tr>
<td>Res. frequency</td>
<td>73</td>
<td>46</td>
<td>40</td>
</tr>
<tr>
<td>Static Rail-modulus</td>
<td>35</td>
<td>26</td>
<td>13</td>
</tr>
<tr>
<td>Dynamic Rail modulus</td>
<td>162</td>
<td>65</td>
<td>48</td>
</tr>
<tr>
<td>Static spring cte</td>
<td>60</td>
<td>49</td>
<td>30</td>
</tr>
<tr>
<td>Dynamic spring cte</td>
<td>281</td>
<td>121</td>
<td>105</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Compact</th>
<th>Classic</th>
<th>Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. deflection</td>
<td>1,22</td>
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<td>35</td>
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<td>162</td>
<td>65</td>
<td>48</td>
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<tr>
<td>Static spring cte</td>
<td>60</td>
<td>49</td>
<td>30</td>
</tr>
<tr>
<td>Dynamic spring cte</td>
<td>281</td>
<td>121</td>
<td>105</td>
</tr>
</tbody>
</table>

**Table 1.1.2: REMS system performance results for the three stiffness classes**

Vertical deflection is within requirements. The static rail stiffness is ok for the compact version and about 25% to high for the classic and comfort. Lowering the density of the strip material supporting the rail foot will allow correcting this. The dynamic rail modulus is relatively high for the three REMS types.

In Enclosure 1.1.4 are shown the detailed rail head displacements of the REMS systems under a load inclined at 26°. A summary is presented in table 1.1.3. The measurements were done at a load of 15kN that is a load producing displacements on the test block which are equivalent to those that would appear with the rolling stock on a real track section. The values obtained are within the requirements for the gauge tolerance.

<table>
<thead>
<tr>
<th></th>
<th>Compact</th>
<th>Classic</th>
<th>Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>15kN inclined at 26°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal displacement</td>
<td>1.01 mm</td>
<td>0.70 mm</td>
<td>1.28 mm</td>
</tr>
</tbody>
</table>

**Table 1.1.3: Railhead displacements under horizontal and inclined load**

The appearance of an opening between rubber REMS elements was also analyzed. The pictures in the figure below show the situation at a 30 kN load. This load is twice as high as in reality in order to
exaggerate the opening phenomena. The interstice in this extreme condition is limited to about one millimeter.

The tests at Polimi determined if pre-compression is required or not (see 3.1.3). Application of pre-compression should preferably be avoided because it increases the complexity of the overall system and its installation.

The electrical resistance of the REMS system measured between two embedded rails ranges from 0.003 M Ohm m without special rail treatment to about 0.035 M Ohm m for a setup with sandblasted and painted rails.

The level of electrical isolation of painted rail is sufficient to effectively prevent stray currents and also allow the use of simple signaling systems through the rail. The limited thickness of the paint film does not trouble the proper fit of the rubber jacket components on the rail.

A rail pull out test to evaluate the resistance against uplift forces of the rail and a longitudinal behavior test are part of the Polimi testing program.
### Tests at Polimi

The following test program has been defined to investigate at Polimi the capabilities of the three REMS prototypes. The validation at POLIMI is part of the SP3 WP 3.1 (see Chapter 3.1.3).

#### 2 Small Scale Tests L300 @ POLIMI

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Situation</th>
<th>Further to</th>
<th>REMS V3 Proto</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Compact</td>
</tr>
<tr>
<td>C-stat 0°</td>
<td>Virgin</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>C-dyn 0°</td>
<td>Virgin</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>C-stat 26°</td>
<td>Virgin</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>C-dyn 25°</td>
<td>Virgin</td>
<td>Fatigue 3M cycles @5 Hz.</td>
<td>x</td>
</tr>
<tr>
<td>C-stat 0°</td>
<td>Fatigued</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>C-dyn 0°</td>
<td>Fatigued</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>C-stat 26°</td>
<td>Fatigued</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>C-dyn 25°</td>
<td>Fatigued</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>C-stat 0°</td>
<td>A&amp;F</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>C-dyn 0°</td>
<td>A&amp;F</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>C-stat 26°</td>
<td>A&amp;F</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>C-dyn 25°</td>
<td>A&amp;F</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Pull out</td>
<td>Virgin</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Longitudinal restraint</td>
<td>Virgin</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

**8 channels:**
- 6 laser
- 1 load cell
- 1 potentiometer

Figure 1.1.50: REMS test set up in the Polimi laboratory.
**VALIDATION AT MDM**

All components to realize a 54 meter long REMS installation test with the three different stiffness classes in the Metro de Madrid network were realized.

![Figure 1.1.51: Pre-assembled REMS jacket components, special gauge frames and new U-clip application tool.](image)

The validation at MDM is part of the SP3 WP 3.1 (see Chapter 3.1). It gave insight in the:

- practical feasibility and speed of the initial installation
- practical feasibility and speed of the rail replacement process
- possibility to cut and weld the rail after lifting it outside the embedment. This eliminates the need of special welding zone reservations every 18 meter of track
- required labor and costs
1.1.3. **Conclusions**

At the moment, the operators and metro way owners are still concerned about the replacement possibilities of embedded rail systems.

In WP1.1 of the Urban track project a low cost Removable Embedded Metro System (REMS) was developed to address these concerns.

Using the case study, the state of the art and track requirements as input, the generation of a new REMS concept was realized.

Several prototypes were made based on the use of keys. FEM analysis results allowed better understanding and fine tuning the systems behavior. The prototypes allowed to check and tests (at CDM and Polimi) the technical performance of the REMS concept. A 54 meter long track section was prepared in a Metro de Madrid depot to check the practical feasibility of the installation and rail removal processes.

At this first stage of the Urban track project the REMS development proved successful while complying with the initial MDM requirements. The REMS development was ready to allow large scale testing and validation in the MDM network during the second half of the Urban track project (see chapter 3.1).
1.1.4. ENCLOSURES (REMS plans and CDM lab tests)

1.1.4.1. REMS plans for FEM modelling at Polimi

Initial version with elliptical key
Version 1 with two flat keys
Version 2 with two identical triangular keys
Version 3 with two different triangular keys
1.1.4.2. Material data sheet of rail encapsulation material

<table>
<thead>
<tr>
<th>Prescription</th>
<th>Unit</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constituent material</td>
<td></td>
<td>PU-Resin bonded rubber</td>
</tr>
<tr>
<td>Type</td>
<td></td>
<td>CDM-49</td>
</tr>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>950-1150</td>
</tr>
<tr>
<td>Shore hardness - ASTM-D2240</td>
<td>%</td>
<td>55-65</td>
</tr>
<tr>
<td>Tensile strength - ISO-37</td>
<td>MPa</td>
<td>&gt; 0.95</td>
</tr>
<tr>
<td>Elongation at break - ISO-37</td>
<td>%</td>
<td>&gt; 30</td>
</tr>
<tr>
<td>Compression set – 50% / 70H RT - DIN-53572</td>
<td>%</td>
<td>&lt; 8</td>
</tr>
<tr>
<td>Creep rate under 0.1 MPa – ISO-8013</td>
<td>%/ decade of time in min.</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Water Absorption – BRB-491</td>
<td>Gr.H2O/cm³</td>
<td>&lt; 0.08</td>
</tr>
<tr>
<td>Static elasticity modulus E_{stat.} (Tangent at 0.04 MPa)</td>
<td>MPa</td>
<td>2.5 &lt; &gt; 8.5</td>
</tr>
<tr>
<td>Dynamic elasticity modulus E_{dyn} (5 Hz, under 0.04 MPa +/- 20%)</td>
<td>MPa</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>Transversal resistivity – CEI93</td>
<td>Ωcm</td>
<td>&gt; 10⁸</td>
</tr>
</tbody>
</table>
1.1.4.3. Lab test results of first two prototypes (CDM lab)

**CDM STATIC TEST**

Method Name: CDM-STATIC-LOAD.mtJ
Name: 4688- Prefarall UIC54

**SAMPLE**
- Area: 120000.00 mm²
- Width: 300.00 mm
- Length: 400.00 mm
- Height: 25.00 mm
- Weight: 0.000000 g

**TEST**
- Operator ID: EV
- Test date: 06/09/07
- Precondition Cycles: 2
- Description: Hold 30 seconds + Test 1 cycle
- Ctrl. mode: Comp. load
- Maximum limit: 30.00 kN
- Rate: 30.00 kN/min

**Note:** T.1441 - Ref: UT REMS (1 Key)

---

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<table>
<thead>
<tr>
<th>Tp &amp; Load (%)</th>
<th>Tp &amp; Load (%)</th>
<th>Tp &amp; Load (%)</th>
<th>Tp &amp; Load (%)</th>
<th>Tp &amp; Load (%)</th>
<th>Tp &amp; Load (%)</th>
<th>Tp &amp; Load (%)</th>
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<tbody>
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<td>30%</td>
<td>40%</td>
<td>50%</td>
<td>60%</td>
<td>70%</td>
</tr>
<tr>
<td>514.4</td>
<td>1138.8</td>
<td>5138.5</td>
<td>1440.7</td>
<td>1516.5</td>
<td>3403.6</td>
<td>5386.9</td>
</tr>
<tr>
<td>10%</td>
<td>20%</td>
<td>30%</td>
<td>40%</td>
<td>50%</td>
<td>60%</td>
<td>70%</td>
</tr>
<tr>
<td>514.4</td>
<td>1138.8</td>
<td>5138.5</td>
<td>1440.7</td>
<td>1516.5</td>
<td>3403.6</td>
<td>5386.9</td>
</tr>
<tr>
<td>10%</td>
<td>20%</td>
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<td>50%</td>
<td>60%</td>
<td>70%</td>
</tr>
<tr>
<td>514.4</td>
<td>1138.8</td>
<td>5138.5</td>
<td>1440.7</td>
<td>1516.5</td>
<td>3403.6</td>
<td>5386.9</td>
</tr>
<tr>
<td>10%</td>
<td>20%</td>
<td>30%</td>
<td>40%</td>
<td>50%</td>
<td>60%</td>
<td>70%</td>
</tr>
<tr>
<td>514.4</td>
<td>1138.8</td>
<td>5138.5</td>
<td>1440.7</td>
<td>1516.5</td>
<td>3403.6</td>
<td>5386.9</td>
</tr>
</tbody>
</table>
CDM DYNAMIC TEST

SAMPLE
Name: 4688
Description: Prefab rail UIC 54 T.1441 - Ref: UT REMS (1ke)

PRECONDITIONING
Cycles [#]: 150
Frequency [Hz]: 15
Mean Load [N]: -12000
Amplitude Load [N]: 1200

DIMENSIONS
Height [m]: 0.02500
Area [m²]: 0.12000
Width [m]: 0.30000
Length [m]: 0.40000

TEST
Settling Cycles [#]: 100
Measures Cycles [#]: 20
Test Date: 09/06/07
Test Time: 15:16:45

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**CDM STATIC TEST**

**Method Name:** CDM-STATIC-LOAD.mtJ  
**Name:** 4689- Prefarall UIC 54

**SAMPLE**
- **Area:** 90000.00 mm²
- **Width:** 300.00 mm
- **Length:** 300.00 mm
- **Height:** 25.00 mm
- **Weight:** 0.000000 g

**Note:** T.1441 - UT REMS (2 Keys)  
Inclined @ 26°

**TEST**
- **Operator ID:** EV
- **Test date:** 06/09/07
- **Pre-cycling Cycles:** 2
- **Description:** Hold 30 seconds + Test 1 cycle
- **Ctrl. mode:** Comp. load
- **Maximum limit:** 30.00 kN
- **Rate:** 30.00 kN/min

![Graph showing test results](image)

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<table>
<thead>
<tr>
<th>Hydromass (T)</th>
<th>Density (kg/m³)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>7.2</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Tg. Stiff. at 10% Load (N/mm)</th>
<th>Tg. Stiff. at 20% Load (N/mm)</th>
<th>Tg. Stiff. at 30% Load (N/mm)</th>
<th>Tg. Stiff. at 40% Load (N/mm)</th>
<th>Tg. Stiff. at 50% Load (N/mm)</th>
<th>Tg. Stiff. at 60% Load (N/mm)</th>
<th>Tg. Stiff. at 70% Load (N/mm)</th>
<th>Tg. Stiff. at 80% Load (N/mm)</th>
<th>Tg. Stiff. at 90% Load (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>6786.7</td>
<td>17210.6</td>
<td>17210.6</td>
<td>15060.8</td>
<td>15060.8</td>
<td>12448.0</td>
<td>70567.1</td>
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</table>
CDM DYNAMIC TEST

SAMPLE

Name: 4689- Prefarrail UIC 5c
Description: T.1441 • Inclined @ 26

PRECONDITIONING

Cycles [#]: 150
Frequency [Hz]: 15
Mean Load [N]: -12000
Amplitude Load [N]: 1200

DIMENSIONS

Height [m]: 0.02500
Area [m²]: 0.12000
Width [m]: 0.30000
Length [m]: 0.40000

TEST

Settling Cycles [#]: 100
Measure Cycles [#]: 20
Test Date: 09/08/07
Test Time: 16:18:22

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<table>
<thead>
<tr>
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<td>19.56</td>
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</table>

CDM Rentenbeek 9 - 3090 Overijse - Belgium
Tel: +32 2 687 79 07 - Fax: +32 2 687 35 52 - Email: general@cdm.be
Print Date: 06/09/07 16:24:23
**CDM STATIC TEST**

**Method Name:** CDM-STATIC-LOAD.mtJ  
**Name:** 4690- Prefarail UIC54

**SAMPLE**
- **Area:** 120000.00 mm²  
- **Width:** 300.00 mm  
- **Length:** 400.00 mm  
- **Height:** 25.00 mm  
- **Weight:** 0.000000 g

**TEST**
- **Operator ID:** EV  
- **Test date:** 07/09/07  
- **Pre-cycling Cycles:** 2  
- **Description:** Hold 30 seconds + Test 1 cycle  
- **Ctrl. mode:** Comp. load  
- **Maximum limit:** 30.00 kN  
- **Rate:** 30.00 kN/min

**Note:** T.1441 - Ref: UT REMS (2 Keys)

---

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CDM DYNAMIC TEST

SAMPLE
Name: 4690-
Description: Prefarail UIC 54 T.1441 - Ref: UT REMS (2 Key)

PRECONDITIONING
Cycles [#]: 150
Frequency [Hz]: 15
Mean Load [N]: -12000
Amplitude Load [N]: 1200

DIMENSIONS
Height [m]: 0.02500
Area [m²]: 0.12000
Width [m]: 0.30000
Length [m]: 0.40000

TEST
Settling Cycles [#]: 100
Measure Cycles [#]: 20
Test Date: 09/07/07
Test Time: 09:28:50

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<table>
<thead>
<tr>
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<td>15</td>
<td>59472667</td>
<td>0.134</td>
<td>23.40</td>
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</tbody>
</table>
CDM STATIC TEST

Method Name: CDM-STATIC-LOAD.mtJ
Name: 4691- Prefarail UIC54

SAMPLE
Area: 120000.00 mm²
Width: 300.00 mm
Length: 400.00 mm
Height: 25.00 mm
Weight: 0.000000 g

Note: T.1441 - Ref: UT REAMS (2 Keys)
Inclined @ 26°

TEST
Operator ID: EV
Test date: 07/09/07
Precycling Cycles: 2
Description: Hold 30 seconds + Test 1 cycle
Ctrl. mode: Comp. load
Maximum limit: 30.00 kN
Rate: 30.00 kN/min

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CDM DYNAMIC TEST

SAMPLE
Name: 4691-
Description: Prefarail UIC 5c T.14441 - Inclined @ 26° (2 Key)

PRECONDITIONING
Cycles [#]: 150
Frequency [Hz]: 15
Mean Load [N]: -12000
Amplitude Load [N]: 1200

DIMENSIONS
Height [m]: 0.02500
Area [m²]: 0.12000
Width [m]: 0.30000
Length [m]: 0.40000

TEST
Settling Cycles [#]: 100
Measure Cycles [#]: 20
Test Date: 09/07/07
Test Time: 10:45:55

Dynamic Stiffness [N/mm]

Mean Def. (m) Mean Load (N) Ampl. Displ. (m) Ampl. Load (N) Exc. F. (Hz) Kdyn (N/m) Tg. Delta Nat. Freq. (Hz)
-0.00074 -2975 0.00012 1684 15 14180199 0.161 34.41
-0.00110 -6811 0.00007 1207 15 17656882 0.158 27.02
-0.00143 -9910 0.00009 1704 15 19808776 0.159 23.43
-0.00175 -11983 0.00011 2391 15 22252529 0.158 21.48
-0.00205 -14865 0.00012 2961 15 24658517 0.159 20.35
-0.00232 -17599 0.00013 3567 15 26088600 0.159 19.69
-0.00256 -21029 0.00014 4217 15 30302173 0.156 19.09
-0.00278 -24004 0.00014 4620 15 33481323 0.154 18.62
-0.00299 -26962 0.00015 5362 15 35791912 0.152 18.15

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Print Date: 07/09/07 10:57:21

D0602_M48_UITP_SP1.doc
### 1.1.4.4. REMS compact performance results.

<table>
<thead>
<tr>
<th>SET-UP</th>
<th>PERFORMANCE TEST</th>
<th>CUPILAE REF.: 6380.1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The performance of the PREFARAIL system is measured in hydraulic press by evaluation of the stiffness (static and dynamic) on a sample of 300 mm. long rail equipped with the CDM-FLEXIWEB-Jacket to be tested - all embedded in a concrete block (see drawing and picture). The test specifications are the following:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydraulic Press:</td>
<td>Instron 8802</td>
</tr>
<tr>
<td></td>
<td>Static test conditions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum load</td>
<td>30 kN</td>
</tr>
<tr>
<td></td>
<td>Loading speed</td>
<td>30 kN/min</td>
</tr>
<tr>
<td></td>
<td>Preconditioning</td>
<td>3 #</td>
</tr>
<tr>
<td></td>
<td>Dynamic Test Conditions (15Hz +/- 20% F, F = variable)</td>
<td></td>
</tr>
<tr>
<td>The bedding modules ( k_{stat} ) or ( k_{dyn} ) ( \text{in MN/m}^2 ) to be taken into account for the design are derived from the stiffness K-test ( \text{(in MN/m)} ) measured in the test procedure by using the formula ( k = \frac{K_{test}}{W^0.3} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### STATIC STIFFNESS RESULTS

<table>
<thead>
<tr>
<th>Load (kN)</th>
<th>deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.14</td>
</tr>
<tr>
<td>10</td>
<td>2.54</td>
</tr>
<tr>
<td>20</td>
<td>1.94E+07</td>
</tr>
<tr>
<td>30</td>
<td>3.00</td>
</tr>
</tbody>
</table>

| Relevant Static stiffness | 1.94E+07 |
| Rail width               | 0.14     |
| Design Static Module     | 2.48E+08 |

### DYNAMIC STIFFNESS RESULTS

<table>
<thead>
<tr>
<th>Preload (kN)</th>
<th>k( \text{dyn} ) (Hz, rad/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.68E+07</td>
</tr>
<tr>
<td>10</td>
<td>3.86E+07</td>
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<td>20</td>
<td>4.50E+07</td>
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<tr>
<td>30</td>
<td>5.00E+07</td>
</tr>
</tbody>
</table>

| Relevant Dyn stiffness | 4.86E+07 |
| Design Dynamic Module | 1.16E+09 |

### RELEVANT DESIGN PARAMETERS

<table>
<thead>
<tr>
<th>Railway type</th>
<th>UIC64</th>
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</thead>
<tbody>
<tr>
<td>Axle-Axe distance</td>
<td>2.035</td>
</tr>
<tr>
<td>kN axle load</td>
<td>154</td>
</tr>
</tbody>
</table>

Design Deflection under Bogie-Bogie (mm)

<table>
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<tr>
<th>Distance (mm)</th>
<th>0.20</th>
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<td>0.10</td>
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<td></td>
<td>0.00</td>
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<td></td>
<td>0.00</td>
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</table>

### RELEVANT RESULTS

<table>
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<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm max. deflection</td>
<td>1.22</td>
</tr>
<tr>
<td>Hz res. frequency</td>
<td>73</td>
</tr>
<tr>
<td>MN/m/m</td>
<td>Static Rail-modulus</td>
</tr>
<tr>
<td>MN/m/m</td>
<td>Dynamic Rail modulus</td>
</tr>
<tr>
<td>MN/m</td>
<td>Static spring cte</td>
</tr>
<tr>
<td>MN/m</td>
<td>Dynamic spring cte</td>
</tr>
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</table>
### 1.1.4.5. REMS Classic performance results

#### PREFARAIL SYSTEM PERFORMANCE RESULTS

<table>
<thead>
<tr>
<th>RAIL DESIGN AXLE LOAD (Q)</th>
<th>UI54</th>
<th>Nm</th>
</tr>
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<tbody>
<tr>
<td>VERSION CLASSIC</td>
<td>LAB-QC</td>
<td>E-Store</td>
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<tr>
<td>FLEXIWEB-material</td>
<td>QA</td>
<td>Y. Blattin</td>
</tr>
<tr>
<td>AV-strip</td>
<td>MD</td>
<td>P. Carden</td>
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<tr>
<td>SET-UP</td>
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<td>PERFORMANCE TEST</td>
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<td></td>
</tr>
<tr>
<td>CDW-MR-REF. 538-1</td>
<td></td>
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</tr>
</tbody>
</table>

**The performance of the PREFARAIL system is measured in hydraulic press by evaluation of the stiffness (static and dynamic) on a sample of 300 mm long rail equipped with the CDM-FLEXIWEB-Jacket to be tested - all embedded in a concrete block (see drawing and picture). The test specifications are the following:**

- **Hydraulic Press:** Instron 8822
- **Static Test conditions**
  - Maximum load: 30 kN
  - Loading speed: 30 kN/min
  - Preconditioning: 3 #
- **Dynamic Test Conditions (1 Hz ± 20% F; F = variable)**

The bending modules (k-slat or k-dyn in N/m²) to be taken into account for the design are derived from the stiffness K-test (in N/m²) measured in the test procedure by using the formula k = K/1000.

#### STATIC STIFFNESS RESULTS

<table>
<thead>
<tr>
<th>Load (kN)</th>
<th>Static Stiffness (N/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7.93E+06</td>
</tr>
<tr>
<td>5</td>
<td>1.85E+07</td>
</tr>
<tr>
<td>10</td>
<td>4.64E+08</td>
</tr>
</tbody>
</table>

#### DYNAMIC STIFFNESS RESULTS

<table>
<thead>
<tr>
<th>Load (kN)</th>
<th>Dynamic Stiffness (N/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.85E+07</td>
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<tr>
<td>5</td>
<td>4.64E+08</td>
</tr>
</tbody>
</table>

#### RELEVANT DESIGN PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail type</td>
<td>UI54</td>
</tr>
<tr>
<td>Axle-Axle distance</td>
<td>2.035</td>
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<tr>
<td>Bao-Bao distance</td>
<td>0.2</td>
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<td>Static rail load</td>
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<tr>
<td>El rail</td>
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</table>

#### DESIGN DEFORMATION UNDER ROD-E-Rogie (mm)

- **Relevant results:**
  - max. deflection: 1.58
  - res. frequency: 48
  - Static rail modulus: 25
  - Dynamic rail modulus: 68
  - Static spring cle: 49
  - Dynamic spring cle: 121
## 1.1.4.6. REMS Comfort performance results

### PREFARAIL SYSTEM PERFORMANCE RESULTS

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### PERFORMANCE TEST

**SET-UP**

The performance of the PREFARAIL system is measured in hydraulic press by evaluation of the stiffness (static and dynamic) on a sample of 300 mm. Long rail equipped with the CDM-FLEXIWEB-Jacket to be tested - all embedded in a concrete block (see drawing and picture). The test specifications are the following:

- **Hydraulic Press:** Instron 8802
- **Static test conditions:**
  - Maximum load: 30 kN
  - Loading speed: 30 kN/min
  - Preconditioning: 3 cycles
- **Dynamic Test Conditions (15Hz +/− 20% F, F = variable)**

The bedding modules (k-stat or k-dyn in MN/m²) to be taken into account for the design are derived from the stiffness K-test (in MN/m) measured in the test procedure by using the formula:

\[ k = \frac{K_{test}}{W^{0.3}} \]

### STATIC STIFFNESS RESULTS

- N/m: Relevant Static Stiffness: 4.02E+08
- m: Rail width: 0.14
- N/m²: Design Static Module: 9.57E+07

### DYNAMIC STIFFNESS RESULTS

- Relevant Dyn. Stiffness: 1.45E+07 N/m
- Design Dynamic Module: 3.41E+08 N/m²

### RELEVANT DESIGN PARAMETERS

- Railtype: UIC54
- m: Axle-Axle distance: 2.035
- m: Bo-Bo distance: 9.3
- kN: axle load: 154
- Nm²: El rail: 4.83E+06

### RELEVANT RESULTS

- mm: max. deflection: 2.99
- Hz: res frequency: 40
- MN/m/mrail: Static Rail-modulus: 13
- MN/m/mrail: Dynamic Rail modulus: 48
- MN/m: Static spring cte: 30
- MN/m: Dynamic spring cte: 105
1.1.4.7. Deflections of test blocks under inclined load in mm.

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1.1.4.8. Parameters applied in FEM analysis.

*Properties of rubber elements (except keys & comfort pad):*

- Elastic modulus: 6.5 MPa
- Poisson ratio: 0.45
- Density: 1000 kg/m$^3$
- Linear elastic isotropic material

*Properties of keys:*

- Elastic modulus: 8.5 MPa
- Poisson ratio: 0.45
- Density: 1000 kg/m$^3$
- Linear elastic isotropic material

*Properties of comfort pad:*

- Elastic modulus: 3.25 MPa
- Poisson ratio: 0.45
- Density: 1000 kg/m$^3$
- Linear elastic isotropic material

*Properties of rails:*

- Type: UIC54
- Elastic modulus: 209000 MPa
- Poisson ratio: 0.30
- Density: 7850 kg/m$^3$
- Linear elastic isotropic material

*Interactions:*

- Rubber-rubber contact: Coulomb friction 0.87
- Rubber-steel contact: Coulomb friction 0.67
- Rubber-concrete contact: clamped
1.2. DESIGN OF MODULAR LOW COST NEW METRO TRACK SYSTEMS: DAMPING MODELS FOR URBAN RAIL SYSTEMS (WP1.1, DEVELOPED BY SU)

This chapter focuses on the development of damping models for urban rail track systems in order to predict the noise and vibration characteristics of urban rail systems. The chapter details a comprehensive literature survey as well as a study of various single degree of freedom discrete damping models and two relaxation type models. This part has been used for further tests (see Chapter 3.1). The overall objective is that the use of such models can lead to a decrease in maintenance and associated costs, as vibrations is a main factor in the degradation of the superstructure and rolling stock.

The literature survey was conducted by searching various online electronic databases and catalogues. By using carefully selected keywords the most appropriate journal articles were identified and downloaded or ordered. The articles were studied, classified and summarised (see below).

The discrete, single degree of freedom damping models, identified from the literature, were evaluated by comparing their dynamic behaviour under various excitation conditions. Each model was programmed in a numerical simulation software suite, Matlab Simulink. By specifying various initial conditions and forcing functions the dynamic response of the models were compared and their dynamic behaviour studied.

Conclusions were drawn and recommendations made from these results.

A large number of damping models are available in literature, as presented in the first part of this chapter. Then different damping models are evaluated and compared.

It was found that the initial conditions are important as these influence the results. Some of the damping models, which are commonly used, are also only valid when the excitation is a single frequency and the damping parameters depend on this frequency so that they need to be adjusted if the excitation frequency changes. This is not frequently recognised or pointed out in the literature with the effect that these models are frequently incorrectly applied to predict the dynamic response of systems subjected to broadband excitation.

The results of this study were incorporated into the models being developed by Politecnico di Milano (POLIMI) and Dynamics, Structures & Systems International (D2S)(see chapter 3.1).

The most important conclusions one can draw from the literature is that:

The damping coefficient of materials depends on preload, strain rate, temperature, humidity and age. Hysteretic damping models give accurate results albeit for only the frequency at which it applies. More general approaches are possible, with more complicated, non-linear models but with the added complexity of obtaining a larger number of parameters from testing.

It is not possible to make a definitive conclusion on which model is the best or most applicable. More work is required, especially on comparing the results of actual experimental data.
This work was the precursor to Phase 3 where a discrete damping model will be implemented in the track system model used to evaluate the noise and vibration characteristics of complete urban track systems (see chapter 3.1 and 3.5).

1.2.1. **Introduction and Project Statement**

Stellenbosch University has established expertise in sound and vibration research, dynamic modelling and structural component testing. In this regard the Sound & Vibration Research Group in association with the Structures Laboratory has access to a variety of test and measurement equipment to conduct structural and material testing and characterisation. In addition, extensive software, including Matlab and Simulink as well as MSC’s Adams dynamic simulation suite is available to model dynamic systems.

Chapter 1.1 has identified the noise and vibration isolation performance as a key functional characteristic. In order to predict the noise and vibration performance of the newly developed track system accurate damping models will be required.

Damping and especially the modelling thereof, is an area where a number of approaches have been proposed over the years. Some of the models are used because they are easy to include in mathematical and/or numerical simulation models, and others, usually more complex, because they represent the non-linear behaviour of, for example, viscous elastic materials better. It is frequently also not clear how the material properties required for the analytical models can be obtained from test results.

In this phase of work a comprehensive literature survey was completed on damping models that have been developed, implemented and tested to date. In particular the damping models associated with rail systems were investigated. A selection of these models was studied by implementing them in appropriate numerical simulation models. The models were compared and the results are documented below.

From the literature study with regard to railway infrastructure modelling, published damping models and testing procedures to determine the damping characteristics, 32 relevant articles were found. Of these articles, 12 were applicable to railway infrastructure modelling, 5 were applicable to damping, 2 were applicable to sound, 2 were applicable to tuned damping devices and 11 articles were applicable to testing. Numerous books and websites were also studied.

A study was completed with regard to existing railway infrastructure. Special focus was placed on urban rail systems as well as the measures taken to reduce vibration and noise generated by these systems. The results of this study are presented below.

Various damping models were implemented in a single degree of freedom simulation model to compare their dynamic behaviour for various initial conditions subjected to a number of forcing functions.

An assessment of the different models was made and is presented in this document.
1.2.2. **Damping of railway infrastructure**

This section deals with a few frequently used isolation systems or vibrations and noise with the main focus on rail applications. With the increasing use of railways, especially for urban transport, the need to isolate the vibrations and noise of these systems from their adjacent surroundings has dramatically increased. An added advantage of these measures is a decrease in maintenance and associated costs, as vibrations is a main factor in the degradation of the superstructure and rolling stock. These vibrations can be damped at the source (i.e. train or tram), along it’s transmission path (the focus of this document) or at the receiver (a very costly measure). Various off the shelf products are already available to reduce the transmission of these sound and vibration, and are listed in this section.

1.2.2.1. **Rail pads and rail bearings**

![Rail pad and rail bearing](www.getzner.at/werkstoffe)

This is the simplest solution to isolate rail track systems. As can be seen in Figure 1.2.1, an elastic element is introduced between the rail and sleeper (rail pad) or slab track (rail bearing). This type of intervention can be easily retrofitted to existing systems but is limited toward the vibration isolation it offers (www.cdm.be). These materials are usually very thin (less than 10 mm) to limit the static deformation of the rail (www.cdm.be). Rail pads are always subjected to a preload (due to the fastening mechanisms) and this can have a large influence on their dynamic properties making them less effective.

1.2.2.2. **Sleeper and base plate pads**

![Sleeper and base plate pad](www.getzner.at/werkstoffe)

This is another simple solution to isolate rail track systems. As can be seen in Figure 1.2.2, an elastic element is introduced between the sleeper and ballast (sleeper pad) or base plate and slab track (base plate pad). This type of intervention can also be easily retrofitted to existing systems and sleeper pads are sometimes incorporated into the design of the sleeper (www.getzner.at/werkstoffe). These materials are usually thicker (approx. 20 mm) and in the case of sleeper pads may require extra protection from the ballast stones (the stones have sharp edges which may damage the pads).
1.2.2.3. Floating trackbeds and ballast mats

![Ballast and base mat](www.getzner.at/werkstoffe)

This is the most effective solution to isolate rail track systems. As can be seen in Figure 1.2.3, an elastic element is introduced between the supporting foundation and the ballast (ballast mat) or slab track (base mat). This type of intervention provides a high degree of damping and is usually incorporated into the design of a rail track system from the start. The ballast and slab track acts as inertia mass and results in a large static load. To be most effective this system is usually used with side mats and in the case of slab tracks even isolators such as steel springs can be used (www.cdm.be).

1.2.2.4. Embedded rails

![Embedded rail](www.getzner.at/werkstoffe)

This is a much specialised solution to isolate rail track systems, it is exclusively used for light rail transport (such as trams) where the rail and road infrastructure are shared. As can be seen in Figure 1.2.4, an elastic filler material is introduced on the sides of the rail and a rail pad encapsulates this assembly. Some manufacturers combine the rail pad and filler. This type of intervention provides a high degree of damping for re-radiated noise and vibration to the foundations and surrounding environment. As these rails are usually embedded in concrete, they are designed to bind with the surrounding concrete and some manufacturers incorporate these rails with a special sleeper to aid with this binding.

1.2.2.5. Resilient sleepers

![Resilient sleeper](www.getzner.at/werkstoffe)

This sleeper is the combination of a number of the solutions mentioned above. As can be seen in Figure 1.2.5, two reinforced concrete platforms are joined with a wooden beam and encapsulated in a
polymer. To further aid with damping, there are elastic rail pads, mantles and sleeper pads incorporated in the design. These sleepers can be used without ballast, their installation is straightforward and they typically last longer than traditional sleepers (www.cdm.be).

1.2.3. Literature review

A large number of articles were published in the literature which deals with damping and rail applications. This study is concerned with the modelling, testing and quantifying of the material properties (especially damping) of viscoelastic materials and therefore the focus was placed on articles pertaining to this. More literature was also sought on general damping and track models (where damping models are usually implemented) to put the testing in context. Since damping can used to minimise sound transmission from rail traffic, a few articles were found on noise generated by rail traffic. As a last point of interest, tuned damping devices were investigated as an alternative method to reduce vibrations.

1.2.3.1. Viscoelastic damping/tests

The most general laboratory test standard for determining the vibration and acoustic transfer properties of resilient materials is ISO-10846 (1997). ISO-10846 (1997) can be used to determine the transmission of low frequency (1 Hz to 80 Hz) vibrations by these elements but makes a number of assumptions. It assumes linearity of the behaviour of the isolator and that all contact surfaces can be considered to be point contacts. According to ISO-10846 (1997) there are three different test methods (direct, indirect and driving point method) that can be used to test the properties of resilient elements used for support.

Carrascal et al. (2007) tested rail pads to determine the degradation experienced by these pads. The pads were fatigue tested at various operating temperatures, humidity and loads for up to 200 000 cycles to determine how their dynamic properties changes over time. They evaluated this deterioration in terms of the dissipated energy per cycle and the change in dynamic stiffness. It was found that the major source of degradation is humidity, in the worst case a stiffness increase of 12% was found. Dynamic stiffness tests were conducted for 1 000 cycles at 5 Hz at different temperatures. To evaluate the change in static stiffness, the pads were tested at five different conditions for 200 000 cycles at 5 Hz with loads between 18 kN and 93 kN.

Carrascal et al. (2007) also conducted conventional fatigue tests for 2 x 106 cycles at room temperature at the same load variation as the dynamic stiffness tests. It was observed that the greatest variation in energy dissipation and dynamic stiffness took place during the first 200 000 cycles and becomes less pronounced thereafter. The dynamic stiffness increased by 18,5 % and the energy dissipation decreased by 41,6 %. It was also noted that the temperature of the pad increased by 7° C during these fatigue tests.

Dall’Asta (2006) et al. tested high damping rubber (HDR) with the aim of to obtain accurate material properties and to develop a non-linear viscoelastic damage model for cyclic loads. HDR consists of natural rubber with black carbon filler added to increase damping and strength. This filler also adds some undesirable material properties. HDR dampers are a very promising energy dissipation devices, they permit energy dissipation even for small events (wind or minor earthquakes) and has no “memory”.

D0602_M48_UITP_SP1.doc
Viscoelastic and viscous dampers have similar properties, but their energy dissipation capacity are sensitive to strain-rates.

Dall’Asta (2006) et al. subjected various materials to tests at various frequencies and amplitudes. Their stiffness and dissipating properties were classified by using three parameters ($K_{\text{eff}}$, $R$, $\xi$). Where $K_{\text{eff}}$ is the conventional stiffness, $R$ gives information about the energy dissipated per cycle (at a specific amplitude) and $\xi$ is the equivalent viscous damping coefficient. Over a test period of three years, the values of $K_{\text{eff}}$, $R$ and $\xi$ reduced by 22 %, 58 % and 15 % respectively. It was also found that the stiffness ($K_{\text{eff}}$) decreases and $R$ increases with increasing amplitude. The stiffness and energy dissipating properties shows major increases when the strain rate is higher than 1 s$^{-1}$. An analytical model was then developed for use in seismic applications.

Guigou-Carter et al. (2006) tested rail pads and resilient sleeper pads to determine their dynamic stiffness. Their tests were conducted by using the direct method and the setup was tested with various combined horizontal and vertical pre-loads. An analytical model for the track system was then developed. For this model, the damping of each component was modelled as hysteric damping. It was found that the resonance frequency decreases when the unsprung mass of the train increases and/or the dynamic stiffness of the sleeper pad is decreased. For their model, there was a decrease in vibrations above the resonance frequency and they found that the model could be used to make more informed choices for rail pads.

As previously mentioned, Guigou-Carter et al. (2006) used the direct test method. They used two different static load set-ups during testing, the one setup applied 40 kN vertically and 10 kN horizontally while the other setup applied 64 kN vertically and 5 kN horizontally. It was found that that the test rig could only be validated for excitation frequencies below 50 Hz (testing was done at 8 Hz, 16 Hz and 31.5 Hz) since the blocking force correction became very pronounced at higher frequencies. For an excitation frequency of 8 Hz, the dynamic stiffness increased by 12 % for both load cases. For the higher frequencies, the dynamic stiffness increased by more than 20 % for the vertical static load of 40 kN and an increase of up to 20 % was found for the 64 kN vertical static load. It was found that the dynamic stiffness increased with increasing static loads, as the model predicted.

Vriend and Kren (2004) investigated an alternate method for quantifying the mechanical properties of viscoelastic materials. This method is called the dynamic indentation method and the Kelvin-Voigt damping model is used to describe the material behaviour. Hardness tests of the material is used to estimate the various properties of materials and the process is similar to the Shore hardness measurement which is already widely used. Traditionally static indentation was used to determine the material properties but with viscoelastic materials, the material properties are velocity dependant so a dynamic method is more appropriate. The model generated by Vriend and Kren (2004) is similar to the Kelvin-Voigt model and makes use of the measured logarithmic decrement to determine the rigidity ($c$) and the viscosity of the material. During testing, it was found that there is a phase shift and residual deformation in the material. The experimental data also showed good correlation for low hardness rubbers without significant creep and can therefore be used to reliably model the damping.
Maciose (2003) explained some methods for quantifying the level of viscoelastic damping in materials. Viscoelastic damping is proportional to the strain and independent of the rate, and can be expressed as follow:

\[ E = E_1 + iE_2 = E_1 (1 + i \eta) \]

where \( E_1 \) is Young’s storage modulus, \( E_2 \) is the loss modulus and \( \eta \) is the loss factor.

The various methods used were the half-power bandwidth (or 3 dB) method, the amplification factor method, the logarithmic decrement method and the hysteresis loop method. The various methods can be compared for low levels of damping where linear behaviour can still be expected.

Maes et al. (2006) tested rail pads and experimentally determined values for the stiffness and damping values (by using a loss factor). Their tests were conducted by using the direct method and they tested in the 20-2500 Hz frequency range with variable pre-loads and three different materials. The materials they studied are all available railpads, these are EVA (the reference pad), DPHI (polyurethane and cork rubber pad) and SRP (resin-bonded rubber pad). They also developed a material model that can be used in a non-linear numerical track model.

Maes et al. (2006) noted that there are three common ways of modelling the dynamic behaviour of rail pads:

- A spring and viscous dashpot in parallel (Kelvin-model) – easy to implement but limited in applications.
- A model with structural damping and a loss factor – very consistent with behaviour of rubber etc. (but limited to a single frequency).
- A model with three parameters (Poynting-Thompson model) – some advantages but very difficult to reliably obtain the parameters.

It was found that finding numerical material models by fitting curves to the experimental data from in situ (onsite) tests has certain shortcomings. These measurements are mostly applicable to a particular measured track and are rarely able to take into account the non-linear stiffness of the pads. Laboratory measurements are therefore necessary to obtain more accurate data.

Maes et al. (2006) made use of the direct method for testing rail pads since small specimens (25 mm x 30 mm) were tested and the loads used were relatively small. The rail pads were tested at preloads of 375, 500, 625, 750 and 1000 N. These loads are equivalent to loads of 15, 20, 25, 30 and 40 kN in rail applications with the first two loads being comparable to the average preloads of rail fixation systems.

The dynamic transfer stiffness and loss factors were then calculated with the guidelines in ISO-10846 and the results were presented for a 500 N preload. It was found that the dynamic stiffness of the pads increase with frequency (very pronounced above 2000 Hz) and preload. It was also found that the EVA pad is the stiffest and the most frequency dependant, while that of the DPHI and SRP pads had similar frequency dependant behaviour. The behaviour observed in the rail pads was similar to at least two other independent reports, keeping in mind that different sizes and materials were used. The results for the loss factor were similar, it also increases with frequency but seems to be independent of the preload.
It was found that the DHPI pad had the highest loss factor and the loss factor of the EVA pad didn’t show the same trend as the other two (possibly because it is stiffer).

Finally, Maes et al. (2006) used a modified Poynting-Thompson (P-T) model for their material model. The dynamic stiffness of the model shows good correlation with the measured results up to 2000 Hz. Above 2000 Hz, this model cannot keep up with the increase in dynamic stiffness. The model of the dynamic damping shows very little correlation to the measured data.

Lin et al. (2005) developed a new test method to determine the frequency dependant behaviour of viscoelastic materials using an impact test. The measured frequency response function and a least squares polynomial curve fitting of test data were used to generate a model for the dynamic stiffness and damping of the material, using a hysteric damping model. The test setup made use of accelerometers and a modal hammer. A fast Fourier transform (FFT) of the system response was then analysed to determine the stiffness and damping values of the material.

It was found that only a region (100 – 300 Hz) of the calculated damping coefficients could be used for the least squares evaluation since low frequency rocking motions and noise on the measured signals were present in the obtained data. Frequency dependant functions for the damping coefficients were found and it was assumed that this function is linear in the relevant frequency range. This function had a maximum error of 10% within the specified frequency range. The stiffness was calculated in three different frequency ranges: below resonance (50 to 135 Hz), within the resonance band (135 to 183 Hz) and above resonance (183 to 600 Hz).

To verify the models obtained, the direct method was used and it was found the stiffness values shows a good correlation below 300 Hz. Above 300 Hz, significant deviations were found and the damping was found to show good correlations below 250 Hz. It was also found that the effects of static preload can be taken into account by adjusting the mass and the amplitude of the impact force.

Lapčík et al. (2001) tested rail pads to determine their dynamic stiffness. Their tests were conducted according to the German DB-TL 918.071 standard and they tested in the 10-100 Hz (at 2 Hz intervals) frequency range with varying static pre-loads (0,03, 0,06 and 0,1 MPa). They observed an increase in dynamic stiffness with frequency and/or static-preload.

It was observed that the materials were more compliant at frequencies below 40 Hz and that the dynamic stiffness is dependent on the amplitude of the vibrations. Decreasing the amplitude tenfold led to maximum decreases of 16,2 %, 15,5 % and 13,5 % for the dynamic stiffness with preloads of 0,03, 0,06 and 0,1 MPa respectively. These changes are relatively small and the amplitude dependence of the dynamic stiffness is not very strong.

Nakra (1998) discussed some of the commercial uses of viscoelastic materials with the focus on vibration control. The two basic forms of energy dissipation are direct and shear strains in the viscoelastic material. Non linearity of the material can be characterized by a loss factor (ηs), which is the ratio of energy dissipated to energy stored in the material.
If a harmonic stress is applied to a viscoelastic material, the stress in the material tends to lag behind the input by an angle $\theta$. Another difficulty with quantifying viscoelastic materials is the fact that they exhibit different mechanical properties for direct and shear strain, these properties are also dependant on strain rate, frequency and temperature. Nakra (1998) also discusses methods to take all these factors into account by using fractional calculus.

Remillat (2007) investigated the damping properties of composite materials, especially polymers filled with elastic particles. The approach followed was self-consistent homogenisation and the elastic-viscoelastic correspondence principle was also used. Remillat (2007) used a composite sphere model to include the different mechanical properties of the different materials and the outcome was to optimise the damping of these composites.

The results/conclusions of previous studies are summarised in Table 1.2.1 below.

<table>
<thead>
<tr>
<th>Observation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness decreases due to fatigue</td>
<td>Dall’Asta (2006)</td>
</tr>
<tr>
<td>Dynamic stiffness decreases as humidity increase</td>
<td>Carrascal et al. (2007)</td>
</tr>
<tr>
<td>Dynamic stiffness increases as due to fatigue</td>
<td>Carrascal et al. (2007)</td>
</tr>
<tr>
<td>Dynamic stiffness increases with increasing strain rate (frequency)</td>
<td>Dall’Asta (2006), Maes et al. (2006), Lapčík et al. (2001)</td>
</tr>
<tr>
<td>Dynamic stiffness increases with increasing static load</td>
<td>Guigou-Carter et al. (2006)</td>
</tr>
<tr>
<td>Dynamic stiffness increases with and increase of preload</td>
<td>Maes et al. (2006), Lapčík et al. (2001)</td>
</tr>
<tr>
<td>Dynamic stiffness decreases with decreasing load amplitude</td>
<td>Lapčík et al. (2001)</td>
</tr>
<tr>
<td>Energy dissipation decreases as a result of fatigue</td>
<td>Carrascal et al. (2007), Dall’Asta (2006)</td>
</tr>
<tr>
<td>Energy dissipation increases when strain rate increases</td>
<td>Dall’Asta (2006)</td>
</tr>
<tr>
<td>Equivalent viscous damping decreases as a result of fatigue</td>
<td>Dall’Asta (2006)</td>
</tr>
<tr>
<td>Loss factor increases with increasing strain rate</td>
<td>Maes et al. (2006)</td>
</tr>
<tr>
<td>Loss factor appears to be independent of preload</td>
<td>Maes et al. (2006)</td>
</tr>
<tr>
<td>Resonance frequency decreases with an increase in load and/or decrease in dynamic stiffness</td>
<td>Guigou-Carter et al. (2006)</td>
</tr>
</tbody>
</table>

Table 1.2.1 Results/conclusions found in literature

### 1.2.3.2. General damping

Bandstra (1983) compared nonlinear damping models with their viscous equivalents by using the energy dissipated per cycle as measure. Viscous, velocity squared, Coulomb, displacement squared and solid (hysteric) damping models were studied and forced as well as transient vibrations applied. Bandstra found that for forced vibrations, these viscous equivalents underestimate the energy dissipated per cycle as well as the steady state amplitude. When considering transient vibrations, these viscous equivalents show different decay shapes (for Coulomb, displacement squared and solid damping) and times. In general the damped natural frequencies were different using viscous equivalents but the differences were considered insignificant.

Bandstra (1983) found that the equivalent viscous damping method can be used for “fairly accurate” predictions as long as the damping is below 10 percent. The frequencies at which this method can be
implemented is critical, in general this technique is not suited for excitation frequencies close to the natural frequency. Finally, if this method is to be implemented accurately, the actual energy dissipation of the nonlinear model has to be known.

Adhikari and Woodhouse (2001) developed a general damping model. This model can be used for both viscous and non-viscous damping and is restricted to linear systems with light damping. Their model takes energy dissipation of a system into account and uses complex experimental data to obtain the parameters for a “relaxation function”. A non-viscous damping model is used with convolution integrals over kernel functions. These convolution integrals enable the damping model to depend on the time-history. The kernel function (also called the “relaxation function”) is an exponential model which is fitted to measured data.

Numerical experiments were conducted with various damping models and parameters. The model was shown to predict the spatial location of the damping accurately and the transfer functions obtained from the model also agree with the exact transfer functions of the system. This is a promising model, although it could be too complicated.

Adhikari and Woodhouse (2001) explained how it can be determined whether a system has viscous or non-viscous damping. The method for quantifying viscous damping is the half-power bandwidth method and the method for quantifying non-viscous damping is iterative.

Woodhouse (1998) investigated linear damping models with emphasis on structural vibration. Two different models were investigated, the dissipation-matrix and general linear model. To simplify the analysis, small damping was assumed and simple expressions for the damped natural frequencies, complex mode shapes and transfer functions were found.

The different damping mechanisms for structural damping can be divided in three different classes:
- Distributed energy dissipation throughout the bulk material (“material damping”).
- Energy dissipation through the junctions or interfaces between the parts of the structure (“boundary damping”).
- Energy dissipation through a fluid in contact with the structure.

A simple numerical model of a two-degree-of-freedom was used as an example for the method and this model provides accurate results over a wide range of values for the different parameters. Woodhouse (1998) also found that it is very difficult to determine the appropriate damping model for a structure since it is very frequency dependant.

Maia et al. (1998) developed a damping model for materials whose behaviour cannot be modelled accurately by the current viscous or hysteric models (like materials with a complex Young modulus). They used the theory of fractional derivatives to develop quite a complicated model.
1.2.3.3. **Track models**

Castellani (2000) developed a mathematical model for the vibrations generated by urban rail vehicles on floating slab tracks. Castellani (2000) measured the displacement and acceleration of a floating slab track when a locomotive with seven passenger cars travels over it at 90 km/h and compared the results to a numerical simulation. The numerical simulation exhibited a good correlation to the physical set-up up to about 63 Hz. Castellani (2000) also found that a major shortcoming in his model was description of elastomeric (resilient) materials with frequency dependant behaviour. These materials show strain rate sensitivity and hysteretic energy dissipation.

Zhai and Cai (1997) generated a numerical model for the dynamic interaction between a rail vehicle and a train track. The different components of the system were mainly modelled as springs, dampers and masses with the ballast being modelled as shear springs and dampers. The wheel/rail interaction was modelled with non-linear Hertzian theory and the equations of motion were solved with Newmark’s explicit integration scheme. Experimental validation of the model was done through various field tests and the model showed good correlation with actual train tracks.

Zhai et al. (2004) focused on the damping mechanisms in the ballast of train tracks. They implemented shear damping and stiffness to model the interaction between the particles. This model was then verified by field testing and found to agree well. The calculated resonance frequencies were on average lower than the measured values, 70-100 Hz compared to 80-110 Hz.

Fiala et al. (2007) developed a numerical model that can be used to predict the vibrations and reradiated sound in buildings due to surface rail traffic. This model accounts for a moving vibration source, dynamic soil structure interaction and sound propagation through layered ground. The methods used are explained using a numerical example and the model shows good correlation for relatively stiff soil and direct excitation of the foundation.

Fiala et al. (2007) further states that the dominant frequencies with regards to noise is determined by the acoustic resonance of the room, this acoustic resonance is very dependant on the wall absorption and room dimensions. It was also found that base isolation is the most effective solution for noise isolation and that the model is very dependant on material properties as well as structural details of the buildings.

Karlström et al. (2006) developed an analytical model to predict ground vibrations caused by railways. The main components involved were rails, sleepers, ground and a rectangular embankment which supports sleepers and rails. There is therefore no railpads or other elastic components involved and focus is placed on modelling the ground vibrations.

Karlström et al. (2006) drew a comparison between two FEM and analytical modelling methods. Analytical methods offer fast computational times and infinite domains but is rather limited towards geometry and nonlinear behaviour. FEM (and other discrimination) methods overcomes the limitations of analytical approaches but has the disadvantages of struggling with infinite domains, long computational times and a small discretised region (it could only deal with 40 m of track).
The results for the model at speeds of 70 km/h and 200 km/h were compared to simplified models and measured data. The simulation was found to agree almost exactly with measured data at low speeds and showed good correlation with the measured data at high speed. The simulation was found to show good correlations with the simplified models up to 1 Hz and then starts differing significantly.

Cox et al. (2006) designed and manufactured a test rig to evaluate slab track structures for specifically underground railways. The main aim was to develop a test rig that bridges the gap between full scale and bench top tests with regard to the measurement/comparison of the dynamic properties of various fixation fastening systems. The frequencies they were mostly interested in was between 40 and 120 Hz as these frequencies are most likely to cause disturbances in surrounding buildings.

A major shortcoming of testing in the field was found to be variables such as train speed as well as soil conditions and therefore a test rig could be better suited for comparison purposes on a shorter timeframe. The track was tested for nine different configurations each using different fasteners and/or railpads. Cox et al. found the measured natural frequencies to be higher than in physical systems since their test rig does not include an equivalent to the unsprung mass of the rail vehicle.

An “excitation” model was used to extract parameters for the resilient elements in the tests. The values for dynamic stiffness and damping were adjusted so the response of the model mimicked the measured responses for each different resilient material. This method is limited since only a single dynamic stiffness value can be obtained at a specific frequency. The study found that floating slab tracks perform best when fitted with soft rail fasteners especially in the frequency ranges of concern.

Lombaert et al. (2006) developed a three-dimensional numerical model for normal train track systems and high speed (200 km/h plus) trains. This model was validated against various physical systems. Experiments were used to determine the dynamic characteristics of the soil and track, the transfer functions of the soil, the transfer functions of the track-soil and the vibrations of the track as well as the free field. Further experiments were also conducted to verify the numerical model. The rail pads were modelled as continuous spring-damper connections and no attention was given to complex damping characteristics.

The validation of the numerical model showed relatively good agreement for the track-free field transfer functions, but the numerical model overestimated the response at small distances. The numerical model for the sleeper response and free field vibrations showed good agreement with the measured data although it has a very high dependence on soil properties and a high level of uncertainties. It was also found that a better understanding of the train-track interaction is needed and more field testing is needed (in general this article is not very applicable to this work since the speeds involved are much higher and the focus is on the soil’s transfer properties (vs. the rail pad properties)).

Kaewunruen and Remennikov (2006) conducted as sensitivity analysis to determine the sensitivity of a concrete sleeper to variations in rail pad parameters. Finite element analysis was used and the rail pad stiffness was varied between 0 and 5000 MN/m with a maximum rail stiffness of 100 MN/m. Their finite element model incorporated sleeper/ballast interaction and the focus of analysis was on in situ mono-
block concrete sleepers. The sleepers’ changes in natural frequencies and dynamic mode shapes were used as comparison between different rail pads.

It was found that rail pad stiffness has a non linear effect on the effective stiffness of the track system and that it mainly affects the first three vibration modes. High effective stiffness can cause changes in the flexural mode shapes of the track.

Lombaert et al. (2006) developed a three-dimensional numerical model for continuous slab track systems. This model was used to determine the effect of various soil, slab and resilient slab mat parameters on the vibration transfer characteristics of the system. The main area of interest was the comparison between normal (un-isolated) slab track and floating slab track systems for different (soft and stiff) soils. It was found that floating slab track systems have pronounced responses at low frequencies and is better suited to applications where the frequencies involved are higher.

Lombaert et al. (2006) also stated that the resonance frequency of the slab track system should be as low as possible for minimum transmissibility. This resonance frequency is generally limited by the maximum allowable static rail deflection, and physical systems can have resonance frequencies as low as 8 to 16 Hz.

Vostroukhov and Metrikine (2003) developed an analytical model for a railway track that is supported by viscous-elastic pads. These pads were modeled according to the Kelvin-Voigt model. The main aim of their model was to determine the elastic drag that a high speed train experiences and they found that the elastic drag is comparable to aerodynamic drag at high velocities.

Nielsen and Oscarsson (2004) developed a numerical method for simulating the dynamic train-track interaction. This method separates the track properties into linear (associated with the unloaded track) and non-linear (associated with the dynamic loading) contributions. A moving mass model was then employed for simulation purposes. The dynamic properties of the rail pads was determined in laboratory measurements and quantified with a three parameter state-dependant viscoelastic model. The model as well as simulation data were compared to field measurements.

Picoux and Le Houédec (2005) developed and validated a numerical model for the vibration generated by trains. The main aim was to model vibrations in the soil and a fairly complex three dimensional model was developed. In situ testing was done to verify this model, these tests made use of optical as well as acceleration measurements. It was difficult to compare numerical and measured data since the excitation frequency was quite difficult to determine, but good agreement was found and the model can be used for further analysis purposes.

1.2.3.4. Sound

Heckl et al. (1996) studied the sources of structure-borne sound and vibration caused by rail traffic. They found that the dominant frequencies for noise was in the range of 40 - 100 Hz and are mostly related to the wheel/track resonance. They also found that most ground vibrations are dominant in the 40 – 80 Hz range, but these vibrations are very dependent on the train speed and infrastructure.
They investigated various possible vibration generation mechanisms distinguishing between supersonic motion and accelerated motion. Supersonic motion causes a Mach cone in front of an object when it’s moving forward at a speed greater than the wave speed in the medium it is moving. Only bending wave speed in the rails and Rayleigh waves in the ground were considered as they had wave speeds which could be lower than that of the train. It was found that neither of these waves were slow enough to coincide with the speeds that normal passenger trains travel at.

Other major contributors to ground-borne vibration are flat spots in wheels, rail gaps and surface irregularities of the rail or wheel. It was found that a maximum acceleration of 1 m/s² at 50 Hz can be caused by a train travelling at 144 km/h with an irregularity in one of its wheels. Parametric excitation was also investigated and it was found that stiff rails can solve most of the problems associated with it. It was also found that the wheel-ballast resonance is at about 66 Hz which makes it very dependant on train speed (slow trains can more easily excite this frequency).

With further investigation, they found that the most effective solution to the vibrations involve a highly resilient element and a very big dead weight (typical of floating trackbeds and ballast mats). Other solutions include smoother wheels and tracks, stiff rails and various resilient elements along the transmission path of vibrations.

Alvelid and Enelund (2007) developed a special finite element model for the rubber in a steel-rubber-steel sandwich. The type of rubber modelled was “Nitrile” and this type of sandwich is usually used for sound insulation. In general this article is not really very applicable to this work since the rubber layers are very thin, and therefore stiff. Their model was compared to an ABAQUS finite element model as well as an analytical solution and found to be accurate and efficient.

1.2.3.5. Tuned damping devices

Thompson et al. (2007) investigated a tuned damping device for reducing the sound radiating from a rail track. This device was designed to be fitted to existing rail tracks and field measurements showed a reduction of up to 6 dB(A) for the installed prototype. The prototype has been successfully installed in various European countries and this project was part of the European Union Silent Track project.

Maes and Sol (2003) developed a double tuned rail damper. This device is mounted to a rail and was designed to minimize the first two pinned-pinned frequencies (950 and 2 200 Hz) and a prototype was tested to determine its effectiveness. The device was successful and the wave decay rates increased by 1,5 dB/m and 0,5 dB/m for the vertical and lateral vibrations respectively.

1.2.3.6. Summary

The most relevant reference found was the ISO-10846 test standard (1997), this is an international test standard for resilient/viscoelastic materials and outlines test procedures. The articles by Dall’Asta (2006), Guigou-Carter et al. (2006), Friend and Kren (2004), Maciose (2003), Maes et al. (2006), Lin et al. (2005), Lapčík et al. (2001) and Remillat (2007) mostly deals with the testing/quantifying of materials and generation of a subsequent material model and their conclusions are summarised in table 1.2.1.
Nakra (1998) gave an overview of viscoelastic materials and their damping characteristics. The articles by Heckl et al. (1996) as well as Alvelid and Enelund (2007) cover noise generated by rail traffic and measures to reduce it. Many articles focus on damping as a whole, they usually describe the most common damping models and provide some form of interrelationships between the models. Articles focusing on these themes include Bandstra (1983), Adhikari and Woodhouse (2000), Adhikari and Woodhouse (2001), Woodhouse (1998) and Maia et al. (1998). Carrascal et al. (2007) studied the time/fatigue effects of the material properties of rail pads.

The most common articles found dealt with numerical models of rail infrastructure. These models usually have various springs, dampers and other models to represent the different components/materials present. Articles by Castellani (2000), Zhai and Cai (1997), Zhai et al. (2004), Fiala et al. (2007), Karlström et al. (2006), Cox et al. (2006), Lombaert et al. (2006), Kaewunruen and Remennikov (2006), Lombaert et al. (2006), Picoux and Le Houédec (2005), Nielson and Oscarsson (2004) as well as Vostroukhov and Metrikine (2003) all follow the same basic methodology.

The most common way to reduce vibrations generated by rail traffic, is by inserting a resilient/viscoelastic material along the transmission path. Another method that can be used, is tuned mass damping devices. The articles by Thompson et al. (2007) as well as Maes and Sol (2003) focuses on the development and implementation of these tuned devices.
1.2.4. **Single degree of freedom Damping Models**

To compare the different damping models to the well known viscous damping model a simple single degree of freedom system was used as shown in Figure 3.1. The same equivalent viscous damping coefficient (ceq) was used and the damping coefficients (α, b and μFN) of the other damping models was calculated accordingly. The equation of motion for a basic spring-damper system with forced vibration is given by:

\[
\ddot{x} = \frac{1}{m} [f(t) - f_c(t) - kx]
\]

Where \(f(t)\) is the driving force and \(f_c(t)\) is the damping force.

![Figure 1.2.6: Single degree of freedom system diagram.](image)

<table>
<thead>
<tr>
<th>Name</th>
<th>Equation</th>
<th>Equivalent Viscous Damping</th>
<th>Description</th>
<th>Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscous damping</td>
<td>(f_c(t) = c\dot{x}(t))</td>
<td>(c_{eq}(\omega) = c)</td>
<td>Laminar flow through orifice e.g. automotive shock absorbers</td>
<td>Most widely used and easiest to implement</td>
</tr>
<tr>
<td>Velocity-squared damping</td>
<td>(f_c(t) = \alpha \text{sgn}(\dot{x}(t)) \dot{x}(t)^2)</td>
<td>(c_{eq}(\omega) = \frac{8\alpha aX}{3\pi})</td>
<td>Aerodynamic drag e.g. object vibrating in air</td>
<td>Not very applicable to rail systems</td>
</tr>
<tr>
<td>Hysteric damping</td>
<td>(f_c(t) = b \text{sgn}(\dot{x}(t))</td>
<td>\dot{x}(t)|)</td>
<td>(c_{eq}(\omega) = \frac{2b}{\pi \omega})</td>
<td>Internal friction energy loss e.g. rubber mount</td>
</tr>
<tr>
<td>Coulomb damping</td>
<td>(f_c(t) = \mu \text{sgn}(\dot{x}(t)) \dot{x}(t))</td>
<td>(c_{eq}(\omega) = \frac{4\mu F_N}{\pi \omega X})</td>
<td>Friction between two objects e.g. disk brakes</td>
<td>Not very applicable to rail systems</td>
</tr>
</tbody>
</table>

Table 1.2.2 Commonly used damping models
1.2.4.1. Damping Models

**Viscous Damping**

\[ f_v(t) = c \dot{x}(t) \]

This is the “classic” damping model and all the other models were compared against it in our analysis by using the equivalent viscous damping approach. This model is linear with the velocity and is therefore very easy and convenient to use.

**Velocity Squared Damping**

\[ f_v(t) = \alpha \text{sgn}(\dot{x}(t)) \dot{x}(t)^2 \]

This is a damping model usually associated with aerodynamic drag. To compare it to viscous damping, the damping coefficient (\( \alpha \)) can be calculated from:

\[ \alpha(\omega) = \frac{3\pi c_\omega}{8\omega F} \]

where \( \omega \) is the driving force frequency and \( F \) is the amplitude of the driving force. Note the dependency on the input frequency (\( \omega \)), therefore this model can only be used for steady state analysis.

**Hysteric Damping**

\[ f_v(t) = b \text{sgn}(\dot{x}(t)) |\dot{x}(t)| \]

This is a damping model usually associated with viscoelastic materials. To compare it to viscous damping, the damping coefficient (\( b \)) must be:

\[ b(\omega) = \frac{\pi \omega c_\omega}{2} \]

where \( \omega \) is the driving force frequency. Note the dependency on the input frequency (\( \omega \)), therefore again this model can only be used for steady state analysis.

**Coulomb Damping**

\[ f_v(t) = \mu F_v \text{sgn}(\dot{x}(t)) \]

This is a damping model usually associated with friction. To compare it to viscous damping, the damping coefficient (\( \mu F_v \)) can be calculated as:

\[ \mu F_v(\omega) = \frac{\pi \omega F c_\omega}{4} \]

where \( \omega \) is the driving force frequency and \( F \) is the amplitude of the driving force. Note the dependency on the input frequency (\( \omega \)), therefore this model can only be used for steady state analysis.
1.2.4.2. Numerical Simulation

The single degree of freedom system was modelled in Simulink® and initially the damping constant \( c \) as well as the driving frequency \( \omega \) was varied. The system parameters used for the simulation were as follow:

\[
\begin{align*}
m & = 1 \text{kg} \\
\frac{k}{m} & = 100 \text{ N/m} \\
F & = 2 \text{ N}
\end{align*}
\]

The damping constant was varied between 0,2, 2 and 20 Ns/m and the driving frequency was varied between 1 and 100 rad/s. The input force \( f(t) \) was also defined as follow:

\[
f(\omega, t) = F \sin(\omega t)
\]

As can be seen from the equations for the damping coefficients \( \alpha, b \) and \( \mu FN \) the system response can only be modelled for forced vibrations since no damping or infinite damping would occur if the amplitude or frequency of driving force is taken as zero. Therefore to model the free vibration response of the system, an initial displacement was given and a small force was applied. The ODE-45 function of Matlab® was used for numerical solutions of the system.

**Low frequency, forced vibration response**

The following figures all represent the system response for an input frequency of 1 rad/s with increasing damping.

![Graphs showing system response for different damping conditions.](image)

*Figure 1.2.7: Low damping (\( \xi = 0.01 \))
As can be seen from Figure 1.2.4, all of the damping models have similar responses to the viscous damping model. This can be attributed to the low frequencies and the fact that the driving force is more substantial than the damping forces.

![Graph showing damping models comparison](Image)

**Figure 1.2.8: Medium damping (ξ = 0.1)**

As can be seen from Figure 1.2.5 all of the damping models, except for the Coulomb damping model, have similar responses to the viscous damping model. This can be attributed to the low frequencies and the fact that the driving force is more substantial than the damping forces.

![Graph showing damping models comparison](Image)

**Figure 1.2.9: Critical damping (ξ = 1)**

As can be seen from Figure 1.2.6, all of the damping models have similar responses to the viscous damping model. This can be attributed to the low frequencies and the fact that the driving force is more substantial than the damping forces.

![Graph showing damping models comparison](Image)
Forced vibration response at the natural frequency of the system

The following figures all represent the system response for an input frequency of 10 rad/s with increasing damping.

![Figure 1.2.10: Low damping (\(\xi = 0.01\))](image)

As can be seen from Figure 1.2.7, all of the damping models, have similar responses to the viscous damping model. This can be attributed to the low frequencies and the fact that the driving force is more substantial than the damping forces.

![Figure 1.2.11: Medium damping (\(\xi = 0.1\))](image)
As can be seen from Figure 1.2.8, only the Hysteric damping model has a similar response to the viscous damping model. In the case of the Velocity squared model, the damping force is too small to have the desired effect on the system and the displacements are significantly bigger.

Figure 1.2.12: Critical damping ($\xi = 1$)

As can be seen from Figure 1.2.9, none of the other damping models has a similar response to the viscous damping model.

**High frequency forced excitation response**

The following figures all represent the system response for an input frequency of 100 rad/s with increasing damping.

Figure 1.2.13: Low damping ($\xi = 0.01$)
As can be seen from Figure 1.2.10, all of the damping models, except for the Coulomb damping model, have similar responses to the viscous damping model. When the spring force becomes too small to overcome the damping force, movement ceases to a large extent in the Coulomb damping model.

Figure 1.2.14: Medium damping (\(\xi = 0.1\))

As can be seen from Figure 5.9, only the Hysteric damping model has a similar response to the viscous damping model. The Velocity Squared and Coulomb damping models also seem to have the same responses.

Figure 1.2.15: Critical damping (\(\xi = 1\))
As can be seen from Figure 1.2.12, only the Hysteric damping model has a similar response to the viscous damping model. The Velocity Squared and Coulomb damping models also seem to have similar responses.

**Free vibration response**

The following figures all represent the system response for an initial displacement of 1 m with increasing damping.

![Figure 1.2.16: Low damping (\(\xi = 0.01\))](image)

As can be seen from Figure 1.2.13, all of the damping models initially have similar responses to the viscous damping model.

![Figure 1.2.17: Medium damping (\(\xi = 0.1\))](image)
As can be seen from Figure 1.2.14, only the Hysteric damping model has a similar response to the viscous damping model. When the spring force becomes too small to overcome the damping force, movement ceases in the Coulomb damping model.

![Graphs showing damping models](image)

Figure 1.2.18: Critical damping ($\xi = 1$)

As can be seen from Figure 1.2.15, none of the damping models has a similar response to the viscous damping model. The Hysteric and Coulomb damping models both have a very long decrement time when compared to the viscous damping model.
1.2.5. Relaxation isolator damping models

Figure 1.2.19: Relaxation isolator damping models

The models shown in Figure 1.2.16 are used to represent systems with a strong frequency dependency and the model on the left (a) is also known as the Poynting-Thompson (P-T) model. Maes et al. (2006) showed that this model can be used with great success to model the dynamic stiffness of elastic pads up to frequencies of 2000 Hz but cannot provide accurate modelling of the dynamic damping. To compare these models with a normal single degree of freedom system, we derived the equations of motion as follow:

\[
\ddot{x}_1 = \frac{1}{m} \left[ f(t) + k_1 x_1 - (k_1 + k_2)x_2 \right]
\]
\[
\ddot{x}_2 = \frac{1}{c_1} \left[ k_1 (x_1 - x_2) \right]
\]

a)

\[
\ddot{x}_1 = \frac{1}{m} \left[ f(t) + k_1 (x_2 - x_1) + c_1 (\dot{x}_2 - \dot{x}_1) \right]
\]
\[
\ddot{x}_2 = \frac{1}{c_1} \left[ k_1 x_1 + c_1 \dot{x}_1 - (k_1 + k_2)x_2 \right]
\]

b)

The system was modelled in Simulink® and initially the damping constant (c) as well as the driving frequency (ω) was varied. The system parameters used for the simulation were as follow:

\[
m = 1\text{kg} \\
F = 2\text{N}
\]

The damping constant was varied between 0.5, 2 and 20 Ns/m and the driving frequency was varied between 1 and 100 rad/s. The input force (f(t)) was also defined as follow:

\[
f(\omega, t) = F \sin(\omega t)
\]
The total spring stiffness in the system \( k \) was the same as previously used \((100N/m)\) and therefore the individual spring’s stiffness was to be calculated accordingly. To simplify the analysis, the two springs \( k_1 \) and \( k_2 \) were assumed to be equal and spring laws were used to calculate their stiffness as follow:

\[
\begin{align*}
    a) & \quad k_1 = k_2 = 50N/m \\
    b) & \quad k_1 = k_2 = 200N/m
\end{align*}
\]

**Low frequency, forced vibration response**

The following figures all represent the system response for an input frequency of 1 rad/s with increasing damping.

![Graphs showing system response](image)

**Figure 1.2.20: Low damping \((c = 0.5 Ns/m)\)**

As can be seen from Figure 1.2.17, the Series Relaxation model has a very similar response to the Viscous damping model. It was also found that the numerical solver (ODE-45) has great difficulty when the simulation is run for a long time and/or the damping value is too small (the previous value of 0.2 Ns/m could not be used). The Parallel Relaxation model also shows a similar (albeit larger) response.
As can be seen from Figure 1.2.18, the Series Relaxation model has a very similar response to the Viscous damping model. The Parallel Relaxation model also shows a similar (albeit larger) response.

As can be seen from Figure 6.4, the Series Relaxation model has a very similar response to the Viscous damping model. The Parallel Relaxation model also shows a similar (albeit larger) response.

**Medium frequency, forced vibration response**

The following figures all represent the system response for an input frequency of 10 rad/s with increasing damping.
Figure 1.2.23: Low damping (c = 0.5 Ns/m)

As can be seen from Figure 1.2.20, the Series Relaxation model has a very similar response to the Viscous damping model. It was also found that the numerical solver (ODE-45) has great difficulty when the simulation is run for a long time and/or the damping value is too small (the previous value of 0.2 Ns/m could not be used). The Parallel Relaxation model doesn’t show a significantly similar response to be useful (it’s out of phase).

Figure 1.2.24: Medium damping (c = 2 Ns/m)

As can be seen from Figure 1.2.21, the Series Relaxation model has the most similar response to the Viscous damping model. The Parallel Relaxation model doesn’t show a significantly similar response to be useful (it’s out of phase).
Figure 1.2.25: High damping (c = 20 Ns/m)

As can be seen from Figure 1.2.22, none of the Relaxation models are really applicable for use with this set of parameters. Different stiffness’ and/or ratios between the two different stiffness’ could possibly better the model responses.

**High frequency, forced vibration response**

The following figures all represent the system response for an input frequency of 100 rad/s with increasing damping.

Figure 1.2.26: Low damping (c = 0.5 Ns/m)

As can be seen from Figure 1.2.23, the Series Relaxation model has a very similar response to the Viscous damping model. It was also found that the numerical solver (ODE-45) has great difficulty when the simulation is run when the damping value is too small (the previous value of 0.2 Ns/m could not be used). The Parallel Relaxation model doesn’t show a significantly similar response to be useful (it’s out of phase).
As can be seen from Figure 1.2.24, the Series Relaxation model has the most similar response to the Viscous damping model. The Parallel Relaxation model appears to start showing a similar response after two seconds.

As can be seen from Figure 1.2.25, the Series Relaxation model has the most similar response to the Viscous damping model. The Parallel Relaxation model doesn’t show a significantly similar response to be useful.

*Free vibration response*

The following figures all represent the system response for the following initial displacements:

\[ x_1 = 1m \]
\[ x_2 = 0.5m \]
As can be seen from Figure 1.2.26, the Series Relaxation model has a very similar response to the Viscous damping model. It was also found that the numerical solver (ODE-45) has great difficulty when the simulation is run when the damping value is too small (the previous value of 0.2 Ns/m could not be used). The Parallel Relaxation model doesn’t show a significantly similar response to be useful (it’s out of phase).

As can be seen from Figure 1.2.27, the Parallel Relaxation model has the most similar response to the Viscous damping model. The Series Relaxation model doesn’t show a significantly similar response to be useful.
As can be seen from Figure 1.2.28, the Series Relaxation model has the most similar response to the Viscous damping model. The steady state response of the Parallel Relaxation model seems to be similar to the response of the Viscous damping model.
1.2.6. Conclusions and Recommendations

1.2.6.1. Conclusions

Many authors have studied the effect of damping in rail systems over the years. The literature review included in this report contains a number of very informative papers. The most important conclusions one can draw from the literature is that:

The damping coefficient of materials depends on preload, strain rate, temperature, humidity and age. Hysteretic damping models give accurate results albeit for only the frequency at which it applies. More general approaches are possible, with more complicated, non-linear models but with the added complexity of obtaining a larger number of parameters from testing.

In general, the articles showed that previous work has been done in this field and that it is a major difficulty to obtain accurate parameters that is applicable to a wide range of operating conditions. This will be an area that will be further investigated in this project.

When comparing the different discrete single degree of freedom damper models, the Hysteric damper model is the best suited for modelling materials with frequency dependant material properties. However this model is only valid for the frequency at which the hysteretic damping value is calculated and it can therefore not be used in a general sense.

When comparing the different Relaxation models, the Series Relaxation model’s response is the closest to that of a viscous damper. These models, with more complexity, could possibly be used to more accurately model frequency dependant material properties, although obtaining the correct parameters might prove difficult.

1.2.6.2. Recommendations

At this time it is recommended that the Hysteric damping model be used where possible and that the international standard, ISO 10846, be used as the test standard to obtain the material properties.
1.2.7. References

1.2.7.1. Books


1.2.7.2. Articles


Dall’Asta, A and Ragni, L, 2006, Experimental tests and analytical model of high damping rubber dissipating devices, Engineering Structures, Vol. 28, 1874 - 1884.


Picoux, B and Le Houédec, D, 2005, Diagnosis and prediction of vibration from railway trains, Soil Dynamics and Earthquake Engineering, Vol. 25, 905 - 921.


1.2.7.3. Websites

www.cdm.be
www.getzner.at/werkstoffe/

1.2.7.4. Standards

1.3. DESIGN OF ECOLOGICAL TRACKS: GREEN TRAM TRACKS (WP1.2.1, DEVELOPED BY ASP)

1.3.1. Introduction

Green tracks have a high potential to reduce the amount of sealed urban areas, since track lengths of 2 km double track already come up to 1 ha unsealed area. Vegetation system increases water retention thus reduces water runoff. This leads to a higher evapo-transpiration compared to sealed surfaces. This again results in higher local air humidity and consequently helps to avoid the build-up of heat islands in urban areas, which is a big problem throughout the world’s cities.

Noise of trams reduces quality of urban life. Noise can cause high blood pressure and heart diseases. In combination with the right track design green tracks can decrease noise reflection.

In addition to the ecological impact the acceptance of a track site is influenced by its optical appearance - all-season. The psychological effect of green is known and reflected in socio-economic costs.

Operators are interested in low life-cycle-costs. A green track does not need any compensatory measures, which can sum up to a considerable sum. In some cities run-off fees are being charged for sealed areas, which in the case of green tracks would as well cease to apply.

Green tracks have to be resistant towards track conditions as for instance drought, urban pollution, crossing of pedestrians, or tram heat, furthermore to the forces of the pulling wind created by the tram. Typical problems that often occur with green tracks are brown grass tracks after long dry periods. Sometimes responsibility for maintenance and irrigation devices is not clarified within the operator’s management structures. Due to lack of maintenance succession takes place in grass tracks which lead to more and more weed and especially clustering grass varieties. Quite often cars drive into tracks by accident and destroy parts of the vegetation system. In addition, usually plants do not withstand high crossing frequencies of pedestrians. Even gravel turf, which is made for crossings or occasional car passage very often looks sparse. With Sedum tracks the connection of the anti root foil to the sides is important to prevent weed growth if the grit size of the material underneath the foil is smaller than 8 mm.

This report addresses the development of green tram tracks regarding certain requirements and problems: Within the Urban Track project a sustainable, low maintenance, improved noise absorbing, well water balanced green track with regard to the particular local climate and required technical standards (stray current) had to be developed, which allows occasional use of emergency vehicles. Track design, materials and plant varieties influence those parameters, thus have to be developed or chosen according to their particular suitability, respectively.

Low maintenance and sustainability can be achieved by using sustainable materials, the right track design, application of vegetation which can cope with urban stress and track conditions in particular.

Regarding water balance the chosen plants need to get along with weather extremes and are supported thereby from the substrate as well as the system design.
Mitigation of tram track noise by the vegetation part of the track can only be achieved by choosing materials which do not transfer vibration and are less reverberant to increase noise absorption.

Objectives were:

- Co-evolution of technical vegetation systems and tram track design
- Finding solutions for sustainable, low maintenance green tram tracks which have neither to be cut nor watered, with regard to the particular local climate and required technical standards (e.g. in compliance with EU-norms for stray currents less than 2.5 mS/m for green tracks)
- Suitability for emergency vehicle use
- Development of vegetation systems for modular track system types with a noise level reducing potential of at least 1.5 dB(A)

Initially, for the development of a new track design the prevailing situation regarding the general set of problems of green tram tracks was surveyed and the situation at Brussels test site in particular. These were compared to the objectives put by the project. Thereof requirements for the whole system as well as its single track parts were derived. Next step was to develop track solutions which met the requirements. The basic track design came from CDM and already exists at Brussels (line 94) since 2006 using grass paver plus grass. The development of the track design solutions was a process, which was based on reviews as well as communication with producers of track parts, operators and scientists but also on tests in the laboratory regarding material properties, e.g. by means of fatigue testing.

Test results from the lab helped to optimise the design. Verification took place at Brussels test site, where installation, noise absorption and LCC were tested (see chapter 3.2).

1.3.2. Green tram track situation and requirements

1.3.2.1. Green tram track situation and requirements in general

Some main requirements and problems which emerge with tram tracks in general and green tram tracks in particular are reflected in our emphases: Stray currents have to be avoided; noise and vibration of the tram have to be mitigated, at least partly by the track design; concerning intense precipitation, which increasingly occur throughout Europe, drainable track systems are in demand to accelerate the run-off of precipitation to prevent flooding of the track or the adjacent roads; at the same time retarding run-off helps to avoid run-off peaks and an capacity overload of the sewerage system; furthermore periods of drought ask for a high water storage capacity of substrates to alleviate the necessity of irrigation; the vegetation used has to be sustainable and has to be able to cope with these weather extremes.

Requirements of green tram track systems:

Sustainable, easy to install, easy access to track electricity, low maintenance (reduced necessity of irrigation, mowing, weeding, fertilising), good optical appearance, noise absorbing, low price respectively relation of price and shelf life.
Requirements of substrate:
Suitable for vegetation growth, substrate level depending on vegetation used (and track design), sufficient storage and release of water and fertiliser, inherently stable - no decomposition.

Requirements of vegetation:
Sustainable, evergreen, location dependent tough vegetation which can cope with weather extremes (drought, flood, frost, heat, sun, shade), low maintenance, no contact with rail to avoid stray current.

Requirements of rail shoulder (part next to rail, often concrete beam or rubber body):
Noise absorbing, drivable, long-run stable, easy installation, must not hinder rail grinding.

Requirements of grass paver:
Drivable, sustainable, easy installation, paver thickness according to vegetation used and to track design, good if suitable for pre-cultivation.

1.3.2.2. Green tram track situation and requirements at Brussels test site which was originally planned

Brussels future test site was originally planned to be the extension of line 94, Boulevard du Souverain, in front of the Melaerts ponds. The lane adjacent to the trees (Figure 1.3.2: Originally planned extension, future test site 2) was converted into a tram track. Trees create shade at times of the day which track vegetation will have to be tolerant to. Also precipitation reaching the ground is partly reduced by the trees. A further problem can be the foliage coming from the trees, especially during autumn. But mostly driving trams take it away with their air stream.

Emergency vehicles will access the track mainly from the crossings which occur regularly (Figure 1.3.3) when using the drivable tram track and follow the concrete beam (rail shoulder) alongside the rails. This influences the angle which the vehicles meet the track parts with and therefore affects the load situation of the track design. Also this path might show up in the vegetation when driven more often.
Typical for some tram types, which are also used in Brussels, is the outlet of the engine cooling air which is directed to the ground, hence plants suffer from heat shock and are sometimes burnt at resting places of the tram (e.g. in front of traffic signals (Figure 1.3.4)). This can only be redressed by changing the ventilation type of the tram (or rather the tram type).

Figure 1.3.3: Access to track from crossing for emergency vehicles

Figure 1.3.4: Burnt areas in grass due to tram heat

Apart from the shade the same requirements apply for the new test site at Boulevard Leopold III.
1.3.3. Developed track design solutions

1.3.3.1. Track system

Three main natural green tram track solutions were developed (Figure 1.3.5), according to the objectives and requirements for green tram tracks. The vegetation systems consist of 5 main parts: vegetation, substrate, *Sedum* paver, anti root layer and drainable base layer. The system is also influenced by the design of the rail jacket and the surrounding concrete beam.

The difference between the three solutions is the material used covering the surface of the concrete beam (see circles in Figure 1.3.5). The version on the left hand side of the picture implements a special noise absorbing, porous material. The version on the right hand side replaces the surface of the concrete beam by *Sedum* paver.

![Design versions for Sedum track. LEFT: special noise absorber incorporated, RIGHT: Sedum paver up to rubber rail jacket. IASP](image)

The noise absorber is either made from drain concrete or from rubber (Figure 1.3.6). Those three design versions were installed in Brussels test zone.
The base layer, a mineral mixture 0/32, has a 1% slope towards the middle of the track and a slope outside the track, analogue, to guarantee good drainage and to avoid the development of puddles. The anti root layer prevents dominance of weed if connected properly to the sides. Therefore overlapping of the anti root layer sheets is necessary. At the sides the anti root layer will either be stapled to the rail jacket or glued to the concrete. Problems have arisen in Berlin in some Sedum tram tracks where the fixation to the sides was not done properly or has loosened. Especially underneath trees the pressure of germinating seeds is high. These cannot survive during a longer period of dry weather without sufficient water supply. Once established, e.g. in a slot with connection to the ground underneath, it is hard to get rid of it. Only hand weeding in early stages (up to 1.5 years of growth the little tree seedlings) is successful. Herbicides cannot be applied since they cause damage to the track vegetation too. After about 1.5 years of tree growth they can hardly be removed without destroying parts of the vegetation system and creating bigger damage. Cutting also supports secondary trunk growth and is no option either.

To guarantee good drainage during heavy rain the anti root layer is a drainable Plantex® fleece.

The Sedum paver used has a thickness of about 50 mm and can be assembled from single elements. Using grass paver makes the track suitable for emergency vehicle use. Furthermore it provides an opportunity to pre-cultivate Sedum, since it does not grow very fast. Similar to grass turf or a Sedum vegetation mat straight after the installation a green cover displays. The substrate level within the grass paver will be 40-45 mm, lower than the paver thickness, to ensure plant re-growth from the rootstock if cut by car tires. Sedum being a succulent can cope with low amounts of water in contrast to weed. Once a period of drought appears, weed will suffer and die. This method serves as a natural weed protection.

The single parts of the system are described subsequently.

1.3.3.2. Track components and tests relating to emphases/requirements

Tests were undertaken to help with the decision for the best choice of material to be implemented in the green track parts in terms of requirements. The main track design was given by CDM. ASP investigated and developed the cover, which are the vegetation system and the noise absorber. The material choice was based on noise measurements (Impedance tube), where materials of track parts were compared for their noise absorption properties. Water balance tests helped with the decision for substrates regarding drainage and storage capacity. Root armour tests showed a minimum pre-cultivation of 3 to 4 months to avoid loss of substrate of the Sedum paver when transported.
NOISE ABSORPTION OF TRACK MATERIALS (SP1)

The single components of the track design can have an essential influence on the behaviour of the overall system. Therefore, their efficiency regarding the noise absorption was investigated. Finally, the behaviour of the track design regarding noise and vibration performance is an interaction of the single components. For that reason, they have to be regarded as part of the overall system and have to be harmonised with each other.

As a result, it can be clearly stated that the main opportunities to reduce noise and vibrations caused by tram-traffic are measures during the construction of the tram itself (e.g. engine noise, type of brakes, closed wheel house) as well as measures regarding the fixed components of the track design, like during its construction and its state of maintenance. Vibrations will be transmitted or reduced depending on the stiffness of the system. Sound will be absorbed or reflected by surfaces. The wheel-rail contact is the main source of noise; surface roughness and wheel unbalances are the main reasons for that effect. Only a part of the sound is directed downwards. This is the portion of the sound which can be minimized by an optimised track design surface as, for example, a vegetation system.

To be able to judge the noise absorption performance of green track parts laboratory tests were done. Smaller samples were investigated and compared in the impedance tube; see Figure 1.3.7, (substrates, Sedum, grass, artificial grass, cavity elements). Bigger samples were investigated in the expanded impedance tube, see Figure 1.3.12, (rubber mat, drain asphalt, cavity elements, and grass paver). The validation of the material choice has been conducted at Brussels test site when measuring the installed track system (see chapter 3.2).

IMPEDANCE TUBE

Test I - Test set-up

Measurements were conducted by means of impedance tube (Kundt's tube of Brüel & Kjær, type 4206, Software BZ 5050) to obtain the absorption coefficient of the test materials in a frequency range of 16 Hz and 1.6 kHz. The test set-up within the tube reflected the layers within vegetation systems in green tracks.

In the lower part of the tube a space of 10 cm was adjusted. The diameter of the tube was also 10 cm. 6 cm of grit (2/11) were filled into the tube, covered by a foil and filled with 4 cm of testing material to the top of the tube. Grit and substrate were compressed each after filling in.
Substrates (expanded shale (Ulopor (1/11)), lava (2/11) + 45 % humus, brick shippings (Bauder), sand (0/4) - 30 % humus-mixture) were measured at 3 different moisture stages (dry - actual moisture; same amount of water in every substrate; 75 % of maximum water capacity).

**Test I - Results**

Differences between substrates in absorption (frequency and intensity) were identified: At frequencies between 200 and 500 Hz the substrate absorption coefficient decreases as follows: expanded shale > brick chipping > lava-humus > sand-humus. At frequencies above 500 Hz the absorption coefficient decreases from: lava-humus > expanded shale > brick chipping > sand humus.
Increasing water content of materials diminishes pore volume and thus reduces noise absorption. Test results showed a bigger, negative, influence of the water content onto absorption performance than differences between substrates (except for sand-humus). Sand-humus, having relatively little pores compared to the other substrates, always performed badly. Even some ml of water on the bottom of the impedance tube (bottom of grit) had a negative influence on noise absorption of the whole set up (6 cm grit, foil, 4 cm substrate).

Comparative measurements also displayed a positive influence of the anti root foil (between grit and substrate) on the absorption performance of the system.

Both cavity elements (SEDRA, KRAIBURG) measured showed an absorption peak at about 300 Hz, other frequencies were hardly absorbed.

**TEST II**

From the choice of growing media we later on tested regarding water storage Xeroterr II performed well and is a preferred extensive growing medium for Sedum. For that reason we tested noise absorption of Xeroterr, vegetation (Sedum small leaved and bigger leaved, artificial grass, grass) and cavity elements also. Compared to the other substrates tested, Xeroterr II performed only moderate, depending on the frequency. Therefore we compared Xeroterr I (a substrate with bigger grit size 0/12 mm) to Xeroterr II (grit size 0/8 mm) for their noise absorption, as in previous noise tests substrates with bigger grit sizes proved to be more sound-absorbing.

**Test II - Test set-up**

The main test set-up was the same as in test run I. Measurements with Xeroterr I were repeated 4 times. With Xeroterr II 6 repetitions were conducted. During this test the mean moisture content of the substrates averaged 2.5 % by weight.

![Example of the materials tested: artificial grass (top left), cavity elements (bottom left), Sedum (right)](image_url)
Test II – Results

As Figure 1.3.11 indicates, Xeroterr I predominantly shows better noise absorption in frequencies above 300 Hz.

There are maximum peaks of Xeroterr I at 400 Hz and at 1.5 kHz, at which the absorption coefficient differs by more than 0.2. Between 800 and 900 Hz Xeroterr I and II absorb relatively similar. The relevant frequencies are above 200 Hz. A good absorption starts an absorption coefficient of 0.5. In that area Xeroterr I performed best.

Between 250 and 500 Hz vegetation, substrates and the absorbed cavity element Sedra absorbed best with a mean absorption coefficient (α) between 0.56 and 0.69. Sand-humus and the cavity element Kraiburg absorbed bad with an α of 0.21-0.4.

Between 500 and 750 Hz vegetation absorbed best (α 0.82-0.55), followed by substrates (0.47-0.24). The cavity elements absorbed less noise.

Between 750 and 1000 Hz the old artificial grass version which is supposed to be filled with sand (not in that case), real grass and brick chipping absorbed best (0.64-051). The others showed an α of 0.46-0.07. Both cavity elements were last.

Figure 1.3.11: Comparison of noise absorption of Xeroterr I 0/12 mm (XE I) and Xeroterr II 0/8 mm (XE II)
Conclusion

As a result Xeroterr I was chosen for the pre-cultivation, due to its noise absorption properties, its water storage capacities and the fact that it has proved a good substrate for technical vegetation systems before (e. g. stability). Vegetation seems to have good noise absorption within the materials compared, no matter whether artificial, real, grass or Sedum, probably because of the bigger pore volume.

EXPANDED IMPEDANCE TUBE

Test set-up

The expanded impedance tube, a box of 380 x 600 x 100 mm, was filled with about 4 cm grit (2/11), a foil was placed above. Either grass paver filled with sand-humus, rubber mat (CDM) or drain asphalt was placed on top. Rubber mats and drain asphalt were also stored in water for 24 h and investigated for water take up and noise absorption.

Results

Very little differences were measured between the paver types. Differences caused from heterogeneous sand-humus mixture are probably bigger. The absorption coefficients achieved for this type of test set up (0.8 up to 0.95) were very stable over the whole measured frequency spectrum. The higher absorption coefficient of the expanded impedance tube compared to the impedance tube is due to the set up. The values are just a measure to compare absorption properties but cannot be taken as real values outside the laboratory.
The rubber mats and drain asphalt samples showed a very irregular absorption. The stiffer CDM 49-rubber mat had absorption peaks around 100, 300, 500, 700 and 1500 Hz and minima at 200, 600, 800 and 1200 Hz. The CDM 46-rubber mat was a bit more stable and showed a mean absorption coefficient of 0.8. Drain asphalt absorbed less up until 500 Hz but above 500 Hz more than the two rubber mats.

Regarding the influence of water, only little water was absorbed by the rubber mats and hardly any influence was measurable. All materials drained very fast.

**Conclusion**

The influence of the paver onto noise absorption of substrates is negligible. So far drain asphalt, being more porous than the rubber elements, absorbed the noise best. Therefore it was a preferred material for the practical tests in Brussels. Later on we heard from drain concrete, which has noise absorption up to 5 dB(A) (HEIDELBERGCEMENT). It incorporates titan dioxide (TiOcem) which is supposed to reduce NOx. Hence TiOcem was chosen for the test site in Brussels and for the prototypes.

We assume that for the noise measurements in Brussels Sedum paver reaching closest to the rail will have a better noise absorption than the absorber version using drain concrete or rubber next to the rail. But the drain concrete and the rubber is expected to show a better noise absorption than the existing version with a concrete shoulder next to the rail.

**Vegetation**

Low maintenance and sustainability can be achieved by using sustainable materials, the right track design, application of vegetation which can cope with urban stress and track conditions in particular.

Sedum L. is a large genus of about 500 species, belonging to the family Crassulaceae DC. Most species are succulent, varying from mat-forming stonecrops to small shrubs. They are distributed throughout the Northern hemisphere with three contrasting areas especially rich in Sedum: Mexico, Mediterranean Sea, Himalayan Mountains (Stephenson 1994, Figure 1.3.16).

They occupy areas of rapid drainage with little competition from other vegetation. The water-retaining properties of Sedum leaves allow them to be used as drought resistant plants. 95-98 % of the leaf weight is water, which diminishes temperature extremes within a cell. The leaf surface of Sedum varieties can be warmed up to 45 °C without harming the plant (Margolina 1982, at Gorbachevskaya 2005).

![Figure 1.3.16: World distribution of stonecrops (Stephenson 1994)](image)
Many Sedums are frost-hardy and suitable for sunny places. Some varieties also tolerate shady places. Creeping stonecrops tolerate being walked on occasionally. Any bits that break off are likely to root again.

Kirschstein (1996 at Gorbachevskaya 2005) showed that Sedum roots stay alive for more than 14 weeks under stress through drought. Highest drought resistance is performed by Sedum album. These succulent plants protect themselves against too high transpiration by their leaf position, which reduces the leaf area directed to the sun (Figure 1.3.17). Decrease of transpiration is also achieved by the shape of leaf, which is often spherical or cylindrical.

The surface of the leaves (epidermis) of succulent plants is built especially thick as protection of transpiration, sometimes it is also hairy. The numbers of stomata are reduced. In tests of Lassale (1998 at Gorbachevskaja 2005) Sedum album showed no decline of vitality after 100 days of artificial stress through drought. Moreover succulents are adapted to dry climate by their type of photosynthesis. Most succulent plants possess the possibility to close the stomata during the day and to open it during the night instead, to prevent transpiration.

Figure 1.3.17: Sedum album

Succulent plants can protect themselves also by using a different metabolism (Crassulacean Acid Metabolism - CAM) other than non-succulent plants (C3), which means they open their stomata during the night to absorb CO2 and release O2, while the rest of the photosynthesis happens during the day. If enough water is provided to the plants they behave like normal C3-plants (stomata open during the day for photosynthesis).

Sedums have been used as green roof coverings for a longer time already. Ready-grown mats of mixed Sedums are grown commercially for this purpose.

Moss usually settles itself and does not have to be applied. In bio-monitoring it is widely used to monitor the concentration of heavy metals in the air, since it absorbs particles which deposit on the plant. During moist winter when the bigger leaved Sedum varieties drop most of their leaves moss covers the substrate and becomes more lively and green.

**Conclusion**

Harmonised with the whole track system Sedum vegetation can widely be used within the Northern hemisphere. Sedum as succulent plant copes well with drought and urban stress e. g. air pollution and has low maintenance needs, which comprise fertilization once a year. Since the maintenance is one of the major cost factor in the LCC Sedum was the plant of choice. Usually foliage coming from surrounding plants like trees, which can settle on Sedum in tracks especially during autumn, is removed by the wind created by passing trams if the vegetation system is at the same level as the top of the rail. Therefore varieties are needed which build an even surface, where leaves are not caught. 90 - 95 % small leaved Sedum varieties as Sedum sexangulare, S. album, S. acre are typically used in technical vegetation systems and were implemented here. Max. 5 - 10 % large leaved Sedum varieties (e. g. S. spurium) were used. Less often used but shade tolerant are S. glaucophyllum, S. ternatum, S. stoloniferum. Some paver were...
precultivated with those varieties to test their development in shaded areas at the originally planned test site. It would have been interesting to find out which varieties dominated after establishment in Brussels. But the test site has changed to a track without shade causing trees nearby. So other varieties will dominate them after a while.

Substrate

Investigated substrates were chosen according to their maximum water storage capacity, as well as drainage properties and noise absorption performance. Apart from sand-humus-mixture all substrates are widely used in roof greening: expanded shale (Ulopor (1/11)), lava (2/11) + 45 % humus, brick shippings (Bauder), Xeroterr II. Sand (0/4) - 30 % humus-mixture is a completely different type of substrate/material, very heavy, and is rather used with certain grass varieties than Sedum. Some properties of the substrates were investigated and compared e. g. for noise absorption and water balance.

WATER BALANCE TEST

As mentioned before, the increasing occurrence of storm water demands, among other things, the utilisation of well drainable substrates to warrant a fast run-off. Investigated were substrates, typically found in roof greening systems to determine the substrate with the best drain performance. In consideration of the fact that at the same time dry periods become a common phenomenon, a good water storage and release is also of great importance for plants. Therefore the coherence of these processes has to be looked at.

Test set-up

Drainage performance and water storage of substrates as well as grass paver on foil filled with lava was determined in the laboratory.

a) Either of the substrates (610 ml each) were put in a sieve (Ø 20 cm, holes: 2 mm) with a wet filter (Whatman-Filterpapier, Ø 24 cm) between sieve and substrate. Substrates tested were: lava-humus, expanded shale, sand-humus, brick shipping and Xeroterr II. Original substrate moisture was between 2 and 4 Vol%. The sieve was place on top of 3 jars and in a tray. Heavy rain was simulated. 0.5 L of water was slowly added within 2 min. Time was taken of the start of the run-off and the end. Also the drained amount of water was measured.

b) Drainage of paver: the paver was placed on a foil with just one drainage hole, filled with lava-humus and was measured as described above.

Results

a) All substrates drained very quickly. Lava-humus started first, sand-humus took the longest to start (delay of 25 s). In exchange lava-humus took the longest to finish drainage and sand-humus was first (difference of 1.5 min). Xeroterr II stored the most water (275 ml), followed by lava-humus (240 ml). Brick chipping stored the least water (145 ml).

b) The existence of a slight slope proved to be most important for the drainage. Drainage of simulated heavy rain was not disturbed or delayed by the foil.
Conclusion

There are no huge differences between the substrates, although they are different in certain properties (pore volume, water storage capacity, drain ability, noise performance).

Since Xeroterr has proved well in practice on roof and tram track greenings it is the preferred substrate. Optimised on noise absorption with bigger grit size Xeroterr I was chosen for the pre-cultivation of 600 m² sedum paver, needed for the test site in Brussels.

PAVER

Necessity for paver

In cities it very often occurs that emergency vehicles have difficulties to drive unhindered to their destination. There is clearly a need for a fast by-passing possibility. Drivable tram tracks pose a solution. For ecological and esthetical reasons this track should be a green track. To make a grass track drivable either a certain amount of grit can be mixed in the substrate (gravel turf) or paver made from plastic or concrete can be applied. Sedum is not as resilient as grass when stepped on, that is why only paver can be implemented to allow a possible vehicle passage, where a certain recovery zone for Sedum regrowth can be provided.

The “right” paver

There exists a wide range of paver designs on the market. Different sizes, shapes, colours, connection solutions, materials, etc. are available. Sedum-vegetation is used as extensive technical vegetation system, which demands a substrate thickness of about 4 cm. By giving the plant an extra centimetre of shelter between substrate surface and grass paver top edge when driven over by vehicles, the resulting paver height needed for our purpose is 5 cm. It should not be thicker because the restriction of the substrate height is a natural weed protection, and thus provides a habitat for plants like Sedum that are tolerant to drought.

Since some of the Sedum varieties draw back slightly during winter a green coloured paver seems to provide a better optical appearance. However, green plastics are not as UV-resistant as black plastics. The paver shown in Figure 1.3.18 were tested within the expanded impedance tube and were pre-chosen because of their thickness of 5 cm. Intewa paver are not being produced anymore and therefore were not tested any further.
Still both pavers do not have straight edges which showed to be an advantage when moving and transport the precultivated paver, so that substrate does not fall out. The following picture shows the first pre-cultivation tests. Since *Sedum* does not root as fast as for instance grass a closed but drainable bottom of the paver seemed necessary.

No suitable pavers which fully meet our demands were available on the market during the first two years of the project. Meetings with paver producers as e.g. Nidagravel from Belgium, which produce gravel paver for driveways and paths did not help to solve our problems.

Paver produced by Eco Raster was chosen which has plastic crosses at most part of the bottom openings which are to prevent the substrate from falling out when being moved. The paver has fairly straight edges which is also useful for pre-cultivation and installation in tracks. Furthermore, the thickness of the sedum paver of 5 cm allows the implementation of a low substrate level, which is necessary for sedum vegetation to avoid excessive weed growth. By limiting the thickness of the substrate layer the water reservoir is limited also. During dry periods only sedum will be able to survive at that location.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>33 cm x 33 cm x 5 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness, wall size</td>
<td>3.5 mm, 50 mm</td>
</tr>
<tr>
<td>Weight per item</td>
<td>1.06 kg</td>
</tr>
<tr>
<td>Weight per m²</td>
<td>9.55 kg</td>
</tr>
<tr>
<td>Material</td>
<td>100 % recycled Polyethylene</td>
</tr>
<tr>
<td>Compression strength</td>
<td>up to 20 t axle load, DIN 1072</td>
</tr>
<tr>
<td>Load capacity per m²</td>
<td>up to 350 t</td>
</tr>
</tbody>
</table>
Strength of shape | temperature span -50 to 90 °C
---|---
Deformation: ca. 0,5 % (at norm temperature +20°) humidity absorption | 0.01 %
Environmental compatibility | harmless, UV- and weatherproof
solubility: acid, alkali, alcohol, oil and petrol resistant
(de-icing salt, ammonia, acid rain, etc.)

Figure 1.3.21: Eco Raster E50 technical data

**Conclusion**

The first 200 m² of pre-cultivation were done with SCHWAB paver which are very strong and long lasting, supported by fleece at the bottom.

The pre-cultivation of the remaining 400 m² for test zone 2 and 3 in Brussels Ecoraster was used for.

**Anti root layer**

As described earlier an anti root layer needs to be part of the vegetation system with *Sedum* to prevent weed growth. So far foil was used for that purpose. Fleece is another product to prevent weed growth and is a well drainable material. Furthermore it is cheaper than the foil. Thus the fleece was installed in Brussels.

![Figure 1.3.22: anti root foil]

![Figure 1.3.23: Anti root fleece Plantex® Pro]

**Drainage, base layer**

The drainage layer has to allow a fast drainage of water coming from precipitation. When used as base layer to carry the load of vehicles a different grit size is needed.

![Figure 1.3.24: Base layer mineral mixture 0/32]

During the fatigue test split and gravel were tested which have good drainage properties but are not applicable as base layer, since the grit size is too similar, so no compression is possible. The mineral base layer mixture (0/32) is compressible and proved stable enough for lorries.
Conclusion

The mentioned base layer 0/32 should have been implemented in the test tracks. STIB used gravel since the chosen test track at Boulevard Leopold III is not meant to be driven on. So in case of a car crossing stability as planned in the track design is not guaranteed.

Special noise absorber Drain concrete (TiOCem)

The drain concrete “TiOCem”, a development of HeidelbergCement, did not show any damage during the fatigue test at STUVA. It was implemented as special absorber as a 10 cm wide stripe next to the rail.

Drain concrete is an open porous concrete which possesses good noise absorption, with up to 5 dB (A) (RIFFEL, HEIDELBERGCEMENT), is drainable, therefore increases evaporation and converts NOx to NO$_3^-$ by incorporated titanium dioxide (HEIDELBERGCEMENT).

![Figure 1.3.25: Drain concrete (Heidelbergcement)](image1)

![Figure 1.3.26: Conversion of NOx to NO3- by titanium dioxide and UV-radiation (Heidelbergcement)](image2)

<table>
<thead>
<tr>
<th>Concrete strength class</th>
<th>C 20/25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate</td>
<td>Fine flint 5/8 mm</td>
</tr>
<tr>
<td>Cement</td>
<td>CEM I 32,5 R</td>
</tr>
<tr>
<td>Water (Fresh water)</td>
<td>50 - 55 kg/m$^3$</td>
</tr>
<tr>
<td>Synthetics dispersion</td>
<td>20 % of weight (10 % solids)</td>
</tr>
<tr>
<td>w/c-factor</td>
<td>0.24 – 0.26 (effective)</td>
</tr>
<tr>
<td>Consistency</td>
<td>V</td>
</tr>
<tr>
<td>Void content</td>
<td>P</td>
</tr>
<tr>
<td>Compression strength</td>
<td>$f_{ck}^*$</td>
</tr>
<tr>
<td>Bending tensile strength</td>
<td>$f_{ct}^*$</td>
</tr>
<tr>
<td>Splitting tensile strength</td>
<td>$f_{ct}^*$</td>
</tr>
<tr>
<td>Adhesive tensile strength</td>
<td>$f_{at}$</td>
</tr>
<tr>
<td>Static modulus of elasticity</td>
<td>$\varepsilon_B$</td>
</tr>
</tbody>
</table>
**Figure 1.3.27:** Typical composition and quality requirements of drain concrete

**Special noise absorber Porous rubber (CDM 46)**

![Porous rubber mat (CDM 46)](image)

The CDM porous rubber mat 46 is made of rubber granules of shredded tires which are bonded with a polyurethane binder under high pressure. During impedance measurements this mat showed the good noise absorption.

<table>
<thead>
<tr>
<th>Prescription</th>
<th>Unit</th>
<th>CDM-46</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td></td>
<td>Resin bonded rubber</td>
</tr>
<tr>
<td>Colour</td>
<td></td>
<td>black</td>
</tr>
<tr>
<td>Density - ASTM-D297</td>
<td>kg/m³</td>
<td>990</td>
</tr>
<tr>
<td>Shore hardness - ASTM-D2240</td>
<td>°A</td>
<td>50-60</td>
</tr>
<tr>
<td>Tensile strength – ASTM-F152</td>
<td>MPa</td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>Elongation at break - ISO-37</td>
<td>%</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>Compressibility at 2.8 MPa – ASTM-F36</td>
<td>%</td>
<td>30-50</td>
</tr>
<tr>
<td>Recovery at 2.8 MPa - ASTM-F36</td>
<td>%</td>
<td>&gt; 90</td>
</tr>
<tr>
<td>Compression set 50%/23°C/70h – DIN53572</td>
<td>%</td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>

**Figure 1.3.29:** Typical composition and quality requirements of CDM 46

**Conclusion**

Both materials were tested and were implemented in the test zones in Brussels (see chapter 3.2).
1.4. **DESIGN OF INTERFACE BETWEEN RAIL AND STREET PAVEMENT (WP1.2.2, DEVELOPED BY D2S)**

This part of the project is dealing with paved tracks only (from trams and Light Rail), and is investigating the possibility to remove quickly the rails without damaging the street pavement, in order to reduce the track maintenance and renewal cost. The focus is on the joint between rail and street pavement, which purpose is to provide a durable, resilient interface allowing moving mainly in vertical and transversal directions. What is addressed here is the development of technical performance specifications for a suitable wide joint - wider than those used today - which allows rail removal without damaging the pavement.

The strategy followed is based upon the following techniques:
- review of existing specifications for narrow joints;
- material selection for a wide joint;
- testing and validation of the wide joint in the laboratory.

Starting from existing specifications, innovation is brought through: new joint material development – the first attempts were not satisfactory -, development of testing methods for wide joints, development of a test loads and acceptance criteria for wide joints. As a result, a solution was found for making a durable wide joint on site.

The validation site has been Seville, Spain (see chapter 3.4).

1.4.1. **Introduction**

Paved tracks for trams and Light Rail use sealing joint between the rail and the street pavement supposed to provide a durable, resilient interface between the fixed street pavement and the rail which has the possibility to move mainly in vertical and transversal directions. Today, bituminous and non-bituminous (epoxy/polyurethane) joints are used. The specifications applied today are derived from those used for road joints.

The objective of this part of the Urban Track project is to offer the possibility to remove quickly the rails without damaging the street pavement. This requires wider joints than those used today. The focus is therefore to identify suitable wide joints and to develop the technical performance specifications for these wide joints.
1.4.2. Current specifications

1.4.2.1. German specifications (ZTB Fug-Stb 01, TL Fug-Stb 01, TP Fug-Stb 01)

The materials used for sealing the gap between the rail and the road surface are typically those that are used to seal the expansion joints of concrete road surfaces that do not use continuous reinforcement from rebar. Hence many of the existing specifications explicitly refer to specifications for road construction. The German specifications can be retained as a benchmark as they are complete in two ways: they address the specific case of the rail joint, and they address the cold (epoxy / polyurethane) joints. These specifications are the following:

- ZTV Fug-StB 01, Ausgabe 2001, Züsatzliche Technische Vertragsbedingungen und Richtlinien für Fugen in Verkehrsflächen
- TL Fug-StB 01, Ausgabe 2001, Technische Lieferbedingungen für Fugenfüllstoffe in Verkehrsflächen
- TP Fug-StB 01, Ausgabe 2001, Technische Prüfvorschriften für Fugenfüllstoffe in Verkehrsflächen

1.4.2.2. General applications

ZTV Fug-StB 01 recommends that both hot and cold joint materials must be capable of absorbing a change in width of an expansion joint of 25%. Since the guideline for maximum variation possible is 5 mm, the maximum width of such an expansion joint is 20 mm. The depth of the joint shall be between 1.5 to 2.5 times its width or between 30 and 50 mm.

If the joint adheres to three surfaces it may crack. In order to prevent such cracking, the sub joint layer must be either elastic or the joint material must be able to slide over the sub layer.

The joint must be installed in such a way that there is no direct contact between the tires of the vehicles and the joint.

1.4.2.3. Rail applications

For rail applications in the above norms, guidance is only given for hot materials. It recommends disclosing the type of track fixation: rigid or elastic.

The gap between the rail and the road should not be wider than 60 mm and not deeper than 55 mm.

A mandatory requirement is that the embedding material, that isolates the rail from the road and over which the joint material is poured, cannot move so that the joint material is prevented from sinking in. The top surface of the joint material shall be at least 3 mm below the top of the rail.

It should be noted that there is no mentioning of a separation strip between the embedding material and the joint material (bild 5). This is in contrast with the normal procedure for road joints wider than 20 mm, where a separation strip must be placed on top of the rectangular joint strips that are inserted in the bottom of the joint groove (bild 6).

1.4.2.4. Incompatibilities

With the introduction of the requirement that it must be possible to remove the rail without damaging the pavement, the width of the joint between the rail and the road has increased to a range of 65 to
130 mm for grooved rail and 80 to 130 mm for vignole rail. This is far wider than the in the above specifications recommended maximum width of 60 mm.

In addition, the minimum thickness of the road joints is specified to be 1.5 times the width. Applying this rule to the new wide rail/road joints means depths of respectively 98 to 195 mm and 120 to 195 mm. Even if we apply a 1 to 1 ratio in the rail case, we still would need a depth of 130 mm. Such a large depth is unacceptable for rail applications since the rail itself is in most cases only 150 mm high.

The wide joints are so wide that contact between vehicle tires and joint is not avoidable. This contact is in contradiction with the existing specifications, but since this is unavoidable, the wide joints have to be developed to cope with this contact.

1.4.3. Modern track environment: Tram bus lanes

To increase capacity with increased frequencies and thus reduced headways, modern tramway tracks are often installed in a separate right of way. The capacity of this arrangement is further maximised by using the right of way as a combined tram/bus lane. Capacity is further increased by increasing the track availability which is achieved by incorporating in the design the possibility to replace rails within the typical 4 hour time frame of night closure, hence the need for wide joints. The tramway tracks and especially the road interface joints therefore have to be properly designed, as the frequent passage of heavy busses over these joints can quickly accumulate damage.

The track system itself has a very low stiffness to combat noise and vibrations. Hence the embedding material moves vertically during tram wheel passage. This behaviour is not in compliance with the German specifications, which requires the embedding material to be rigidly fixed.

It is clear that the wide joint discussed above cannot meet the criteria of the German standard or any other national standard. A new joint material is needed and additional specifications and testing methods must be developed to reflect the particular case of the wide joints.

1.4.4. Design considerations

1.4.4.1. Joint/tire interaction

The wide joints are so wide that contact between vehicle tires and joint is unavoidable. This is especially true for a combined tram bus lane where bus drivers find it convenient to use the outer rail as guidance. The driving on the rail causes the tires to deform as they try to adapt to the shape of the uneven road-joint- rail surface.

This behaviour has two consequences:
- The tires are in frequent contact with the joints;
- The joint experiences frequent braking and accelerations from the busses.

1.4.4.2. Joint specifications

With the tires frequently in contact with the joint, the joint must be wear resistant. Thus, a hard joint material was developed that is composed of two components: a polyurethane/epoxy polymer and a
water inert cycloalipathic amine hardener. Both components contain rubber granules and mineral fillers. The rubber granules provide damping in the joint. The two component system does not contain any solvents. The fully cured material is waterproof, creep free and elastic. More importantly, it is impact and shock resistant. As it must be possible to install these joints everywhere in Europe, it must be possible to do this under the not so ideal conditions of Western Europe where frequent rain is combined with relatively low temperatures. Hence the specifications call for a material that can be installed under widely ranging temperatures and in rainy conditions.

The material has the following specifications:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td>Black</td>
</tr>
<tr>
<td>Form</td>
<td>Liquid</td>
</tr>
<tr>
<td>Density</td>
<td>0.9 +/- 0.1 kg/dm³</td>
</tr>
<tr>
<td>Hardness</td>
<td>Selectable above Shore A 60</td>
</tr>
<tr>
<td></td>
<td>Standard Shore A 80 +/- 5</td>
</tr>
<tr>
<td>Tear strength</td>
<td>&gt; 1 N/mm²</td>
</tr>
<tr>
<td>Potlife</td>
<td>about 30 minutes at 15°C</td>
</tr>
<tr>
<td>Adhesion</td>
<td>&gt; 2.5 N/mm² on pre-treated and clean surfaces</td>
</tr>
<tr>
<td>Curing time at 15°C</td>
<td>after 24 h: Can be handled</td>
</tr>
<tr>
<td></td>
<td>after 2 days: serviceable</td>
</tr>
<tr>
<td></td>
<td>after 7 days: chemically permanent</td>
</tr>
<tr>
<td>Application temperature</td>
<td>between 0°C and 30°C:</td>
</tr>
<tr>
<td></td>
<td>Lower temperatures result in longer curing times</td>
</tr>
<tr>
<td></td>
<td>There is no curing reaction at -20°C until the temperature rises</td>
</tr>
<tr>
<td>Electrical resistance</td>
<td>&gt; 1.10⁹ Ohm</td>
</tr>
<tr>
<td>Curing process</td>
<td>unaffected by water; material hardens when submerged</td>
</tr>
<tr>
<td>Durability</td>
<td>UV resistant, water resistant,</td>
</tr>
</tbody>
</table>

**Note:** ZTV Fug-StB 01 recommends that both hot and cold joint materials must be capable of absorbing a change in width of an expansion joint of 25%. It is clear that the proposed joined is not capable of handling such large deformations.

### 1.4.4.3. Joint dimensions

The selected joint material is very hard. Installing this material with a conventional 1 to 1 or even a 1 to 2 aspect ratio would be very costly. In addition, as the material is very stiff, fatigue cracking could occur under the frequent high loads from the tires of the passing vehicles. Hence a thickness of 25 mm was selected.

### 1.4.4.4. Joint installation

The joint experiences frequent braking and accelerations from the busses. This results in both vertical and horizontal loads on the joint. Thus the proper adhesion of the joint is of prime importance. Bonding to the various surfaces available was evaluated.
Bonding to the vertical surfaces alone

Bonding the joint to the vertical surfaces alone (rail and pavement) does not provide sufficient adhesion. Indeed, with a depth of only 25 mm, the adhesion area would not even be half the width of the joint. The longitudinal efforts of the tires would easily rip the joints out, especially with the hard joint material that is selected.

Bonding to all three surfaces (vertical and embedding material)

As we have seen, the German standard from 2001 allows the bonding of hot (bituminous) joints on three surfaces. However, as we are dealing with a very stiff joint installed on a soft embedding material, the vertical displacements of the joint due to the track resiliency would force the joint to shear off of the vertical surfaces or simply crack.

Bonding to the embedding material alone

This configuration solves the mismatch of the hard joint with the vertically resilient track system. Indeed, the joint can move vertically in sync with the embedding material. Although this installation would not seal the groove 100%, it was estimated by lab testing that after 3 million wheel passages, there would only be an opening between the rail and the joint of less than 0.4 mm during wheel passage. This is small enough to prevent water penetration. Bonding to the embedding material alone was withheld.

1.4.5. Development of additional test procedures

1.4.5.1. Conditions to be replicated

The primary condition that may lead to failure of the wide joints is not the typical differential displacement between the rail and the pavement, but the direct contact of the tires with the joints. This is exacerbated by the frequent stopping and accelerating of the vehicles. Thus the new joint must be capable of withstanding these forces. The forces on the joint can be estimated as follows:

- The vertical load of trucks is estimated at 150 kN per axle (2 wheels).
- The tire/road contact area is about 100 000 mm$^2$.
- The tire/road contact pressure is estimated at 0.75 MPa.
- A plate with dimensions 80 X 200 mm will be used to replicate the tire contact area.
- The equivalent force on the plate thus must be 0.75 MPa X 16 000 mm$^2$ or 12 kN.
- The horizontal component is 30 % or 3.6 kN.

1.4.5.2. Vertical testing

A section of the track system with a length of 1.5 m was fabricated and brought into the lab. A plate with dimensions 80 * 200 mm is glued to the joint to replicate the contact area of the tire.
Initial static testing

The initial static test showed that a vertical displacement of about 10 mm is achieved under a load of 3.6 kN. This is the displacement of the combined embedding material and the joint and is mainly the result of the vertical resiliency of the embedding material.

The test was executed at a speed of 0.2 mm/s with 30 seconds pause between the three successive loadings. After the first loading cycle there is an initial permanent deformation of 1 mm. No defects were observed.
Fatigue testing

The fatigue testing is done by controlling the displacement of the actuator between 0 and 10 mm for 3 000 000 cycles at a rate of 3 Hz. The variation in vertical deflection was measured with an independent LVDT transducer.

The vertical displacement is initially 6.5 mm and after 1 000 000 cycles remains around 4.5 mm. No defects were observed.

![Fatigue test graph](image1)

**Figure 1.4.3**

The maximum load remains in the range between 2.9 and 3.5kN.

![Maximum load graph](image2)

**Figure 1.4.4**
Final static testing after fatigue testing

The static test after fatigue testing was executed in the same way as the initial test and showed a permanent deformation of 3 mm, which includes the initial deformation of 1 mm. Or the fatigue testing caused an additional permanent deformation of 2 mm. No defects were observed.

Figure 1.4.5
1.4.5.3. Inclined pulling test

A plate with dimensions 80 X 200 mm to replicate the horizontal contact forces of the tire was glued to the joint on the same track section as used for the vertical testing. The purpose of the test is to evaluate the behaviour of the joint when it is pulled quasi horizontally under an angle of 10°.
**Initial static testing**

As discussed under 1.4. 5.1, the joint is subjected to horizontal forces estimated at 3.6 kN. Thus the joint is subjected to an initial horizontal pulling test of 4 kN (3.6 kN + 10% safety). Both vertical and horizontal displacements are measured during the test. At 4 kN, the vertical displacement is a very low 0.34 mm, and the horizontal displacement is 3 mm. No defects were observed.

![Graph of Initial static test](image1)

*Figure 1.4.8*
**Fatigue testing – Part 1**

Fatigue testing is done by cycling the load between 1.2 and 2.4 kN (1/3 and 2/3 of the estimated horizontal force) during 3 million cycles at a frequency of 6.8 Hz. The variations in vertical and horizontal displacement are minimal. No defects were observed.

![Fatigue testing graphs](image)

*Figure 1.4.9*
Fatigue testing – Part 2

Additional fatigue testing is done by cycling the load between 0.36 kN and 3.6 kN (1% and 100% of the estimated horizontal force) during 20 000 cycles at a frequency of 3.5 Hz. The variations in vertical and horizontal displacement are minimal. No defects were observed.

Figure 1.4.10
**Final static testing after fatigue testing**

After fatigue testing the joint is subjected to additional pulling tests.

With a security coefficient of 1.1 or 4 kN: The displacements up to 4 kN are similar as those of the initial test. No defects were observed.

With a security coefficient of 2 or 7.2 kN: At 6 kN a tear appeared in the joint at the edge of the plate. The test proceeded which caused the tear to widen. It appeared that the tear did not run the full depth of the joint.

Until failure: The test continued to 11.35 kN when the glue between the plate and the joint failed. It should be noted that the curve continued its initial slope (before 4 kN) until the end, further indicating that the tear was not significant.

After the test, with the load removed, the joint returned to its initial state, and the tear was no longer visible with the naked eye.
1.4.5.4. **Freeze thaw cycling**

The joint must be capable of operating under all climatic circumstances (high and low temperatures, rain and frost) of the region where it is installed. This means it must be resistant to freezing and thawing cycles.

**Test setup**

A track section with a length of 0.4 m was used to simulate this behaviour. The test section was equipped with tubes to fill its inner section before the test. A thermocouple was inserted near the bonding area between the joint and the embedding material. The track section is than placed in a cryogenic chamber, which is cooled down by periodic injections with liquid nitrogen. An electric resistance heating element allows the temperature to be raised if necessary.

*Figure 1.4.12*

![](image1)

*Figure 1.4.13*
Test conditions

The section of test track is subjected to ten series consisting of 7 freeze thaw cycles. Each cycle consists of:

- Cooling the chamber down to about – 17°C, until the internal temperature as measured by the thermocouple reaches – 5°C.
- Maintain this temperature for 10 minutes.
- Heating the chamber up to about + 15°C, until the internal temperature as measured by the thermocouple reaches + 5°C.
- Maintain this temperature for 10 minutes.

At the start and before each series, the chamber is heated to about + 50°C, until the internal temperature as measured by the thermocouple reaches + 35°C.

Test results

The graphs below show the temperature evolution over time in the chamber and in the joint for the full test and in more detail for the last series of 7 cycles. No defects were observed.
1.4.5.5. **Practical experience**

The joint tested according to above procedure was installed on site under normal service conditions (tram & bus passages). No defects are observed so far. This is a clear indication that joints that pass these tests that replicate the actual in service behaviour will endure.
1.4.6. Recommendations

1.4.6.1. Installation

It is clear that the wide joints cannot be installed in such a way that the tires cannot come in direct contact with the joint surface. The result is that the joint must be capable of withstanding the loads of trucks and busses operating over the tracks. This requires a very hard and stiff joint. These hard and stiff joints must be relatively thin (25 mm) and show excellent adhesion that cannot be achieved by bonding to the rail and road surface alone. Bonding to the three surfaces is not acceptable as the deflections of the resilient track system would lead to the joint being ripped from the vertical surfaces to which it is bonded.

Joints wider than 40 mm shall be bonded to the embedding material alone. The vertical surfaces of the rail and the road shall be treated with a primer to prevent the joint material from adhering to these surfaces.

1.4.6.2. Testing

As the wide joints do come into direct contact with the tires of trucks and busses operating over the tracks, they must be capable to withstand the loads exercised by these vehicles. To demonstrate this capacity, additional tests were performed on site (see chapter 3.3).
1.4.7. **Functional requirements**

1.4.7.1. **Functional requirements for conventional narrow joints**

The functional requirements for conventional narrow joints were well described by Ir. Claude De Backer of the Belgian Research Center for Road Construction. See “The joint between the rail and the street pavement” /“De voeg tussen de rail en de wegverharding”, By Claude De Backer and Lieve Glorie – OCW Brussels. Paper presented at the Workshop on Construction of mixed tram bus lanes in Antwerp on October 16, 2002.

The joint material between rail and pavement must:

- be suitable for the dimensions of the gap to be filled;
- be capable of resisting the direct impact of the traffic and the lateral loads from the roadbed;
- not stick to the wheels of the tram or the tires of road traffic, so they cannot be ripped out and transported by the wheels;
- be flexible to absorb the vertical and lateral displacements of the rail and the roadbed;
- remain attached to the rail and the road surfaces;
- be watertight (if required and or if no other water drainage system is provided));
- be durable and maintain its properties under all climatological circumstances (high and low temperatures, rain and frost).

1.4.7.2. **Functional requirements for wide joints**

Although the wide joint is considerably different than the narrow joint in terms of dimensions, stiffness and installation, the functional requirements for wide joints are the same with the exception of item 5 (remain attached to the rail and the road surface) and item 4 (be flexible).

In contrast with normal narrow joints which must be installed so that they do not come in direct contact with tires of passing vehicles, the wide joints are regularly in contact with these tires. Therefore a requirement should be added that the joint is wear resistant.

In order to resist the high tear forces, the joint has to be rigid and detached from the rail and pavement. The joint is attached to the embedment material only. In this way, vertical and lateral displacements of the roadbed are of no concern and high tear forces can be resisted.
1.4.8. Conclusion

A wide joint design has been presented, developed and validated. This joint can be used in appropriate applications with paved tracks, discrete rail fixation systems and the requirement to replace the rail without damaging the pavement.

The test conditions of this joint have been discussed as well as general performance requirements. This is a first step in the development of technical specifications for wide joints. The validation site has been Seville, Spain (see chapter 3.4)
1.5. ALTERNATIVES FOR FLOATING SLABS: DESIGN OF LOAD REDISTRIBUTION SLAB FOR TRAM TRACK AT GRADE (WP1.2.3, PART A, DEVELOPED BY APT)

This part of the report deals with the design of a floating slab alternative mainly for tram tracks at grade, but also applicable for metro tracks and more generally for tracks in tunnel, with the objective to find a solution with a good vibration isolation performance and without the disadvantages of the classical floating slab: high costs and increased airborne noise emission.

The strategy adopted is based upon the following steps:

- review of latest literature in terms of high vibration isolation;
- development of an alternative for floating slab, the load redistribution plate (LRP: a load redistribution plate), based upon the idea of a better load redistribution;
- dimensioning of some possible designs for the load redistribution plate (LRP);
- computation of the effect of the LRP in terms of vibration isolation.

The idea to introduce a load redistribution plate (LRP) is new, it has been patented and tentative designs for the LRP have been made and dimensioned. The effect of the LRP in terms of vibration isolation has been calculated. The LRP does not interfere in the design of the track and its components: it is a low cost solution without any adverse effects on noise emission.

As a result of the project, an alternative for floating slab has been developed. Validation on site has been done on the Brussels STIB/MIVB tram network (see chapter 3.6).

1.5.1. Introduction

The classical floating slab has several disadvantages: high costs and increased airborne noise emission. The project aims therefore at reducing these, and at finding a solution with a good vibration isolation performance, which can be used in several contexts. It is applicable mainly for tram tracks at grade, but also for metro tracks and for tracks in tunnel. As well direct fixation track (on a concrete slab) as track on ballast can be considered.

The idea of working with a load redistribution plate came after analysing the contents of a specific article “In service tests of the effectiveness of vibration control measures on the BART rail transit system” by Hugh Saurenman and James Philips, Journal of Sound and Vibration 293 (2006) 888-900.

In this article they show the measured vibrations and line source transfer mobility at different sites: standard ballasted track and floating slab. From the presented measurements, it is suggested that a big part of the vibration isolation performance of the floating slab must be coming from the presence of the thick concrete slab under the floating slab.

Also NS (Dutch railways) did experiments (1996) with a continuous concrete slab under the ballast tracks with the objective of reducing vibration levels in the neighbourhood. This has been reported in an article ‘Proefvak trillingsarm spoor nabij Oosthuizen’ by H.G. Stuit, Holland Railconsult, Innovatieforum 231096. With a continuous concrete slab under the tracks, a reduction of the vibration levels has been measured by only in the very low frequencies.
No vibration reduction has been measured above 5 Hz, which can be explained by the fact that the concrete slab itself exhibits low frequency resonance frequencies, which can increase the transmitted vibrations.

The observations described above are used to introduce a load redistribution plate (LRP) which can be a concrete slab, under the classical track (e.g. ballasted track) or integrated in the classical track (in case of a direct fixation track). In order to perform well in terms of vibration isolation in the frequency range up to 70 Hz, such a LRP must exhibit a first bending resonance frequency which is above the first wheel/rail bending resonance frequency (typically around 63 Hz or lower). This idea has been patented and tentative designs for the LRP have been made and dimensioned. The effect of the LRP in terms of vibration isolation has been calculated. The LRP does not interfere in the design of the track and its components: it is a low cost solution without any adverse effects on noise emission.

1.5.2. Concept of the LRP (Load Redistribution Plate)

The LRP is a load redistribution plate, which is installed under the tracks (ballasted tracks) or integrated within the direct fixation track slab. The idea is to redistribute the forces such that they do not act locally at the point of application but that they are distributed over a larger area. This distribution of static and dynamic loads will yield reduced soil vibration levels at the source (under the LRP) and hence reduced vibration levels at the receiver side. In order to be able to perform well as load redistribution plate, the LRP must be very rigid (dynamically). Its first bending resonance frequency has to be above the first resonance frequency of the wheel on the l and its fixation (e.g. sleepers and ballast) of the reference track. This is typically above 40 Hz.

The concept of the LRP is well described in appendix A1.5.

1.5.3. Design possibilities for the LRP

The main characteristic of the LRP is its first bending resonance frequency to be between 40 - 80 Hz, depending on the reference track.

This can be achieved in different ways:

- a concrete slab of 400 mm thick and 4 m long (max. 4 m wide) yields a first bending resonance frequency of 80 Hz (figure 3.1);
- a concrete slab of 200 mm thick and 4 m long (max. 4 m wide) with 2 longitudinal members 500 mm high and 200 mm thick yields a first bending resonance frequency of 81 Hz (figure 3.2).
- a concrete slab of 120 mm thick, 500 mm long and 2.3 m wide yields a first bending resonance at 62 Hz, effective for a reference track with a first wheel/rail resonance around 40 Hz.

Many other designs are possible including designs which use other materials than concrete.

The different LRP structures (of limited length) have to put next to each other to follow the track alignment over the length, which requires vibration attenuation.
1.5.4. Vibration attenuation performance of the LRP

A finite element model has been made of a typical ballasted track section considering plain ballasted track, ballasted track with a continuous concrete slab under the ballast (4 m wide and 400 mm thick) and ballasted track with discrete concrete slabs under the ballast (each 4 m wide, 400 mm thick and 4 m long). Standard values have been selected for the E modulus and damping of ballast, soil and concrete.

The modelled track has been dynamically loaded in the middle of the model by 4 force impacts (at the location of the 4 wheels of the bogie).

In order to compute the frequency response of points situated at different distances from the track (2 m, 3.5 m, 5 m, 6.5 m and 8 m), a frequency domain calculation (by steps) has been made. This allows a comparison of the vibration levels (in function of frequency) caused by the impact excitation in the different selected points for the three different cases.

The results are graphically shown in figures 1.5.3 to 1.5.5, where one observes the vibration spectra with a peak at 50 Hz, corresponding with the first wheel/rail resonance frequency.

It is clear that the LRP solution with discrete slabs under the ballast yields lower vibration levels in the environment. The gain in terms of vibration reduction is up to between 5 and 10 dB above 30 Hz, as shown in figure 1.5.6 (difference between vibration levels with continuous and discrete slab) and in figure 1.5.7 (difference between vibration levels without slab and with discrete slab). The performance is function of the distance between track and receiver point. At no frequency, there is an amplification of the vibration (in contrast with the floating slab solution). In the low frequencies (below 30 Hz), there is an attenuation of about 2 dB.
Figure 1.5.3

soil 8.00E+09 - ballast 2.00E+07 - no slab

<table>
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<th>6.5</th>
<th>8</th>
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<td>5</td>
<td>6.5</td>
<td>8</td>
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</tbody>
</table>

Figure 1.5.4

soil 8.00E+09 - ballast 2.00E+07 - continuous slab

<table>
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<th>6.5 m</th>
<th>8 m</th>
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<tbody>
<tr>
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<td>3.5 m</td>
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<td>6.5 m</td>
<td>8 m</td>
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</table>

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Figure 1.5.5

soil 8.00E+09 - ballast 2.00E+07 - discrete slab

Figure 1.5.6

soil 8.00E+09 - ballast 2.00E+07 - difference continuous vs discrete slab
Figure 1.5.7
1.5.5. **Conclusion**

A load redistribution slab (LRP) to be integrated in the track foundation has been designed. The performance of such an LRP has been mathematically calculated to be between 5 dB and 10 dB in comparison with the same track without the LRP (in the relevant frequency domain).

At no frequency, there is an amplification of the vibration (in contrast with the floating slab solution). In the low frequencies (below 30 Hz), there is an attenuation of about 2 dB.

This solution has been validated in a tram track of the MIVB/STIB network (see chapter 3.6).
1.5.6. **APPENDIX A1.5– Description of the concept (Document in French)**

Assise à niveau vibratoire réduit pour voie ferrée

La présente invention concerne les systèmes de support pour voie ferrée sur un chemin de voie.

Une voie ferrée pour tramway, métro ou train génère toujours des vibrations qui se propagent dans et nuisent à l’environnement. Les niveaux vibratoires engendrés dépendent des caractéristiques des véhicules circulant sur la voie ferrée et des caractéristiques du chemin de voie ferrée. Pour une voie ballastée standard, la fréquence principale des vibrations générées se situe aux environs de 60 Hz. Cette fréquence est déterminée par la raideur du ballast et de sa sous-couche, et par la masse non suspendue du bogie du véhicule circulant sur la voie ferrée.

Pour une voie posée directement sur béton, la fréquence principale des vibrations générées se situe dans une gamme de 40 à 60 Hz, en fonction de la raideur du système de fixation des rails. Cette fréquence est déterminée par la raideur du système de fixation de rail et du radier en béton, et par la masse non suspendue du bogie du véhicule.

Sur le plan de la propagation des vibrations, il se trouve qu’une voie posée sur un sol rigide (par exemple un sol rocheux) résulte en des niveaux vibratoires ayant une amplitude moins importante qu’une voie posée sur un sol souple (par exemple un sol argileux). D’autre part, les vibrations générées dans un sol rigide se propagent plus loin (elles sont moins amorties) que dans un sol souple, plus amortissant.

La présente invention a pour but de réduire le niveau vibratoire engendré par le passage des bogies des véhicules circulant sur les rails, quel que soit l’assise du chemin de voie ferrée. Cet objectif est atteint suivant l’invention par un système de support pour rails de voie ferrée comprenant plusieurs plaques de répartition dynamiquement très rigides disposées côte à côte sur le chemin de voie, en dessous de la voie ferrée, chacune de ces plaques de répartition ayant une surface et une épaisseur prédéterminées de manière que sa première fréquence de résonance soit supérieure à la première fréquence de résonance des vibrations engendrées localement dans les rails par le passage des bogies d’un véhicule circulant sur la voie ferrée.

Les plaques de répartition précitées sont des plaques relativement courtes, assez épaisses, qui s’étendent sur le sol, en dessous de la voie ferrée. Ces plaques peuvent être jointives avec des joints qui permettent la libre rotation d’une plaque de répartition par rapport aux plaques adjacentes. Les plaques de répartition peuvent être faites en béton, en matériau composite, ou autre matériau capable de répartir les charges des véhicules devant circuler sur la voie ferrée. Elles peuvent être fabriquées sur place ou être préfabriquées (modules).

Ainsi, au lieu d’exciter le sol très localement en dessous d’un bogie du véhicule circulant sur la voie ferrée, l’excitation se distribue sur une grande surface (sans amplification dynamique), avec comme résultat un niveau vibratoire plus faible. Un gain vibratoire d’au moins 8 dB est obtenu en utilisant une telle plaque de répartition sur un sol classique non rocheux. Cette réduction du niveau vibratoire s’explique comme suit: au lieu que les efforts dynamiques des quatre roues d’un bogie soient répartis sur 4 m² (soit 4 fois 1 m²), les efforts sont ici répartis sur une surface d’au moins 10 m² (en considérant une plaque de répartition de 4 m de long et 2,5 m de large), ce qui donne un facteur 2,5 (ou environ 8 dB) de réduction de l’amplitude vibratoire. Cette répartition des efforts dynamique résulte en un niveau
vibratoire du sol en dessous de cette plaque de répartition, nettement inférieur à celui que l'on aurait sans cette plaque de répartition.

Pour être efficace, chaque plaque de répartition doit avoir une première fréquence de résonance supérieure à environ 1.4 fois la première fréquence de résonance des vibrations engendrées localement dans les rails par le passage d'un véhicule sur les rails de la voie ferrée. Dans le cas où cette première fréquence de résonance des vibrations engendrées localement est de 57 Hz, par exemple, la première fréquence de résonance de la plaque de répartition doit être supérieure à 80 Hz. Ainsi, lors du passage d'un véhicule sur la voie ferrée au-dessus de la plaque de répartition, celle-ci se déforme conformément à sa déformation statique, sans avoir des amplifications dynamiques importantes, dues aux résonances. Dans l'exemple cité ci-dessus, pour arriver à une première fréquence de résonance de la plaque de répartition supérieure à 80 Hz avec une dalle en béton ayant une longueur de 4 m (et pas plus large que 4 m), il faut qu'elle ait une épaisseur d'au moins 400 mm.

Chaque plaque de répartition dans le système de support suivant l'invention peut être réalisée sous la forme d'une poutre simple ou sous toute autre forme appropriée pourvu qu'elle ait une première fréquence de résonance (torsion ou flexion) supérieure à la première fréquence de résonance des vibrations engendrées localement par le passage d'un véhicule circulant sur les rails de la voie ferrée. Les plaques de répartition peuvent être utilisées en dessous de voies normales (en alignement et en courbes), en dessous d'appareils de voie ou en dessous d’un ballast. Elles peuvent être posées sur le sol ou éventuellement intégrées dans le revêtement d’une voirie de train ou tramway. Elles peuvent être posées sur le radier d’un tunnel de métro ou de train.

D'autres détails et particularités de l'invention ressortiront de la description des dessins ci-joints (présentés en fin d'annexe), qui illustrent des exemples de mode de réalisation de l’invention:

La figure 1 montre une coupe longitudinale dans un système de support de voie ferrée suivant l’invention, avec ballast.

La figure 2 est une vue en plan montrant les plaques de répartition de la figure 1.

La figure 3 montre une coupe longitudinale dans un système de support de voie ferrée suivant l’invention pour fixation de rails sur blocs de béton.

La figure 4 est une vue en plan du système de support de voie ferrée de la figure 3.

La figure 5 montre une vue en plan d’un système de support de voie ferrée suivant l’invention pour intégration de rails dans des plaques de répartition en béton.

La figure 6 est une vue en coupe suivant la ligne A-A de la figure 5.

La figure 7 illustre quelques sections transversales possibles pour les plaques de répartition.

Se reportant aux figures 1 et 2, on voit un exemple de système de support de voie ferrée suivant l’invention avec ballast. Le système de support de voie ferrée, désigné dans son ensemble par la référence 10, comprend des traverses 11 sur lesquelles viennent se fixer les rails (non représentés) d’une manière habituelle, et un ballast 12. Conformément à l’invention, en dessous du ballast s’étend un ensemble de plaques de répartition dynamiquement rigides 13, qui elles-mêmes reposent sur le sol du chemin de voie14. Les plaques de répartition 13 sont des plaques relativement courtes, assez épaisses qui
Les plaques de répartition 13 peuvent être fabriquées sur place ou préfabriquées (modules). Dans le système de support de voie ferrée suivant l'invention, les plaques de répartition 13 peuvent également être prévues pour la fixation directe des rails sur béton par l’intermédiaire d’un système de fixation de rail (discret ou continu) quelconque. Les figures 3 et 4 illustrent un exemple de réalisation d’un système de support de voie ferrée pour fixation directe des rails au moyen de systèmes de fixation de rail 15 fixés sur plusieurs plaques de répartition 13. Celles-ci peuvent être intégrées dans le revêtement de la voirie. Les plaques de répartition 13 sont des plaques relativement courtes, assez épaisses qui sont disposées l’une derrière l’autre sur le sol 14. Ces plaques de répartition peuvent être réunies par des joints qui permettent la libre rotation d’une plaque par rapport aux plaques adjacentes. Les plaques de répartition peuvent être fabriquées sur place ou préfabriquées (modules).

Les figures 5 et 6 représentent un système de support de voie ferrée suivant l’invention dans lequel les rails se trouvent intégrés dans les plaques de répartition. Celles-ci comportent des rainures 13A dans lesquelles peuvent être intégrés les rails (non représentés). Les plaques de répartition elles-mêmes peuvent être intégrées dans le revêtement de la voirie. Elles consistent en plaques relativement courtes, assez épaisses qui sont disposées l’une derrière l’autre sur le sol, et qui peuvent être réunies par des joints qui permettent la libre rotation d’une plaque par rapport aux plaques adjacentes. Les plaques de répartition peuvent être fabriquées sur place ou être préfabriquées (modules).

Les systèmes de support de voie ferrée selon l’invention peuvent être utilisés en dessous de voies normales (en alignement et en courbes) et en dessous des appareils de voie. Comme indiqué plus haut pour le cas d’une voie ballastée, chaque plaque de répartition doit avoir une surface et une épaisseur prédéterminées, de manière que sa première fréquence de résonance soit supérieure à 1,4 fois la première fréquence de résonance des vibrations engendrées localement dans les rails par la circulation d’un véhicule sur la voie ferrée. Le comportement des plaques de répartition et la réduction de l’amplitude vibratoire qui en résulte sont les mêmes que dans le cas d’une voie ballastée.

Chaque plaque de répartition peut être réalisée sous la forme d’une poutre simple comme illustré à la figure 7A ou toute autre forme appropriée pourvu qu’elle ait une première fréquence de résonance supérieure à la première fréquence de résonance des vibrations engendrées localement dans les rails par la circulation d’un véhicule sur la voie ferrée comme si elle a été indiqué plus haut. Les figures 7B à 7D illustrent quelques exemples de section transversale pour les plaques de répartition 13. La figure 7B montre une section comportant une plaque portante 13 avec des flancs latéraux 13B qui s’étendent vers le...
dessous de la plaque portante. La figure 7C montre une section qui différe de celle de la figure 7B par la présence d’une nervure longitudinale 13C. Plusieurs nervures pourraient également être prévues. La figure 7D montre une section dans laquelle la plaque 13 comporte des rainures 13A destinées à recevoir les rails de la voie ferrée.

**Revendications**

Système de support pour rails de voie ferrée sur un chemin de voie (14), caractérisé en ce qu’il comprend plusieurs plaques de répartition en matière rigide (13) disposées côte-à-côte sur le chemin de voie, en dessous de la voie ferrée, chaque plaque de répartition ayant une superficie et une épaisseur prédéterminées de manière que sa première fréquence de résonance soit supérieure à la première fréquence de résonance des vibrations engendrées localement dans les rails par le passage des roues d’un véhicule circulant sur les rails.

Système de support pour rails de voie ferrée suivant la revendication 2, caractérisé en ce que les différentes plaques de répartition (13) sont reliées entre elles par des joints permettant le pivotement de chaque plaque de répartition par rapport aux plaques de répartition adjacentes.

Système de support pour rails de voie ferrée suivant l’une quelconque des revendications précédentes, caractérisé en ce que la première fréquence de résonance de chaque plaque de répartition (13) est supérieure à 1,4 fois la première fréquence de résonance des vibrations engendrées localement dans les rails par le passage des roues d’un véhicule circulant sur les rails.

Système de support pour rails de voie ferrée suivant l’une quelconque des revendications précédentes, caractérisé en ce que chaque plaque de répartition (13) est posée sur le sol du chemin de voie (14).

Système de support pour rails de voie ferrée suivant l’une quelconque des revendications précédentes, caractérisé en ce que chaque plaque de répartition (13) est posée sur le radier d’un tunnel.

Système de support pour rails de voie ferrée suivant l’une quelconque des revendications précédentes, caractérisé en ce que chaque plaque de répartition (13) est intégrée dans le revêtement d’une voirie.

Système de support pour rails de voie ferrée suivant l’une quelconque des revendications précédentes, caractérisé en ce qu’au moins une plaque de répartition (13) porte un ballast (12) qui lui-même porte des traverses (11) sur lesquelles viennent se fixer les rails.

Système de support pour rails de voie ferrée suivant l’une quelconque des revendications précédentes, caractérisé en ce que chaque plaque de répartition (13) porte des systèmes de fixation (15) sur lesquels viennent se fixer les rails.

Système de support pour rails de voie ferrée suivant l’une quelconque des revendications précédentes, caractérisé en ce qu’au moins une plaque de répartition (13) porte des rainures (13A) pour recevoir les rails de la voie ferrée.

Système de support pour rails de voie ferrée suivant l’une quelconque des revendications 1 à 4, caractérisée en ce qu’au moins une plaque de répartition (13) porte un ballast (12) qui lui-même porte des traverses (11) sur lesquelles viennent se fixer les rails.

Système de support pour rails de voie ferrée suivant l’une quelconque des revendications 1 à 4, caractérisée en ce qu’au moins une plaque de répartition (13) porte des systèmes de fixation (15) sur lesquels viennent se fixer les rails.

Système de support pour rails de voie ferrée suivant l’une quelconque des revendications précédentes, caractérisée en ce que chaque plaque de répartition (13) est réalisée sous la forme d’une poutre.
Système de support pour rails de voie ferrée suivant l’une quelconque des revendications précédentes, caractérisée en ce qu’au moins une plaque de répartition (13) comporte des flancs latéraux (13B) s’étendant vers le dessous de la plaque.

Système de support pour rails de voie ferrée suivant la revendication 9, caractérisée en ce qu’au moins une plaque de répartition (13) comporte en outre au moins une nervure longitudinale (13C).
1.6. **ALTERNATIVES FOR FLOATING SLABS: REVIEW OF EXISTING DAMPING SYSTEMS (WP1.2.3, PART B1, DEVELOPED BY ALSTOM)**

This chapter focuses on the specific context of the metro in tunnel. It provides a state of the art and a classification of all proven damping track system for metros which are available in tunnel section, in order to identify systems that, in principle, can be considered as efficient and as viable contenders for the floating track slab.

It starts with a description of all existing damping systems, and follows with an assessment of each system to meet simultaneously the following criteria:

- Achieve the best practicable vibration attenuation,
- Comply with operational railways constraints,
- Constructability, maintainability...
- Lead to acceptable life cycle costs.

Background information comes from the literature and past projects. They constitute a benchmark for the innovation that is developed.

The analysis demonstrates that all potential system which can reach the performance use a sleeper (mono or bi block) to ensure vibration mitigation.

The validation site was initially planned in Singapore and moved later to Valenciennes (see chapter 3.11).

1.6.1. **Introduction**

The installation of floating slabs for vibration mitigation of tracks at grade and in tunnels is often requested (average of 15-20% of total alignment length). It constitutes a technical and financial adventure: it increases costs drastically (additional investment cost of 2500 Euro/m for single track at grade, huge additional cost to increase tunnel diameter to accommodate floating slab in tunnel), it increases maintenance, it increases the airborne noise, it is very slow to install, for tracks at grade it leads to deep foundations which are not compatible with an urban environment where lot of utility infrastructure is situated directly under the street pavement.

The main objectives of developing ‘Alternatives for Floating Slab Track’ in tunnels are to develop a track system with high attenuation capabilities and with minimised installation depth. Such a design will allow for:

- A reduction in size of the civil works especially in tunnel,
- Easy replacement of track components (from sleeper and sleeper pad to rail fastening).

The main purpose of this part of the project is to make a state of the art and a class list of all proven damping track systems for MRT (Mass Rapid Transit = Metro) which are available and efficient (such a floating track slab) in tunnel section. The required vibration mitigation is to be provided by the concrete track form, and is defined in term of insertion gains with respect to a given track form taken as reference. A mitigation reference level had been defined with TAPEI floating track slab.
The first part of this chapter provides a description of all damping system. The second presents the assessment of each system to meet simultaneously the following criteria:

- Achieve the best practicable vibration attenuation,
- Comply with operational railways constraints,
- Constructability, maintainability ...
- Lead to acceptable life cycle costs.

### 1.6.2. Noise and vibration attenuation objectives

The vibration mitigation is determined in insertion gain requirements regards to a reference track form that shows limited attenuation performance.

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</tr>
<tr>
<td>Concrete base slab</td>
<td>1000</td>
<td>-</td>
<td>0.1</td>
<td>3668</td>
</tr>
</tbody>
</table>

Table 1.6.1: reference track

The underlying ground has to be given the following properties:

- Elastic modulus: $E = 372$ MN/m²
- Poisson’s ratio: $\nu = 0.47$
- Volumetric mass: $\rho = 2000$ kg/m³
- Loss factor: $\eta = 0.1$

The maximum unsprung mass to be used in the predictions is: 1000 kg/axle

The insertion gain of TAIPEI floating slab regards to a reference track is:
The evaluation of the vibration attenuation performance of the track form will be:

- Performance assessment of the system with its current stiffness characteristics;
- Anticipated improved performance resulting from a further reduction of the stiffness.

The main issue (for the noise and vibration point of view) is to be as close as possible of the TAIPEI track insertion gain during the stage of stiffness reduction.

1.6.3. List of generic types and generic systems

The systems reviewed were classified into 5 categories:

- Directly fastened rail,
- Embedded rail,
- Resilient rail chairs,
- Resilient base plates, and
- Booted systems.

Floating slab track

The list of the generic systems is given in the table below. It is important to note that, considering the main objective of the review exercise at that time was to classify the systems with respect to their
vibration attenuation performances, different systems having the same attenuation performance (because they share the same fastening system) were treated simultaneously.

Abbreviations used are as follows:
- LRT: Light Rail Transit (Light Rail and tramway)
- MRT: Mass Rail Transit (Metro)
- CTRL: Channel Tunnel Rail Link
- RAM: Reliability, Availability, Maintainability

<table>
<thead>
<tr>
<th>Generic Type</th>
<th>Type/Supplier/System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directly Fastened Rail</td>
<td>DFR/Pandrol/Base plate</td>
</tr>
<tr>
<td></td>
<td>Cast-in fastening / Pandrol / Base plate</td>
</tr>
<tr>
<td></td>
<td>Direct rail fastening / AEA TR / PACT</td>
</tr>
<tr>
<td></td>
<td>Direct rail fastening / JNR / Type 4</td>
</tr>
<tr>
<td>Direct rail fastening / JNR / Type 1</td>
<td></td>
</tr>
<tr>
<td>Direct rail fastening / JNR / Type 2</td>
<td></td>
</tr>
<tr>
<td>Resilient fastening / Vossloh / System 300 System DFF 300</td>
<td></td>
</tr>
<tr>
<td>Embedded Rail</td>
<td>Embedded Rail / Edilon</td>
</tr>
<tr>
<td>Embedded Rail</td>
<td>Embedded Rail / Ortec</td>
</tr>
<tr>
<td>Embedded rail / Balfour Beatty / ERT</td>
<td></td>
</tr>
<tr>
<td>Resilient Rail Chairs</td>
<td>Resilient fastening / Pandrol / Vanguard</td>
</tr>
<tr>
<td>Resilient Base plate</td>
<td>Floating base plate / Clouth / Cologne Egg</td>
</tr>
<tr>
<td></td>
<td>Floating base plate / Clouth / Alternative 1</td>
</tr>
<tr>
<td></td>
<td>Floating base plate / LORD / RF-1023-9 with elastomer A066P</td>
</tr>
<tr>
<td>Twin Clip base plate / Vossloh / 1403</td>
<td></td>
</tr>
<tr>
<td>Twin Clip base plate / Pandrol / VIPA-DFC</td>
<td></td>
</tr>
<tr>
<td>Bolted base plate / Vandorl / VIPA SP</td>
<td></td>
</tr>
<tr>
<td>Bolted base plate / Vossloh / Systems 314, 366 and 300</td>
<td></td>
</tr>
<tr>
<td>Bolted base plate / Pandrol / Cast base plate</td>
<td></td>
</tr>
<tr>
<td>Base plate / VARIOUS / CTRL Design</td>
<td></td>
</tr>
<tr>
<td>Booted systems</td>
<td>Twin Block Booted Sleeper / STEDEF / RS STEDEF</td>
</tr>
<tr>
<td>Twin Block Booted Sleeper / Sonnevile / LVT</td>
<td></td>
</tr>
<tr>
<td>Monoblock Booted Sleeper / JNR / Danchoku Tie</td>
<td></td>
</tr>
<tr>
<td>Booted Sleeper / VARIOUS / CTRL Design</td>
<td></td>
</tr>
<tr>
<td>Floating slab track</td>
<td>The TAIPEI rapid transit system (the reference track for noise and vibration performance)</td>
</tr>
</tbody>
</table>

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1.6.4. Categories for evaluation

1.6.4.1. Directly fastened rail

Directly fastened rail systems are characterised by a very low or low resilience, which is fully provided within the fastening system.

1.6.4.2. Embedded rail systems

Three distinct proprietary Embedded Rail Systems were evaluated:

- Edilon system,
- Ortec system, and
- The ESTS (Embedded Slab Track System) developed by Balfour Beatty.

From a vibro-acoustic viewpoint, those system could provide a sufficiently low dynamic stiffness to comply with the attenuation requirements.

1.6.4.3. Resilient Rail Chairs

The only currently available system falling into this category is the recently developed Pandrol Vanguard system. As an industrial party and despite a good attenuation potential, the Pandrol Vanguard system was not sufficiently tested and proven to be considered at the time of this evaluation.
1.6.4.4. Resilient Base plates

Numerous systems fall in this category that has been divided into three generic sub-categories:

- Floating resilient base plates,
- Bolted resilient base plates,
- Double-clip resilient base plates.

1.6.4.5. Floating resilient base plates

Four distinct proprietary systems were considered: Clouth systems (Cologne Egg and alternative), Lord system and Sika Rail system. Those systems, at least the Clouth and Lord, have very good attenuation performances. This generic type is however more dedicated to MRT and LRT applications.

1.6.4.6. Bolted resilient base plates

There are various systems available in this category. The vibro-acoustic depends on the resilience level provided by the under plate pad. The following systems were reviewed:

- JNR system,
- Vossloh 314 and 336 systems,
- Pandrol Cast Base plate,
- Pandrol VIPA SP,
- Bespoke CTRL design.

JNR system is provided with rather stiff characteristics that do not allow complying with the vibration attenuation requirements and was therefore rejected.

Vossloh types 314 / 336 as well as Pandrol cast base plate systems are available with low stiffness characteristics and show rather good attenuation performance.

Figure 1.6.5: Vossloh 336

Pandrol VIPA SP system, its standard design characteristics do not allow to comply with required attenuation. It was however noted that further reduction of the stiffness in a range compatible with the required attenuation was achievable.
1.6.4.7. **Double clip resilient base plate**

Two systems:
- Double Fast Clip system,
- Vossloh 1403 systems.

In their standard design configuration, those systems do not meet the required vibration attenuation. In addition, the use of a clip to fasten the plate makes those systems less adapted than bolted base plate systems to further reduce the vertical stiffness.
1.6.4.8. Booted systems

There are numerous applications worldwide falling within this category, either with twin-blocks sleepers or monobloc sleepers.

The following systems are considered:

- Stedef system (twin-block sleepers),
- Sonneville system (monoblock sleepers),
- Monoblock booted system (JNR application),
- CTRL design.

Stedef and Sonneville systems were positively evaluated, even if no installation to date is recorded with the stiffness level that would be required to achieve the adequate attenuation, considering that further reduction of the dynamic stiffness was possible.

1.6.4.9. Floating slab track

There are numerous applications worldwide falling within this category either with sleepers or fastening system. A concrete slab is laid on a resilient layer, this system, from a vibro-acoustic viewpoint, could provide a sufficiently low dynamic stiffness to comply with the attenuation requirements.

![Figure 1.6.9: TAIPEI floating slab track](image)
1.6.5. **Criteria of analysis**

The analysis of the system performances, for the pre-selected systems, was carried out with respect to the following topics.

**Vibration attenuation performance**

The evaluation of the vibration attenuation performance of the track form will be twofold: the performance of the system with its current stiffness characteristics and the anticipated improved performance resulting from a further reduction of the stiffness.

**Design concept proven**

The performance level for which the system has been tested and qualified is considered: axle load, speed, stiffness characteristics…

**Service proven**

Records form projects where the system has been introduced has been analysed. Specific situation where the system would have not proven satisfactory will be highlighted.

**Constructability**

The constructability of the system, in the specific context of the tunnels will be evaluated. The criteria to be taken into consideration will include:

- Easy to install,
- Compatibility of the installation process with the project requirements (quality of track geometry, installation rate, …),
- Need for special equipment.

**RAM characteristics / durability**

- Track supports shall be easily replaceable.
- The track shall not require heavy maintenance for the lifetime of the rails; only rail pads replacement and common maintenance and cleaning operations are acceptable.
- After an incident, traffic shall resume quickly, with possible speed restrictions.

**System integration compatibility**

This is also a major aspect in the context of URBANTRACK. The suitability of the track form has to be analysed in regards to its compatibility with other sub-systems, in particular:

- The system shall fit in the tunnel geometry, as the available space is limited (compatibility with the civil sub-system).
- The system shall facilitate the evacuation of water and be compatible with the drainage system design.
- The system shall not cause interference with the signalling sub-system.
- The system shall provide adequate electrical insulation.
- Cable crossings, fixing for signalling devices on track, etc. shall be easy to incorporate.
Interfaces management and control as a result of the introduction of the slab track system and the possibility of solving the above specific interface issues will be analysed according issues and results of SP5 – Functional Requirements.

Cost effectiveness
Even though the primary objective is the identification of technically compliant solution, the cost effectiveness of the systems is to be considered. Costs of the system life cycle will be assessed, at least on a comparative basis between systems. Financial considerations form an integral part of the evaluating whether 'Best Practicable Means' has been employed in terms of vibro-acoustic performance.

Optimisation capability / Risks
This item will address the capability of the system to be improved or developed in the perspective of noise and vibration compliance. The specific risks to be anticipated if the system was to undergo a development process will be highlighted: time constraints, technical risks, impact on RAM characteristics or costs…

Important note: The above criteria are not independent and that modifying the features of the system with respect to one criterion will impact on some of the others. For instance, improving the vibration attenuation performance is likely to impact on the cost effectiveness of the system. It may also change the system from a proven state to an unproven state… Similarly, modifying the design characteristics of a system to cope with a specific interface issue may also change the constructability of the system…
1.6.6. Selected systems for evaluation

The systems selected for analysis and final review are given in the table below:

<table>
<thead>
<tr>
<th>No</th>
<th>Generic Type</th>
<th>Type/Supplier/System</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Directly fastened rail</td>
<td>Vossloh system 300</td>
</tr>
<tr>
<td>2</td>
<td>Embedded Rail</td>
<td>Edilon System</td>
</tr>
<tr>
<td>3</td>
<td>Embedded Rail</td>
<td>Balfour Beatty Embedded Slab Track System (ESTS)</td>
</tr>
<tr>
<td>4</td>
<td>Resilient Rail Chairs</td>
<td>Pandrol Vanguard</td>
</tr>
<tr>
<td>5</td>
<td>Bolted Resilient Base plate</td>
<td>Vossloh 314 / 336 systems</td>
</tr>
<tr>
<td>6</td>
<td>Bolted Resilient Base plate</td>
<td>Pandrol Cast Base plate</td>
</tr>
<tr>
<td>7</td>
<td>Bolted Resilient Base plate</td>
<td>Pandrol VIPA SP</td>
</tr>
<tr>
<td>8</td>
<td>Booted Sleeper</td>
<td>Stedef system</td>
</tr>
<tr>
<td>9</td>
<td>Booted Systems</td>
<td>Sateba S312 system</td>
</tr>
<tr>
<td>10</td>
<td>Booted Systems</td>
<td>Sateba monoblock system</td>
</tr>
<tr>
<td>11</td>
<td>Booted Systems</td>
<td>Sonneville LVT system</td>
</tr>
<tr>
<td>12</td>
<td>Booted Systems</td>
<td>Sonneville High Attenuation LVT</td>
</tr>
</tbody>
</table>
## 1.6.6.1. Evaluation

<table>
<thead>
<tr>
<th>No 1: Vossloh System 300</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Item</strong></td>
</tr>
<tr>
<td>Vibration attenuation performance</td>
</tr>
<tr>
<td>Design Concept Proven</td>
</tr>
<tr>
<td>Service proven</td>
</tr>
<tr>
<td>Constructability</td>
</tr>
<tr>
<td>RAM characteristics / Durability</td>
</tr>
<tr>
<td>System integration compatibility</td>
</tr>
<tr>
<td>Cost-effectiveness</td>
</tr>
<tr>
<td>Development capability / Risks</td>
</tr>
<tr>
<td>Item</td>
</tr>
<tr>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>Vibration attenuation performance</td>
</tr>
<tr>
<td>Design Concept Proven</td>
</tr>
<tr>
<td>Service proven</td>
</tr>
<tr>
<td>Constructability</td>
</tr>
<tr>
<td>RAM characteristics / Durability</td>
</tr>
<tr>
<td>System integration compatibility</td>
</tr>
<tr>
<td>Cost-effectiveness</td>
</tr>
<tr>
<td>Development capability / Risks</td>
</tr>
</tbody>
</table>
No 3: Balfour Beatty Embedded Slab Track System (ESTS)

<table>
<thead>
<tr>
<th>Item</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration attenuation</td>
<td>Data provided by the supplier suggest that meeting the required attenuation should be achievable. The resilience of the system is provided by a pad that wraps the rail. This system should thus be more effective than other embedded systems for vibration mitigation.</td>
</tr>
<tr>
<td>performance</td>
<td></td>
</tr>
<tr>
<td>Design Concept Proven</td>
<td>The system has been tested at TU Munich lab. Tests have been carried out on a test track in Spain (V = 240 km/h). The system does not provide any room for vertical/horizontal adjustment of the geometry, to compensate for wear, settlement and at transitions. Longitudinal rail restraint of the system has to be confirmed to ensure there is no risk of creep at transitions and to limit gaps in case of rail breaking.</td>
</tr>
<tr>
<td>Service proven</td>
<td>The system is not proven in service. The proposed rail profile is a completely new profile. It is not proven in service condition.</td>
</tr>
<tr>
<td>Constructability</td>
<td>Control of track geometry at construction requires the use of robust gantries. The gantries proposed by Balfour Beatty, albeit they incorporate large possibilities of adjustment, hold the rails from the top (only accessible part of the rail profile) with the following disadvantages: It is not possible to run the geometry recording trolley when the gantries are installed, The geometry can only be measured once the gantries have been removed and the rail locally supported at regular spacing. At this stage, the rail is partially embedded and the track geometry cannot be easily adjusted. The rail is only supported by the gantries and there is no reference to control the rail inclination. The inclination has to be carefully measured. This is an additional adjustment operation, which is uneasy, especially in situation of curve with high cant values. (In the case of systems on sleepers, the inclination is controlled by the geometry of the sleeper table). Rail has a totally new profile. Supply of rails may therefore be an issue.</td>
</tr>
<tr>
<td>RAM characteristics /</td>
<td>Even though developer of embedded rail systems claim that replacement of a broken rail is achievable during night possession, the system is not sufficiently proven. Maintenance of the ERT system would necessitate applying specific techniques, provision of dedicated equipment, and extensive training of the maintenance staff. No vertical adjustment is possible to allow for rail wear or settlement. The fact that the system does not provide any possibility of geometry adjustment is a major inconvenient for its maintainability. Rail has a totally new profile. Supply of rails may therefore be an issue during maintenance. The system being not proven in service, there is no evidence regarding its reliability. Possible generation of smoke and risk of fire when grinding rails should be investigated.</td>
</tr>
<tr>
<td>Durability</td>
<td></td>
</tr>
<tr>
<td>No 3: Balfour Beatty Embedded Slab Track System (ESTS)</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Item</strong></td>
<td><strong>Analysis</strong></td>
</tr>
<tr>
<td>System integration compatibility</td>
<td>The standard design is proposed with a reinforced slab that would create an interface issue with the signalling system. Incorporating discontinuities in the reinforcement or using non-reinforced concrete would be necessary. Accommodation of signalling devices bonded on rails would be difficult. Accommodation of provisions for drainage would require specific arrangement and complicate the installation.</td>
</tr>
<tr>
<td>Cost-effectiveness</td>
<td>Detail data not available regarding the cost of the system. The lack of experience with the installation (learning curve for installation) of the system is likely to make it non-effective.</td>
</tr>
<tr>
<td>Development capability / Risks</td>
<td>The system is not proven in service. Comments raised in RAM topic are a major risk.</td>
</tr>
</tbody>
</table>
No 4: Pandrol Vanguard System

<table>
<thead>
<tr>
<th>Item</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration attenuation performance</td>
<td>Vanguard has specifically been developed to provide strong vibration attenuation.</td>
</tr>
<tr>
<td></td>
<td>The system is provided with a very low dynamic modulus. It has not however been demonstrated whether it meets the floating slab performance on the whole frequency spectrum.</td>
</tr>
<tr>
<td>Design Concept</td>
<td>The design concept is proven for MRT applications (80 km/h).</td>
</tr>
<tr>
<td>Proven</td>
<td>Longitudinal rail restraint of the system has to be confirmed to ensure there is no risk of creep at transitions and to limit gaps in case of rail breaking. Wear of the resilient material may also have an impact on the longitudinal restraint of the system.</td>
</tr>
<tr>
<td>Service proven</td>
<td>Available references of the system involve localised applications of a few hundreds meters. The experience gained with the system is deemed too limited to fully prove the system. Maximum performances so far are: 16 t/axle and 70 km/h.</td>
</tr>
<tr>
<td>Constructability</td>
<td>Typical mounting of Vanguard system is on continuous plinths, socles or concrete slab.</td>
</tr>
<tr>
<td></td>
<td>Track structure on plinths or concrete slab are usually designed with reinforced concrete elements, which is not in compliance with the signalling system (minimum distance of 600 mm between top of rail and reinforcement). Distribution of the system along the track cannot be easily mechanised and careful protection of the fastening is required during pouring of track concrete (either plinth, or slab,…). This usually leads to relatively low installation rate. Robust installation gantries are required, as the two rail stretches are not connected. Adjustment of the geometry before concrete installation is relatively uneasy. One way to solve the issues mentioned in the three points above would be to pre-assemble the system on sleepers. Design of sleeper could be similar to Rheda 2000 system, in order to improve construction quality at to ensure proper bonding of sleeper with 2nd stage concrete, which would not be reinforced. The process of rail de-stressing, considering the shape of the system, cannot be carried out with standard methods (installation of hydraulic tensors).</td>
</tr>
<tr>
<td>RAM characteristics / Durability</td>
<td>Maintenance of Vanguard system would necessitate applying specific techniques, provision of dedicated equipment, and extensive training of the maintenance staff. The system being not sufficiently proven in service, there is no evidence regarding its RAM and durability characteristics. Repair after major incident could necessitate heavy maintenance works as the system is cast-in the concrete. This may lead to significant unavailability of the track.</td>
</tr>
<tr>
<td>System integration compatibility</td>
<td>When installed on plinth/socle or reinforced slab, the issue of interference with the signalling system arises. Cast-in sleeper installation could solve this interference issue with signalling system, as sleepers can be embedded in non-reinforced 2nd stage concrete.</td>
</tr>
<tr>
<td>Cost-effectiveness</td>
<td>The effectiveness of the system, from a cost viewpoint, in particular in the perspective of an installation on sleepers, will be low.</td>
</tr>
<tr>
<td>Development capability / Risks</td>
<td>Vanguard has only been installed so far in the context of MRT projects, and for short applications, amounting totally to a few hundred meters.</td>
</tr>
</tbody>
</table>
### No 5: Vossloh 314/336 Systems

<table>
<thead>
<tr>
<th>Item</th>
<th>Analysis / Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration attenuation performance</td>
<td>The Vossloh systems on base plate can be provided with rather low stiffness. Further analysis would be necessary to exactly define their attenuation with respect to the project specifications.</td>
</tr>
<tr>
<td>Design Concept Proven</td>
<td>The design is proven for a stiffness of 100 KN/mm/m.</td>
</tr>
<tr>
<td>Service proven</td>
<td>The system has been extensively used on metro projects. It is also service proven on Railway application at: speed up to 160 km/h 28 t axle load (TBC).</td>
</tr>
<tr>
<td>Constructability</td>
<td>Systems on base plate are commonly installed on continuous plinths, socles or concrete slab using either a bottom-up or (preferably) a top-down method. Track structure on plinths or concrete slabs are usually designed with reinforced concrete elements, which is not in compliance with the signalling system (minimum distance of 600 mm between top of rail and reinforcement). Distribution of the system along the track cannot be easily mechanised and careful protection of the fastening is required during pouring of track concrete (either plinth, or slab,…). This usually leads to relatively low installation rate. Robust installation gantries are required, as the two rail stretches are not connected. Adjustment of the geometry before concrete installation is relatively uneasy. One way to solve the issues mentioned in the three points above would be to pre-assemble the system on sleepers. Design of sleeper could be similar to Rheda 2000 system, in order to improve construction quality at to ensure proper bonding of sleeper with 2nd stage concrete, which would not be reinforced.</td>
</tr>
<tr>
<td>RAM characteristics / Durability</td>
<td>Normally good RAM performance is achieved by the system. The system can be adjusted by introducing shims under the resilient pad. Durability of component would have to be verified in case of installation with reduced stiffness. Repair after major incident could necessitate heavy maintenance works as the fastening system is cast-in a support which is not replaceable. This may lead to significant unavailability of the track.</td>
</tr>
<tr>
<td>System integration compatibility</td>
<td>When installed on plinth/socle or reinforced slab, the issue of interference with the signalling system arises. Cast-in sleeper installation could solve this interference issue with signalling system, as sleepers could be embedded in non-reinforced 2nd stage concrete.</td>
</tr>
<tr>
<td>Cost-effectiveness</td>
<td>Based on data from other projects. Installation on sleeper likely to impact on cost-effectiveness.</td>
</tr>
<tr>
<td>Development capability / Risks</td>
<td>Point regarding the availability of the system is a major risk. Compliance with railway constraints would have to be demonstrated with a reduced stiffness. Need of heavy maintenance work in case of incident is a very substantial risk. Transfer of lateral forces with reduced stiffness would have to be checked, as transverse forces are transmitted in shear by the plate pad.</td>
</tr>
<tr>
<td>Item</td>
<td>Analysis / Evaluation</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Vibration attenuation performance</td>
<td>The Pandrol Cast Base plate system can be provided with rather low stiffness. Further analysis would be necessary to exactly define their attenuation with respect to the project specifications.</td>
</tr>
<tr>
<td>Design Concept Proven</td>
<td>The design is proven with a stiffness of 100 KN/mm/m. (TBC)</td>
</tr>
<tr>
<td>Service proven</td>
<td>The system has been extensively used on metro projects. It is also high speed proven at 275 km/h.</td>
</tr>
<tr>
<td>Constructability</td>
<td>Systems on base plate are commonly installed on continuous plinths, socles or concrete slabs using either a bottom-up or (preferably) a top-down method. Track structure on plinths or concrete slabs are usually designed with reinforced concrete elements, which is not in compliance with the signalling system (minimum distance of 600 mm between top of rail and reinforcement). Distribution of the system along the track cannot be easily mechanised and careful protection of the fastening is required during pouring of track concrete (either plinth, or slab,...). This usually leads to relatively low installation rate. Robust installation gantries are required, as the two rail stretches are not connected. Adjustment of the geometry before concrete installation is relatively uneasy. One way to solve the issues mentioned in the three points above would be to pre-assemble the system on sleepers. Design of sleeper could be similar to Rheda 2000 system, in order to improve construction quality at to ensure proper bonding of sleeper with 2nd stage concrete, which would not be reinforced.</td>
</tr>
<tr>
<td>RAM characteristics / Durability</td>
<td>Normally good RAM performance is achieved by the system. Durability of component would have to be verified in case of installation with reduced stiffness. Repair after major incident could necessitate heavy maintenance works as the fastening system is cast-in a support which is not replaceable. This may lead to significant unavailability of the track.</td>
</tr>
<tr>
<td>System integration compatibility</td>
<td>When installed on plinth/socle or reinforced slab, the issue of interference with the signalling system arises. Cast-in sleeper installation could solve this interference issue with signalling system, as sleepers can be embedded in non-reinforced 2nd stage concrete.</td>
</tr>
<tr>
<td>Cost-effectiveness</td>
<td>Based on data from other projects. Installation on sleeper likely to impact on cost-effectiveness.</td>
</tr>
<tr>
<td>Development capability / Risks</td>
<td>Point regarding the availability of the system is a major risk. Compliance with railway constraints would have to be demonstrated with a reduced stiffness. Need of heavy maintenance work in case of incident is a very substantial risk. Transfer of lateral forces with reduced stiffness would have to be checked, as transverse forces are transmitted in shear by the plate pad.</td>
</tr>
<tr>
<td>Item</td>
<td>Analysis / Evaluation</td>
</tr>
<tr>
<td>------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Vibration attenuation performance</td>
<td>The Pandrol VIPA SP system can be provided with rather low stiffness (standard static stiffness is about 20 KN/mm, thus a dynamic modulus of 100 KN/mm/m. The system has been designed to provide good vibration mitigation performance. Pandrol has indicated the lowering the static stiffness of the pad until 15 KN/mm would be feasible in principle. Further analysis would be necessary to exactly define their attenuation with respect to the project specifications.</td>
</tr>
<tr>
<td>Design Concept Proven</td>
<td>The design is proven with a stiffness of 100 KN/mm/m. VIPA includes a specific device that ensures a good transfer of transverse forces. This is an advantage of the system in view of reducing its stiffness. SNCF has recently qualified VIPA (Static stiffness measured in laboratory is 17 KN/mm) for introduction in a conventional line tunnel.</td>
</tr>
<tr>
<td>Service proven</td>
<td>The system has been operated at speeds up to 130 km/h. Maximum axle load is 28 t/axle.</td>
</tr>
<tr>
<td>Constructability</td>
<td>Systems on base plate are commonly installed on continuous plinths, socles or concrete slab using either a bottom-up or (preferably) a top-down method. Track structure on plinths or concrete slabs are usually designed with reinforced concrete elements, which is not in compliance with the signalling system (minimum distance of 600 mm between top of rail and reinforcement). Distribution of the system along the track cannot be easily mechanised and careful protection of the fastening is required during pouring of track concrete (either plinth, or slab,…). This usually leads to relatively low installation rate. Robust installation gantries are required, as the two rail stretches are not connected. Adjustment of the geometry before concrete installation is relatively uneasy. One way to solve the issues mentioned in the three points above would be to pre-assemble the system on sleepers. Design of sleeper could be similar to Rheda 2000 system, in order to improve construction quality at to ensure proper bonding of sleeper with 2nd stage concrete, which would not be reinforced.</td>
</tr>
<tr>
<td>RAM characteristics / Durability</td>
<td>Good RAM performance is achieved by the system. VIPA systems is mounted on a base plate that incorporates the possibility of adjusting the geometry without interfering with the resilient layers. Durability of component would have to be verified in case of installation with reduced stiffness. Repair after major incident could necessitate heavy maintenance works as the fastening system is cast-in a support which is not replaceable. This may lead to significant unavailability of the track.</td>
</tr>
<tr>
<td>System integration compatibility</td>
<td>When installed on plinth/socle or reinforced slab, the issue of interference with the signalling system arises. Cast-in sleeper installation could solve this interference issue with signalling system, as sleepers can be embedded in non-reinforced 2nd stage concrete.</td>
</tr>
<tr>
<td>Cost-effectiveness</td>
<td>Based on data from other projects. Installation on sleeper likely to impact on cost-effectiveness.</td>
</tr>
<tr>
<td>Development capability / Risks</td>
<td>Point regarding the availability of the system is a major risk. Compliance with railway constraints would have to be demonstrated with a reduced stiffness.</td>
</tr>
</tbody>
</table>
No 8: Stedef System

<table>
<thead>
<tr>
<th>Item</th>
<th>Analysis / Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration attenuation performance</td>
<td>The performances of the system are reputed to be good, thanks to the contribution of the intermediary mass to the attenuation. The friction between of the sleeper on the lateral faces of the boot could alter the attenuation performances in case of further reduction of the stiffness. This is particularly true in curve where the part of the load transmitted by friction could become very substantial as the transverse load increase.</td>
</tr>
<tr>
<td>Design Concept Proven</td>
<td>The system is design proven for a stiffness range from 75 to 150 KN/mm/m.</td>
</tr>
<tr>
<td>Service proven</td>
<td>Numerous installations on subway and railway projects. Axle load: 22.5 t</td>
</tr>
<tr>
<td>Constructability</td>
<td>Experience has proven good Constructability. Same installation rate as current plan (250 m/day). The boots are not waterproof and there is a risk of water or concrete penetration in between the boot and the sleeper at construction stage. Risk of deformation of the boot at concrete pouring that can induce a degraded behaviour.</td>
</tr>
<tr>
<td>RAM characteristics / Durability</td>
<td>The reliability and availability of the system is proven. Maintainability of the system is good. But, operation of sleeper substitution is somewhat uneasy as substitution sleeper of smaller size have to be used.</td>
</tr>
<tr>
<td>System integration compatibility</td>
<td>No interface issue as twin-block sleeper is embedded in a non-reinforced second stage concrete.</td>
</tr>
<tr>
<td>Cost-effectiveness</td>
<td>Good</td>
</tr>
<tr>
<td>Development capability / Risks</td>
<td>Friction between sleeper and boot could impact on the dynamic stiffness and consequently on the vibro-acoustic performance. Verification of railway constraints with reduced stiffness would have to be demonstrated. Impact of reduced stiffness on durability to be analysed.</td>
</tr>
</tbody>
</table>
No 9: Sateba S312 System

<table>
<thead>
<tr>
<th>Item</th>
<th>Analysis / Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration attenuation performance</td>
<td>The performances of the system are reputed to be good, thanks to the contribution of the intermediary mass to the attenuation. The introduction in the system of lateral pad in between the rigid shell and the sleeper has allowed to “de-couple” the vertical and transversal modes. This suggests that the system is better suited than systems using rubber boots to accept further stiffness reduction.</td>
</tr>
<tr>
<td>Design Concept Proven</td>
<td>The system is design proven for a stiffness range from 75 to 150 KN/mm/m, for: 17 t/axle up to 300 km/h, and 22.5 t/axle up to 200 km/h</td>
</tr>
<tr>
<td>Service proven</td>
<td>High-speed proven: 230 km/h (Marseilles tunnel)</td>
</tr>
<tr>
<td>Constructability</td>
<td>Experience has proven good Constructability. Current installation plan developed around this system (250 m/day). Constructability of the system is enhanced by some design features: Waterproofing of joint at sleeper/shell interface, Rigidity of shells. The possibility of running on boots before pouring of 2nd stage will have to be verified.</td>
</tr>
<tr>
<td>RAM characteristics / Durability</td>
<td>The reliability and availability of the system is proven. Maintainability of the system is good. The system design allows easy substitution of sleepers.</td>
</tr>
<tr>
<td>System integration compatibility</td>
<td>No interface issue as twin-block sleeper is embedded in a non-reinforced second stage concrete.</td>
</tr>
<tr>
<td>Cost-effectiveness (CAPEX)</td>
<td>Reference system for cost comparison.</td>
</tr>
<tr>
<td>Development capability / Risks</td>
<td>Verification of railway constraints with reduced stiffness would have to be demonstrated. Impact of reduced stiffness on durability to be analysed.</td>
</tr>
<tr>
<td>Item</td>
<td>Analysis / Evaluation</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Vibration attenuation performance</td>
<td>Same advantages as the SAT 312 system. in addition: The mass of the monoblock sleeper can improve the attenuation performance, The rigidity brought by the monoblock sleeper can allow further reduction of the stiffness without increased rail roll/twist, and thus improved attenuation performance within railway constraints.</td>
</tr>
<tr>
<td>Design Concept Proven</td>
<td>Design is proven for application in turnout bearers.</td>
</tr>
<tr>
<td>Service proven</td>
<td>Service proven for turnout bearers: Eole line (Paris Suburban Network), Le Bourget (SNCF conventional Line).</td>
</tr>
<tr>
<td>Constructability</td>
<td>Installation methodology foreseen for twin-block sleeper can be extended to monoblock sleepers. Same installation rate can be achieved. The introduction of monoblock sleepers would conflict with the current arrangement for drainage. Locally, use of single blocks would be necessary at the location of drainage openings. The possibility of running on boots before pouring of 2nd stage will have to be verified.</td>
</tr>
<tr>
<td>RAM characteristics / Durability</td>
<td>RAM and durability characteristics should be the same for the SAT 312 system.</td>
</tr>
<tr>
<td>System integration compatibility</td>
<td>Same as for SAT 312 Local conflict with drainage to be solved.</td>
</tr>
<tr>
<td>Cost-effectiveness</td>
<td>The cost of the system in monoblock configuration is about 2 times higher than the cost of the twin-block configuration.</td>
</tr>
<tr>
<td>Development capability / Risks</td>
<td>The system is likely to offer a very good option to achieve S3.</td>
</tr>
</tbody>
</table>
No 11: Sonneville LVT system

<table>
<thead>
<tr>
<th>Item</th>
<th>Analysis / Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration attenuation performance</td>
<td>The performances of the system are reputed to be good, thanks to the contribution of the intermediary mass to the attenuation. The friction between of the sleeper on the lateral faces of the boot could alter the attenuation performances in case of further reduction of the stiffness. This is particularly true in curve where the part of the load transmitted by friction could become very substantial as the transverse load increase. This is the same concern as for the Stedef system, but the situation is even worse in the case of LVT compared with Stedef, as the transverse load on one block is higher (no distribution between the blocks by the tie-bar) and block encasement in the concrete is deeper.</td>
</tr>
<tr>
<td>Design Concept</td>
<td>Standard design with stiffness of 150 KN/mm/m Test section installed with a stiffness of 100 KN/mm/m using “finned boots” (Hong-Kong MRT). Test section at 200 km/h in Grauholzt tunnel (Switzerland).</td>
</tr>
<tr>
<td>Cost-effectiveness</td>
<td>Proven with a stiffness of 150 KN/mm Max speed: 160 km/h in operation. Resilient pads in the channel tunnel have appeared to quickly stiffen in service causing accelerated deterioration of the fastening system and a loss of vibration attenuation. This has led the supplier to change the raw material of the resilient pad.</td>
</tr>
<tr>
<td>Constructability</td>
<td>Robust installation supports have to be used, as the rail stretches are not connected (control of the track geometry). Same installation rate as for reference solution is achievable (track assembly) in principle. However, the second stage concrete in the case of the Sonneville system is about 30 % deeper than in the case of the Sateba system. The impact on the installation rate (concreting operation) would be a reduction of the same magnitude. The boots are not waterproof: risk of water/concrete penetration at construction stage. The possibility of running on boots before pouring of 2nd stage will have to be verified.</td>
</tr>
<tr>
<td>RAM characteristics / Durability</td>
<td>The reliability and availability of the system is proven. However, Eurotunnel has been a bad experience as regards the fastening system. Maintainability of the system is good. But, operation of sleeper substitution is uneasy, as substitution blocks of smaller size have to be used.</td>
</tr>
<tr>
<td>System integration compatibility</td>
<td>No interface issue as twin-block sleeper is embedded in a non-reinforced second stage concrete.</td>
</tr>
<tr>
<td>Cost-effectiveness</td>
<td>Similar to reference design. The embedding depth in second stage concrete is higher than for twin-block system. Application in tunnels would require thickening the second stage concrete (cost impact to be evaluated).</td>
</tr>
<tr>
<td>Development capability / Risks</td>
<td>Verification of railway constraints with reduced stiffness would have to be demonstrated. Impact of reduced stiffness on durability to be analysed. Practical effectiveness of reduced stiffness on vibration mitigation because of friction on the rubber boot, especially in curve.</td>
</tr>
<tr>
<td>Item</td>
<td>Analysis / Evaluation</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Vibration attenuation performance</td>
<td>Should provide improved attenuation with respect to the standard Sonneville System (lower stiffness and bigger block). However, same problem as for standard LVT regarding the attenuation performance (increase of the dynamic stiffness due to the friction of the block on the rubber boot).</td>
</tr>
<tr>
<td>Design Concept Proven</td>
<td>Test section in Hong-Kong with a stiffness of 50 KN/mm/m</td>
</tr>
<tr>
<td>Service proven</td>
<td>No record aside from test section above.</td>
</tr>
<tr>
<td>Constructability</td>
<td>Same comments as for the standard LVT.</td>
</tr>
<tr>
<td>RAM characteristics / Durability</td>
<td>The reliability and availability of the system is proven. Maintainability of the system is good. Operation of sleeper substitution is uneasy.</td>
</tr>
<tr>
<td>System integration compatibility</td>
<td>No interface issue as twin-block sleeper is embedded in a non-reinforced second stage concrete.</td>
</tr>
<tr>
<td>Cost-effectiveness</td>
<td>The cost of the system is approximately 1.5 times higher than the cost of standard LVT. The embedding depth in second stage concrete is higher than for twin-block system. Application in tunnels would require thickening the second stage concrete (cost impact to be evaluated).</td>
</tr>
<tr>
<td>Development capability / Risks</td>
<td>Verification of railway constraints with reduced stiffness would have to be demonstrated. No major improvement compared with the LVT system is likely to be expected. Concept of composite block pad (resilient material + fill) has to be validated by adequate tests. Impact of reduced stiffness on durability to be analysed. Practical effectiveness of reduced stiffness on vibration mitigation because of friction on the rubber boot, especially in curve.</td>
</tr>
</tbody>
</table>
1.6.7. Evaluation results

For each topic, a quoted evaluation ranging from 0 (very bad performance) to 10 (best performance of the analysed systems) is given to the systems.

To calculate the total score, each topic is attributed a given weight, as follows:

<table>
<thead>
<tr>
<th>Topics</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration attenuation</td>
<td>5</td>
</tr>
<tr>
<td>Design concept proven</td>
<td>3</td>
</tr>
<tr>
<td>Service proven</td>
<td>4</td>
</tr>
<tr>
<td>Constructability</td>
<td>3</td>
</tr>
<tr>
<td>RAM characteristics / Durability</td>
<td>6</td>
</tr>
<tr>
<td>System integration capability</td>
<td>3</td>
</tr>
<tr>
<td>Cost-effectiveness</td>
<td>2</td>
</tr>
<tr>
<td>Development Capability/Risks</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>30</td>
</tr>
</tbody>
</table>

The quotation has been developed with respect to the URBANTRACK project’s objectives and in the perspective of introduction of the evaluated systems in the tunnel sections, keeping in mind the particular requirements and specificity of the project. The reader cannot therefore understand this quotation as an absolute evaluation of the systems as other project context may have led to very different outputs and other conclusions.

<table>
<thead>
<tr>
<th>Vibration attenuation</th>
<th>Design proven</th>
<th>Service proven</th>
<th>Constructability</th>
<th>RAM / durability</th>
<th>System integration</th>
<th>Cost Effect</th>
<th>Development risk</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vossloh 300</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>129</td>
</tr>
<tr>
<td>Edilon system</td>
<td>Not quoted.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balfour Beatty ERT</td>
<td>Not quoted.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pandrol Vanguard</td>
<td>Not quoted.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vossloh 314/336</td>
<td>3</td>
<td>8</td>
<td>4</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>117</td>
</tr>
<tr>
<td>Pandrol Cast Base plate</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>133</td>
</tr>
<tr>
<td>Pandrol VIPA SP</td>
<td>5</td>
<td>8</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>143</td>
</tr>
<tr>
<td>Stedef system</td>
<td>6</td>
<td>8</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>10</td>
<td>8</td>
<td>174</td>
</tr>
<tr>
<td>Sateba SAT 312 system</td>
<td>8</td>
<td>10</td>
<td>8</td>
<td>10</td>
<td>8</td>
<td>10</td>
<td>6</td>
<td>254</td>
</tr>
<tr>
<td>Sateba Monoblock</td>
<td>10</td>
<td>6</td>
<td>2</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>10</td>
<td>210</td>
</tr>
<tr>
<td>Sonneville LVT system</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>6</td>
<td>207</td>
</tr>
<tr>
<td>Sonneville high attenuation</td>
<td>9</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>4</td>
<td>183</td>
</tr>
</tbody>
</table>
1.6.8. Conclusion

The review has identified systems that, in principle, can be considered as viable contenders for the floating track slab in the specific context of the metro tunnel. It demonstrate that all potential system which can reach the performance use a sleeper (mono or bi block) to ensure vibration mitigation.

So, the preferred way of achieving the required noise and vibration performance is to describe a two level elasticity system, with an intermediary mass inserted between both levels.

The main advantages of this concept are:

- To improve the low-pass filter, and
- To avoid high stresses in the main resilient level, taking into account the large vertical deflection of the track.

A solution is to have two resilient levels, one below the rail and a second below an intermediary support, which can be a sleeper, (a concrete slab -> reference solution, or a base plate-> couldn’t achieve N&amp;V performance).

To minimise the transmission of vibrations, it is more beneficial to maximise the stiffness of the layer below the rail and minimise the stiffness of the layer below the intermediary mass and to maximise the mass above the resilient layer. The ultimate, from a noise or vibration perspective, extension of this design concept is a floating slab track where a complete concrete slab is provided between the two resilient layers.
1.7. **ALTERNATIVES FOR FLOATING SLABS IN TUNNELS: SLEEPER FEASIBILITY (WP1.2.3, PART B2, DEVELOPED BY ALSTOM)**

The objective of this part of the project is to confirm the feasibility (cost and mechanic viability) of a booted sleeper (mono or bi-bloc) laying on a very low stiffness pad, able to achieve a high floating track slab acoustic performance for the proposed slab-track systems.

The aim is to define a lower “intrinsic” limit for the vertical stiffness – which induces strain and stresses modifications in the components of the track - to comply with components technical limits (maximum strain, resistance to repeated loading, inner maximum displacements).

In order to achieve the objective, a mechanical model of a sleeper track was developed with an analytical method, considering a concrete sleeper linked to the tunnel slab by means of elastic components. Various loading cases were applied to this system in order to check that both the mechanical stresses in sleepers were acceptable and the track geometry is kept.

Starting from an existing system which has been notably implemented on the CTRL (Channel Tunnel Rail Link) Section 2, an investigation was carried out in order to check the feasibility of decreasing the resilience of the system while keeping a sleeper track.

As a conclusion, the standard bi-block system show its limits when the resilient pad stiffness is low, whereas with the same loads the mono-block system behaviour is acceptable. This system seems, mechanically speaking, to be more efficient for the development of a booted sleeper which could reach the floating slab track performances with the respect of railway constraint.

The validation site for a monoblock sleeper placed on highly resilient pads and embedded in a plastic rigid hull was initially planned in Singapore and moved later to Valenciennes (see chapter 3.11).

1.7.1. **Definitions & abbreviations**

The notion of *railway constraints* designates the whole technical limits that, from a railway-engineering viewpoint, have to be complied with to ensure the safety and RAM performance of the slab track systems on the life cycle. Railway constraints are related to:

- Safety,
- RAM: Reliability, Availability, Maintainability,
- Passenger comfort aspects.
1.7.2. Analysis

1.7.2.1. Track geometry

The parameters to be taken into account for the dynamic loads calculations are the following:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Parameter</th>
<th>Adopted value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal level</td>
<td>( \sigma (LL) ) = Root mean square on a 25 m basis = NL(LL)</td>
<td>0.85</td>
</tr>
<tr>
<td>Alignment</td>
<td>( \sigma (A) ) = Root mean square on a 25 m basis = NL(A)</td>
<td>0.6</td>
</tr>
<tr>
<td>Track geometry index ( U = 2 \ NT + D )</td>
<td>( U = 2.6 \times \sigma (LL) )</td>
<td>2.2</td>
</tr>
<tr>
<td>Track geometry (short wave)</td>
<td>( A )</td>
<td>0.2 (Good rail and track geometry)</td>
</tr>
<tr>
<td>Minimal radius (m)</td>
<td>( R )</td>
<td>300</td>
</tr>
<tr>
<td>Cant deficiency (mm)</td>
<td>( I_d )</td>
<td>150</td>
</tr>
</tbody>
</table>

1.7.2.2. Vehicle load

The characteristics of the vehicles to run are the following:

<table>
<thead>
<tr>
<th>Description</th>
<th>Metro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue speed (km/h)</td>
<td>90</td>
</tr>
<tr>
<td>Commissioning speed (1.10xRevenue Speed) (km/h)</td>
<td>100</td>
</tr>
<tr>
<td>Maximum axle load (kN)</td>
<td>120 to 180</td>
</tr>
<tr>
<td>Maximum nominal wheel load ( Q_N ) (kN)</td>
<td>60 to 90</td>
</tr>
<tr>
<td>Maximum unsprung mass per wheel ( M_{\text{maxUS}} ) (kg)</td>
<td>750 to 1125</td>
</tr>
<tr>
<td>Height of the centre of gravity: ( h ) (mm)</td>
<td>1500</td>
</tr>
<tr>
<td>Axles spacing (same bogie, m)</td>
<td>2.4</td>
</tr>
</tbody>
</table>

1.7.2.3. Definition of the loads

**NOTATIONS**

\[
Y_{\text{inner}} + Q_{\text{inner}} \quad H = Y_{\text{outer}} - Y_{\text{inner}} \quad Y_{\text{outer}} + Q_{\text{outer}}
\]
VERTICAL LOADS
In a very general way, the vertical wheel load applied to the track can be described as the sum of 4 terms:

\[ Q = Q_N + \Delta Q_{\text{Curve}} + \Delta Q_{\text{SM}} + \Delta Q_{\text{UM}} \]

Where:
- \( Q_N \): Nominal wheel load in kN
- \( \Delta Q_{\text{Curve}} \): Quasi-static wheel load due to cant deficiency (\( I_d \))
- \( \Delta Q_{\text{SM}} \): Dynamic load due to sprung masses
- \( \Delta Q_{\text{UM}} \): Dynamic loads due to unsprung masses

Note:
\[ \Delta Q_{\text{DYN}}\text{ : Dynamic loads} = \Delta Q_{\text{DYN}} = \Delta Q_{\text{UM}} + \Delta Q_{\text{UM}} \]

TRANSVERSAL LOADS
Note: In the following, the letter H will refer to the total transverse load applied to the track by the axle and \( Y \) to the transverse load applied at the wheel/rail contact.

\[ H = \Delta H_{\text{Curves}} + \Delta H_{\text{dyn}} \]

Where:
- \( \Delta H_{\text{Curves}} \): Quasi-static transverse load due to cant deficiency (\( I_d \))
- \( \Delta H_{\text{Curve}} = \alpha \cdot \frac{2 \cdot Q_N \cdot I_d}{e} \)
  - \( e \): track gauge ~1500 mm
  - \( \alpha \): a coefficient (generally taken as 1.2) taking into account the distribution of loads between the 2 axles of one bogie.
- \( \Delta H_{\text{DYN}} \): Dynamic loads due to the track geometry defects (as per vertical loads)

The loads \( Y_{\text{outer}} \) and \( Y_{\text{inner}} \) can be derived from the following formulas:

\[ Y_{\text{outer}} = H + Y_{\text{inner}} \]

With \( Y_{\text{inner}} = \mu Q_{\text{inner}} \)

With \( \mu \): the quasi-sliding coefficient between the rail and the wheel (\( \mu = \frac{135}{150 + R} \) for typical wagon with R the curve radius) and \( Q_{\text{inner}} = Q_N \left[ 1 - 2 \frac{I_d \cdot h}{e^2} \right] \).
LOADS CASES FOR MECHANICAL BEHAVIOUR

The standard loads for mechanical behaviour will be used for the effect of repeated loading tests (fatigue test) and for nominal stresses and deflection calculations.

Nominal case: MB1

\[
Q_{\text{outer}} = Q_N + \Delta Q_{\text{Curve}} + \Delta Q_{\text{DYN}} \\
Q_{\text{inner}} = Q_N - \Delta Q_{\text{Curve}} + k \cdot \Delta Q_{\text{DYN}} \\
Y_{\text{outer}} = H_{\text{curve}} + H_{\text{dyn}} + \mu \left( Q_N - \Delta Q_{\text{Curve}} + k \cdot \Delta Q_{\text{DYN}} \right) \\
Y_{\text{inner}} = \mu \left( Q_N - \Delta Q_{\text{Curve}} + k \cdot \Delta Q_{\text{DYN}} \right)
\]

with \( k = 0 \) or \( 1 \)

and with \( \Delta Q_{\text{DYN}} \) the dynamic load with 2 standard deviations.

For this load case, the overloads are calculated with the Revenue speed (RS) of the vehicles.

Extreme case for running vehicles: MB2

(Calculations to be carried out with pads Dynamic stiffness)

Maximum wheel load, Maximal transverse load

\[
Q_{\text{outer}} = Q_N + \Delta Q_{\text{Curve,CS}} + \Delta Q_{\text{DYN}} \text{ (CS)} \\
Q_{\text{inner}} = Q_N - \Delta Q_{\text{Curve,CS}} + k \cdot \Delta Q_{\text{DYN}} \text{ (CS)} \\
Y_{\text{outer}} = H_{\text{MAX}} + \mu \left( Q_N - \Delta Q_{\text{Curve,CS}} + k \cdot \Delta Q_{\text{DYN}} \text{ (CS)} \right) \\
Y_{\text{inner}} = \mu \left( Q_N - \Delta Q_{\text{Curve,CS}} + k \cdot \Delta Q_{\text{DYN}} \text{ (CS)} \right)
\]

with \( k = 0 \) or \( 1 \)

For this load case, the overloads are calculated with the Commissioning Speed (CS) of the vehicles \((=1.10 \times \text{Revenue speed})\) \( \Delta Q_{\text{Curve}} = \Delta Q_{\text{Curve,CS}} \) and \( \Delta Q_{\text{DYN}} \text{(CS)} = 1.10 \cdot \Delta Q_{\text{DYN}} \text{(RS)} \).

The stresses and deflection calculations with these loads must be undertaken to validate that the system is able to support the maximum loads without damages.

Load case due to a stopped vehicle: MB3

(Calculations to be carried out with pads static stiffness)

\[
Q_{\text{outer}} = Q_N - \Delta Q_{\text{stat}} \\
Q_{\text{inner}} = Q_N + \Delta Q_{\text{stat}} \\
\Delta Q_{\text{stat}} = \frac{2 \cdot Q_N \cdot h \cdot \text{Cant}}{e^2} \\
Y_{\text{outer}} = 0 \text{ (Conservative assumption)} \\
Y_{\text{inner}} = H_{\text{stat}} = \frac{2Q_N \cdot \text{Cant}}{e}
\]

with \( \Delta Q_{\text{stat}} \) the vertical overload due to the cant in curve (stopped vehicle).
\( \Delta H_{\text{sur}} \) the horizontal load due to the cant in curve (stopped vehicle).

This load case may be detrimental to the systems especially when freight trains are stopped in the most critical curve. In that case, especially if the dynamic to static stiffness ratio is high, the displacements (and the stresses) could be greater than for a running vehicle.

A conservative value for the maximum transverse load to apply to the track is given by the maximum transverse load used for vehicle qualification:

\[
H_{\text{MAX}} = 0.85 \cdot \left( 10 + \frac{2Q_{\text{v}}}{3} \right) \text{ in kN}
\]

**Load distribution factor**

For the system, after determination of its actual dynamic vertical stiffness, the appropriate distribution factor for the train will be calculated by using the Zimmermann formula applied to 2 axles.

For the distribution of the transverse load, we use the constant and conservative value 0.5.

Zimmermann formula for one wheel is given by:

\[
\rho = \frac{1}{2\sqrt{2}} \sqrt{\frac{s^3 K_{\text{dyn}}}{EI_{xx}}}
\]

With 
\( s \): the sleeper spacing and 
\( EI_{xx} \): the rail bending stiffness.
\( K_{\text{dyn}} \): the vertical dynamic stiffness

This formula is true for one wheel, so one must made a Zimmermann analyse for two axles because with two axles the first axle has an influence on the second. The result of this analyse is given by the following table:

<table>
<thead>
<tr>
<th>Metro</th>
<th>axle load</th>
<th>180kN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>one same bogie, axle to axle distance</td>
<td>2.4m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Track</th>
<th>rail</th>
<th>UIC60</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sleeper spacing</td>
<td>0.6m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( K_{\text{dyn}} ) (MN/m)</th>
<th>Load distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.263</td>
</tr>
<tr>
<td>6</td>
<td>0.267</td>
</tr>
<tr>
<td>7</td>
<td>0.271</td>
</tr>
<tr>
<td>8</td>
<td>0.275</td>
</tr>
<tr>
<td>9</td>
<td>0.278</td>
</tr>
<tr>
<td>10</td>
<td>0.282</td>
</tr>
</tbody>
</table>
1.7.3. Calculation

1.7.3.1. Sleeper loads

<table>
<thead>
<tr>
<th>Effort</th>
<th>MB1-1</th>
<th>MB1-2</th>
<th>MB2-1</th>
<th>MB2-2</th>
<th>MB3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_o$</td>
<td>39.35</td>
<td>39.35</td>
<td>42.35</td>
<td>42.35</td>
<td>19.47</td>
</tr>
<tr>
<td>$Q_i$</td>
<td>22.52</td>
<td>34.90</td>
<td>20.76</td>
<td>34.37</td>
<td>30.03</td>
</tr>
<tr>
<td>$Y_o$</td>
<td>27.65</td>
<td>32.98</td>
<td>38.69</td>
<td>35.61</td>
<td>0.00</td>
</tr>
<tr>
<td>$Y_i$</td>
<td>9.70</td>
<td>15.03</td>
<td>8.94</td>
<td>5.86</td>
<td>9.60</td>
</tr>
</tbody>
</table>

1.7.3.2. Sleeper model

A simplified model of mono-block and bi-block sleeper, taking in account the sleeper characteristics, was develop to find displacement and stress for each type of sleeper.

In this model, the fastening system stiffness is considered as infinite, it means that there is no displacement between rail foot and the base-plate (conservative assumption).

1.7.3.3. Bi-bloc model

1.7.3.4. Mono-bloc model
## Calculation results

### Bi-block

<table>
<thead>
<tr>
<th>Bi-block</th>
<th>Unit</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 1</th>
<th>Block 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer edge displacement</td>
<td>mm</td>
<td>-2.76</td>
<td>-1.08</td>
<td>-4.86</td>
<td>-0.22</td>
<td>-2.26</td>
<td>-0.14</td>
<td>-3.59</td>
<td>-0.18</td>
</tr>
<tr>
<td>Center displacement</td>
<td>mm</td>
<td>-3.80</td>
<td>-3.93</td>
<td>-5.52</td>
<td>-3.77</td>
<td>-3.86</td>
<td>-4.03</td>
<td>-5.32</td>
<td>-4.27</td>
</tr>
<tr>
<td>Inner edge displacement</td>
<td>mm</td>
<td>-4.85</td>
<td>-6.78</td>
<td>-6.17</td>
<td>-7.31</td>
<td>-5.45</td>
<td>-7.93</td>
<td>-7.05</td>
<td>-8.36</td>
</tr>
<tr>
<td>Block rotation</td>
<td>°</td>
<td>-0.18</td>
<td>0.49</td>
<td>-0.11</td>
<td>0.61</td>
<td>-0.28</td>
<td>0.68</td>
<td>-0.50</td>
<td>0.71</td>
</tr>
<tr>
<td>Top rail displacement</td>
<td>mm</td>
<td>0.25</td>
<td>3.84</td>
<td>1.04</td>
<td>4.90</td>
<td>0.07</td>
<td>5.14</td>
<td>-0.20</td>
<td>5.17</td>
</tr>
<tr>
<td>Gauge widening</td>
<td>mm</td>
<td>-3.59</td>
<td>-3.86</td>
<td>-5.07</td>
<td>-5.37</td>
<td>2.03</td>
<td>3.67</td>
<td>1.92</td>
<td>0.15</td>
</tr>
<tr>
<td>Horizontal displacement</td>
<td>mm</td>
<td>1.53</td>
<td>0.34</td>
<td>1.84</td>
<td>0.56</td>
<td>2.03</td>
<td>0.36</td>
<td>1.92</td>
<td>0.15</td>
</tr>
<tr>
<td>Tie-bar maximum stress</td>
<td>MPa</td>
<td>388.96</td>
<td>901.82</td>
<td>473.71</td>
<td>1026.43</td>
<td>467.57</td>
<td>1190.58</td>
<td>297.62</td>
<td>1064.46</td>
</tr>
<tr>
<td>(&lt;0 for traction)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Mono-block

<table>
<thead>
<tr>
<th>Mono-block</th>
<th>Unit</th>
<th>Inner</th>
<th>Outer</th>
<th>Inner</th>
<th>Outer</th>
<th>Inner</th>
<th>Outer</th>
<th>Inner</th>
<th>Outer</th>
<th>Inner</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation (at rail seat)</td>
<td>°</td>
<td>-0.027</td>
<td>-0.022</td>
<td>0.383</td>
<td>0.373</td>
<td>-0.064</td>
<td>-0.006</td>
<td>0.207</td>
<td>0.248</td>
<td>0.402</td>
<td>0.295</td>
</tr>
<tr>
<td>Top rail displacement</td>
<td>mm</td>
<td>-0.14</td>
<td>-0.11</td>
<td>1.94</td>
<td>1.89</td>
<td>-0.32</td>
<td>-0.03</td>
<td>1.05</td>
<td>1.26</td>
<td>2.03</td>
<td>1.49</td>
</tr>
<tr>
<td>Gauge widening</td>
<td>mm</td>
<td>-0.03</td>
<td>0.05</td>
<td>-0.29</td>
<td>-0.21</td>
<td>-0.03</td>
<td>0.05</td>
<td>-0.29</td>
<td>-0.21</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td>Bending moment at rail seat</td>
<td>kN.m</td>
<td>-1.28</td>
<td>-1.012</td>
<td>-2.19</td>
<td>-1.18</td>
<td>-1.27</td>
<td>-1.34</td>
<td>-2.21</td>
<td>-1.23</td>
<td>-1.67</td>
<td>-0.87</td>
</tr>
<tr>
<td>Bending moment at sleeper center</td>
<td>kN.m</td>
<td>2.50</td>
<td>3.50</td>
<td>0.96</td>
<td>2.06</td>
<td>5.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1.7.4. Conclusion

1.7.4.1. Bi-block

The block displacement and rotation induce rail rotation and so a rail gauge variation and a stress in the tie bar which are not acceptable for the sleeper.

1.7.4.2. Mono-block

The rail gauge variation under load is correct consequently the gauge widening is stable. The bending moment is correct for a mono-block sleeper (the minimal value for a mono-bloc sleeper is close to 12kN/m).

1.7.4.3. Recommendation

The standard bi-block system shown its limits when the resilient pad stiffness is low, whereas with the same loads the mono-block system behaviour is acceptable. This system seems, mechanically speaking, to be more efficient for the development of a booted sleeper which could reach the floating slab track performances with the respect of railway constraint.

Such a mono-block sleeper has been validated in Singapore and in Valenciennes, France (see chapter 3.11).
### 1.7.5. Appendix A1.7

#### 1.7.5.1. Load cases coefficient matrix

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Load</th>
<th>$Q_N$</th>
<th>$\Delta Q_{curve}$</th>
<th>$\Delta Q_{DYN}$</th>
<th>$\Delta Q_{Stat}$</th>
<th>$\Delta H_{curve}$</th>
<th>$\Delta H_{DYN}$</th>
<th>$H_{MAX}$</th>
<th>$H_{Stat}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB1</td>
<td>$Q_{outer}$</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Q_{inner}$</td>
<td>1</td>
<td>-1</td>
<td>0 or 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Y_{outer}$</td>
<td>$\mu$</td>
<td>$-\mu$</td>
<td>0 or $2\mu$</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Y_{inner}$</td>
<td>$\mu$</td>
<td>$-\mu$</td>
<td>0 or $2\mu$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MB2</td>
<td>$Q_{outer}$</td>
<td>1</td>
<td>1 (*)</td>
<td>2 (*)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Q_{inner}$</td>
<td>1</td>
<td>-1 (*)</td>
<td>0 or 2 (*)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Y_{outer}$</td>
<td>$\mu$</td>
<td>$-\mu$ (*)</td>
<td>0 or $2\mu$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Y_{inner}$</td>
<td>$\mu$</td>
<td>$-\mu$ (*)</td>
<td>0 or $2\mu$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MB3</td>
<td>$Q_{outer}$</td>
<td>1</td>
<td></td>
<td></td>
<td>-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Q_{inner}$</td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Y_{outer}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Y_{inner}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(*) For Maximum loads, $\Delta Q_{curve,CS}$ is used in replacement of $\Delta Q_{curve}$ and $1.10 \times \Delta Q_{DYN}$ replaces $\Delta Q_{DYN}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_d$</td>
<td>120 mm</td>
<td></td>
</tr>
<tr>
<td>$H$</td>
<td>1500 mm</td>
<td></td>
</tr>
<tr>
<td>$E$</td>
<td>1500 mm</td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>420 m</td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.237</td>
<td></td>
</tr>
<tr>
<td>$U$</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>$V$</td>
<td>90 km/h</td>
<td>$I_d = 67.57142857$</td>
</tr>
<tr>
<td>$\gamma_{dyn/QS}$</td>
<td>0.25</td>
<td>$V = 90 \text{km/h}$</td>
</tr>
<tr>
<td>Cant</td>
<td>160 mm</td>
<td></td>
</tr>
<tr>
<td>$V(CS)$</td>
<td>100 km/h</td>
<td>$I_d = 120.952381$</td>
</tr>
<tr>
<td>$\gamma_{dyn/QS} (CS)$</td>
<td>0.28</td>
<td>$V = 90 \text{km/h}$</td>
</tr>
<tr>
<td>$K_{dyn}$</td>
<td>8MN/m</td>
<td>Half sleeper or block</td>
</tr>
</tbody>
</table>

With $\Delta Q_{DYN} = \gamma_{dyn/QS} \cdot Q_N$

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>$Q_N$ (kN)</th>
<th>$\Delta Q_{curve}$ (kN)</th>
<th>$\Delta Q_{DYN}$ (kN)</th>
<th>$\Delta Q_{Stat}$ (kN)</th>
<th>$\Delta H_{curve}$ (kN)</th>
<th>$\Delta H_{DYN}$ (kN)</th>
<th>$H_{MAX}$ (kN)</th>
<th>$H_{Stat}$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>90.00</td>
<td>8.11</td>
<td>22.50</td>
<td>19.20</td>
<td>9.73</td>
<td>26.17</td>
<td>59.50</td>
<td>19.20</td>
</tr>
<tr>
<td>100</td>
<td>90.00</td>
<td>14.51</td>
<td>24.75</td>
<td>17.42</td>
<td>14.72</td>
<td>26.17</td>
<td>59.50</td>
<td>19.20</td>
</tr>
</tbody>
</table>
### Distribution factor

<table>
<thead>
<tr>
<th>Distribution factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_Q )</td>
</tr>
<tr>
<td>( \rho_Y )</td>
</tr>
</tbody>
</table>

### Load Case

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Effort</th>
<th>( Q_N )</th>
<th>( Q_{curve} )</th>
<th>( Q_{DYN} )</th>
<th>( Q_{stat} )</th>
<th>( \Delta H_{curve} )</th>
<th>( \Delta H_{dyn} )</th>
<th>( H_{MAX} )</th>
<th>( H_{stat} )</th>
<th>Wheel Loads</th>
<th>Fastening Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB1-1</td>
<td>K = 0</td>
<td>( Q_o )</td>
<td>1.00</td>
<td>1.00</td>
<td>2.00</td>
<td></td>
<td></td>
<td></td>
<td>143.11</td>
<td>39.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Q_i )</td>
<td>1.00</td>
<td>-1.00</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td>81.89</td>
<td>22.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Y_o )</td>
<td>0.24</td>
<td>-0.24</td>
<td>0.00</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
<td>55.29</td>
<td>27.65</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Y_i )</td>
<td>0.24</td>
<td>-0.24</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td>19.40</td>
<td>9.70</td>
<td></td>
</tr>
<tr>
<td>MB1-2</td>
<td>K = 1</td>
<td>( Q_o )</td>
<td>1.00</td>
<td>1.00</td>
<td>2.00</td>
<td></td>
<td></td>
<td></td>
<td>143.11</td>
<td>39.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Q_i )</td>
<td>1.00</td>
<td>-1.00</td>
<td>2.00</td>
<td></td>
<td></td>
<td></td>
<td>126.89</td>
<td>34.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Y_o )</td>
<td>0.24</td>
<td>-0.24</td>
<td>0.47</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
<td>65.95</td>
<td>32.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Y_i )</td>
<td>0.24</td>
<td>-0.24</td>
<td>0.47</td>
<td></td>
<td></td>
<td></td>
<td>30.05</td>
<td>15.03</td>
<td></td>
</tr>
<tr>
<td>MB2-1</td>
<td>K = 0</td>
<td>( Q_o )</td>
<td>1.00</td>
<td>1.00</td>
<td>2.00</td>
<td></td>
<td></td>
<td></td>
<td>154.01</td>
<td>42.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Q_i )</td>
<td>1.00</td>
<td>-1.00</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td>75.49</td>
<td>20.76</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Y_o )</td>
<td>0.24</td>
<td>-0.24</td>
<td>0.00</td>
<td>1.00</td>
<td></td>
<td></td>
<td>77.38</td>
<td>38.69</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Y_i )</td>
<td>0.24</td>
<td>-0.24</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td>17.88</td>
<td>8.94</td>
<td></td>
</tr>
<tr>
<td>MB2-2</td>
<td>K = 1</td>
<td>( Q_o )</td>
<td>1.00</td>
<td>1.00</td>
<td>2.00</td>
<td></td>
<td></td>
<td></td>
<td>154.01</td>
<td>42.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Q_i )</td>
<td>1.00</td>
<td>-1.00</td>
<td>2.00</td>
<td></td>
<td></td>
<td></td>
<td>124.99</td>
<td>34.37</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Y_o )</td>
<td>0.00</td>
<td>0.00</td>
<td>0.47</td>
<td>1.00</td>
<td></td>
<td></td>
<td>71.22</td>
<td>35.61</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Y_i )</td>
<td>0.00</td>
<td>0.00</td>
<td>0.47</td>
<td></td>
<td></td>
<td></td>
<td>11.72</td>
<td>5.86</td>
<td></td>
</tr>
<tr>
<td>MB3</td>
<td></td>
<td>( Q_o )</td>
<td>1.00</td>
<td>1.00</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
<td>70.80</td>
<td>19.47</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Q_i )</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td>109.20</td>
<td>30.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( Y_o )</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td></td>
<td></td>
<td>( Y_i )</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td>19.20</td>
<td>9.60</td>
<td></td>
</tr>
</tbody>
</table>
### 1.7.5.2. Booted sleepers characteristics

#### Bi-block

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twin-block system</td>
<td></td>
</tr>
<tr>
<td>Rail inter axis distance</td>
<td>G 1.5 m</td>
</tr>
<tr>
<td>Height of rail+pad</td>
<td>H_rail 0.19 m</td>
</tr>
<tr>
<td>Block height</td>
<td>H 0.215 m</td>
</tr>
<tr>
<td>Block length</td>
<td>B 0.66 m</td>
</tr>
<tr>
<td>Block width</td>
<td>w 0.23 m</td>
</tr>
<tr>
<td>Axle load eccentricity</td>
<td>eQ -0.055 m</td>
</tr>
<tr>
<td>Tie bar vertical eccentricity</td>
<td>evT 0.11 m</td>
</tr>
<tr>
<td>Tie bar Inertia</td>
<td>lx 5.94E+01 cm²</td>
</tr>
<tr>
<td>Steel modulus</td>
<td>E 210000 MPA</td>
</tr>
<tr>
<td>Tie bar section</td>
<td>S 8.96 cm²</td>
</tr>
<tr>
<td>Tie bar 60/60/8</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resilient pads</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the horizontal pad</td>
<td>l_hpad 0.66 m</td>
</tr>
<tr>
<td>Width of the horizontal pad</td>
<td>w_hpad 0.23 m</td>
</tr>
<tr>
<td>Vertical stiffness</td>
<td>Kv 8 MN/m</td>
</tr>
<tr>
<td>Block height Stiffening ratio</td>
<td>b 0.5</td>
</tr>
<tr>
<td>Height of the vertical pad</td>
<td>h_vpad 0.08 m</td>
</tr>
<tr>
<td>Side pads Stiffening ratio</td>
<td>a 0.66 m</td>
</tr>
<tr>
<td>Width of the vertical pad</td>
<td>w_vpad 0.23 m</td>
</tr>
<tr>
<td>Horizontal stiffness</td>
<td>Kh 20 MN/m</td>
</tr>
<tr>
<td>Tie bar I/v</td>
<td>I/v 6.04 cm³</td>
</tr>
</tbody>
</table>

#### Mono-block

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono-block system</td>
<td></td>
</tr>
<tr>
<td>Rail inter axis distance</td>
<td>G 1.5 m</td>
</tr>
<tr>
<td>Height of rail+pad</td>
<td>H_rail 0.19 m</td>
</tr>
<tr>
<td>Mono-block height</td>
<td>H 0.2 m</td>
</tr>
<tr>
<td>Mono-block length</td>
<td>B 2.3 m</td>
</tr>
<tr>
<td>Mono-block width</td>
<td>w 0.2 m</td>
</tr>
<tr>
<td>Axis rail distance</td>
<td>b 0.4 m</td>
</tr>
<tr>
<td>Concrete young modulus</td>
<td>E 40 000 MPA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resilient pads</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical stiffness (complete pad)</td>
<td>Kv 16 MN/m</td>
</tr>
<tr>
<td>Side pad length</td>
<td>a 2.30 m</td>
</tr>
<tr>
<td>Side pads Stiffening ratio (max =0.5)</td>
<td>b 0.5</td>
</tr>
<tr>
<td>Height of the vertical pad</td>
<td>h_vpad 0.08 m</td>
</tr>
<tr>
<td>Horizontal stiffness</td>
<td>Kh 20 MN/m</td>
</tr>
</tbody>
</table>
1.8. **ALTERNATIVES FOR FLOATING SLABS IN TUNNELS: DESIGN OF ECOLOGICAL TRACKS (WP1.2.3, PART C, DEVELOPED BY CDM)**

1.8.1. **Introduction**

In the past track infrastructure manufacturers have developed several direct rail fixations systems. These systems are not able to reach the performances of floating slab tracks in terms of noise and vibration. Therefore and in order to be able to reduce the tunnel diameter of new metro systems and to reduce the foundation depth of LRT/tram track infrastructure, a resilient fixation ‘Elastiplus’ has been developed as an alternative solution for floating slab track systems in metro tunnels and for LRT/tram tracks at grade. The validation sites have been Brussels, Belgium, see chapter 3.7, and Barcelona, Spain, see chapter 3.8.

1.8.2. **Elastiplus development**

1.8.2.1. **Floating slab working principles**

In order to come to an alternative to the floating slabs, we have to first understand the working principle of floating slab track. A floating slab track is vibration isolation system of 3rd level, based on the principle of a concrete slab supported on an elastic medium. This medium can be pads, strips or mats. The noise and vibration performance of such a system can be approximated by mass spring system, where the concrete slab, the rail fixation, the rail and the rolling stock represent the mass and the resilient mat acts as the spring. For such system, the resonance frequency is given by:

\[ f_{res} = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \text{ (Hz)} \]

with \( k \) = dynamic stiffness of resilient mat (N / mm)

\( m \) = mass

Since a floating slab is a 3rd level isolation system, the suspended mass \( m \) is very high. This results in a system with a low resonance frequency, mostly around 20Hz. From the insertion loss given in Figure 1.8.1, we can clearly see that a track infrastructure system with a resonance frequency of around 20Hz will have a high attenuation performance in the critical frequency range of 30 – 120 Hz.
1.8.2.2. Precompression technique

In order to develop an alternative system to a floating slab, a low resonance frequency is required. A low resonance frequency can be obtained by increasing the mass of the system or by using resilient material with a lower dynamic stiffness. A direct rail fixation is a 2nd level isolation system, which means that there is no possibility to act on the suspended mass (these are: base plate, rail and rolling stock). A low resonance frequency can only be achieved by decreasing the dynamic stiffness of the resilient material, and thus also decreasing the static stiffness (up to 5kN/mm), which will increase rail deflection enormously. On the other hand, rail deflection is limited to 4mm to ensure track stability and thus puts a limit on lowering the dynamic system of the resilient material for classical direct fixations. Whereas the classical direct rail fixations are limited by track stability, the Elastiplus fixation imposes a precompression of the resilient material in order to deal with this limitation.

The working principle of the Elastiplus fixation is given in Figure 1.8.2. The precompression imposed by the compression spring is such that the additional deflection at maximum load is less than 4mm. Furthermore, in order to use the low dynamical stiffness of the resilient mat and to prevent the transmission of structure borne noise from the base plate through the springs into the tunnel invert, it is very important that these compression springs release as quick as possible during wheel passage.
1.8.2.3. Realisation of the Elastiplus fixation

**MATHEMATICAL DESCRIPTION OF THE SYSTEM**

A mathematical description of the system can be given as follows:

- **Situation 1**: Precompression (in factory) of the fixation

\[ 2F_s = F_{precompression} \]
\[ 2K \cdot x_{s0} = Ke_{(sp)} \cdot x_e = Ke_{(sp)} \cdot x_p \]
\[ x_{s0} = \frac{Ke_{(sp)} \cdot x_p}{2K_s} \]

(Equation 1)
Situation 2: Loading of the fixation (train passage)

\[
2F_s + F_{\text{train}} \uparrow = F_{\text{precompression}} \uparrow
\]
\[
2K_s(x_{s0} - \Delta) + F_{\text{train}}^\Delta = Ke_{xp+\Delta} \cdot (x_p + \Delta)
\]
\[
F_{\text{train}}^\Delta = Ke_{xp+\Delta} \cdot (x_p + \Delta) - 2K_s(x_{s0} - \Delta)
\]
\[
= \left(Ke_{xp+\Delta} - Ke_{xp}\right) \cdot x_p + \left(Ke_{xp+\Delta} + 2K_s\right)\Delta
\]
\[
\approx \left(Ke_{xp} + 2K_s\right)\Delta
\]
(Equation 2)

This is true until \( \Delta = x_{s0} \Rightarrow F_s = K_s(x_{s0} - \Delta) = 0 \)

In this point:

\[
F_{\text{train}} = Ke_{xp+x(0)} \cdot (x_p + x_{s0})
\]
\[
= Ke_{xp} \exp{\left[\frac{Ks \cdot x_p}{2Ks}\right]} \cdot \left( x_p + \frac{Ke_{xp} \cdot x_p}{2Ks} \right)
\]
\[
= Ke_{xp} \exp{\left[\frac{Ks \cdot x_p}{2Ks}\right]} \cdot x_p \left( 1 + \frac{Ke_{xp}}{2Ks} \right)
\]
(Figure 3)

\[
F_{\text{train}} > F_{\text{precompression}} \approx F_{\text{precompression}}
\]

Situation 3: Loading of the fixation, pre-compression springs releases.

\[
F_{\text{train}} = Ke_{ \cdot 1} \cdot x_e
\]
(Equation 4)
GRAPHICAL DESCRIPTION OF THE SYSTEM

The Elastiplus performance can be easily understood through the diagram shown in Figure 1.8.3.

The thinner lines represent each of the elements before the precompression is reached; the thicker lines represent the separate elements in the system (elastomer in blue; springs in green and the full system in red).

The springs forces the elastomer to stay precompressed. When the train approaches the fixation the springs are losing contact with the elastomer. The elastomer is now bearing the full load of the train. After the passage the precompression springs limit the relaxation of the elastomer again.
INSERTION LOSS FOR ELASTIPLUS SYSTEM

A calculation of the insertion loss was made for an Elastiplus fixation with a static stiffness of 5kN/mm and compared with the insertion loss obtained by a floating slab track. From the results, depicted in figure 1, we can conclude that the Elastiplus fixation has similar N&V performances as a floating slab track. An alternative for floating slab track has been found.

Figure 1.8.4: Comparison of insertion loss for a floating slab track and Elastiplus fixation
FUNCTIONAL AND TECHNICAL REQUIREMENTS

In collaboration with TMB and Ineco-Tifsa the following technical and functional requirements have been defined:

<table>
<thead>
<tr>
<th>Track parameters metro Barcelona</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rail type</strong></td>
</tr>
<tr>
<td><strong>Gauge</strong></td>
</tr>
<tr>
<td><strong>Rail inclination</strong></td>
</tr>
<tr>
<td><strong>Axle load</strong></td>
</tr>
<tr>
<td><strong>Assembly tolerances</strong></td>
</tr>
<tr>
<td><strong>Electrical resistance</strong></td>
</tr>
<tr>
<td><strong>Minimal curve radius</strong></td>
</tr>
<tr>
<td><strong>Maximum canting</strong></td>
</tr>
<tr>
<td><strong>Canting variation</strong></td>
</tr>
<tr>
<td><strong>Gauge widening in curves</strong></td>
</tr>
<tr>
<td><strong>Variation of gauge widening in curves</strong></td>
</tr>
<tr>
<td><strong>Maximum slope</strong></td>
</tr>
<tr>
<td><strong>Maximum deflexion</strong></td>
</tr>
<tr>
<td><strong>Distance between sleepers</strong></td>
</tr>
<tr>
<td><strong>Clip type</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Assembly tolerances slab track</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gauge</strong></td>
</tr>
<tr>
<td><strong>Gauge tolerance between adjacent sleepers</strong></td>
</tr>
<tr>
<td><strong>Transversal leveling</strong></td>
</tr>
<tr>
<td><strong>Longitudinal leveling</strong></td>
</tr>
<tr>
<td><strong>Straightness of the track</strong></td>
</tr>
<tr>
<td><strong>Curvature (R&lt;500)</strong></td>
</tr>
<tr>
<td><strong>Canting</strong></td>
</tr>
<tr>
<td><strong>Slope variation towards canting</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gauge widening – Deyl Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Curve radius</strong></td>
</tr>
<tr>
<td>250 &lt; R ≤ 500 m and straight</td>
</tr>
<tr>
<td>150 &lt; R ≤ 250 m</td>
</tr>
<tr>
<td>R ≤ 150 m</td>
</tr>
</tbody>
</table>
Technical requirements:

⇒ Chemical anchorage required.
⇒ Necessary to calculate accurately the precompression before installation and easy tuning of the precompression during operation.

Minimum length of test track: 180 lmst since the length of the train is about 85 meters.

COMPONENTS OF THE SYSTEM
The Elastiplus fixation consists of the following parts.

Mounting plate
The mounting plate is made of metal and has two M24 bolts welded to it for fixation of the UBP and the base plate of the fixation.
We have opted for a mounting plate instead of fixing the UBP and base plate directly onto the slab because of two main reasons:
– Lateral forces will mainly be absorbed by the UBP and the M24 bolts welded on the mounting plate and not by the anchoring bolts.
– The fixation can be pre-mounted, with the correct pre-compression in the factory, in order to facilitate the installation.

For small adjustments of the track gauge a lateral adjustment system has been integrated. Two metal pieces with teeth are integrated in the mounting plate. This device allows a lateral adjustment of -16 mm to +18 mm with 2mm steps.

For vertical adjustment of the fixation 10mm HDPE or EVA sheets can be put under the mounting plate of the fixation.

Resilient under base plate pad
The UBP is made of special resilient material with a static stiffness of 5kN/mm and it has just 2 holes for the bolts. The UBP is put directly on the mounting plate and underneath the base plate. The other elements of the system are described hereafter.

1. Base plate

A cross-section of the metal base plate is given in Figure 1.8.5:
2. Rail clips

The used rail clips are of the SKL-3 type.

3. Spring system

The spring systems consist of:

*Ertalon washers:*
These washers are used to position the springs and the base plate on the mounting plate. Furthermore, the washers are made of a material electrically isolating the base plate, and thus the rail, from the mounting plate.

*System stabilizing springs:*
The smaller springs of 50N/mm are used to generate a minimal preload to maintain system stability. Washers are pushed against the M24 locking nuts and the base plate to ensure that they remain in place during wheel passage.

*Compression springs:*
These springs will generate the necessary pre-load to limit the rail deflection to 4mm. The stiffness of the compression springs play therefore an important role and need to satisfy to the following requirements:

- Springs are able to provide the required preload
- Springs have to release during wheel passage, this for 2 reasons:
  - Prevents the transmission of structure borne noise from the base plate through the springs into the tunnel invert.
  - Eliminates completely the pre-load of the compression springs. There will be no added stiffness of the springs, only the stiffness of the UBP determines the global stiffness.

Since deflection felt by the rail must be lower than 4mm, the compression of the spring must be less than 4mm to release during wheel passage.

We therefore need a fast releasing of the spring and a spring that generates high preload with small compression. This means the spring needs to have a high stiffness.

Since the dimensions of the springs are limited by the base plate dimensions, normal helicoidal springs can not be used. Furthermore they are quiet expensive. A solution to this problem is to use washers made of elastic material. The system stabilizing springs can still be used by adapting the ertalon washers as showed in Figure 1.8.6.

![Figure 1.8.6: Spring system using helicoidal springs and spring system using new washers.](image)
4. Railpad

The railpad placed under the rail foot is made of resilient material and has a thickness of 5 mm.

Elastiplus anchoring

The screws for the Elastiplus to be fixed to the soil have been selected from the large product range an expert manufacturer for railway screws offered. The screws can be installed in both top-down and bottom-up procedures, making use of chemical resins. In order to ensure an electrical isolation between the soil and the device, a collar brush of plastic material is provided.

Prototype

Different prototypes have been developed. In figures 1.6.7 and 1.6.8 some assembled prototypes of the Elastiplus fixation are shown.

![Initial Elastiplus prototype](image1)

**Figure 1.8.7: Initial Elastiplus prototype**

![Final assembled Elastiplus prototype](image2)

**Figure 1.8.8: Final assembled Elastiplus prototype**

The last prototype for Elastiplus device is shown in Figure 1.8.8. The new prototype is 50mm shorter than its predecessor and it also includes the lateral and vertical adjustments.
1.8.2.4. Testing

COMPRESSION-WASHERS

The new washers were tested in order to see if they could be used as an alternative for the helicoidal springs. Following tests were performed:

*Static test to determine the necessary deflection to pre-load the fixation*

![Graph showing static loading test on new compression-washers](image)

<table>
<thead>
<tr>
<th>Test</th>
<th>Load 10%</th>
<th>Load 20%</th>
<th>Load 30%</th>
<th>Load 40%</th>
<th>Load 50%</th>
<th>Load 60%</th>
<th>Load 70%</th>
<th>Load 80%</th>
<th>Load 90%</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14251.0</td>
<td>14771.4</td>
<td>15510.1</td>
<td>17583.6</td>
<td>19557.3</td>
<td>21068.1</td>
<td>24537.0</td>
<td>28328.3</td>
<td>29364.7</td>
<td>10.13</td>
</tr>
</tbody>
</table>

Looking at the static loading we can conclude that the washers have a static stiffness of about 18kN/mm

- Tests showed just 1% change in static stiffness after fatigue.
- Creep test in order to see if there is no loss of pre-load in time.
Figure 1.8.10: Creep test on compression-washers

From these tests we can conclude that the washer springs can be used as an alternative for the helicoidal springs.
ELASTIPLUS PROTOTYPE

The last Elastiplus prototype was tested with different kinds of UBP for overall static and dynamic stiffness and fatigue. The static and dynamic loading tests were performed on the prototype with a preload of 18kN, using a resilient mat of 50mm of thickness. Results are depicted in Figure 1.8.11 and Figure 1.8.12.

As we can see, the Elastiplus fixation had a static stiffness of approximately 5kN/mm in the load range of 20–30 kN. Furthermore we can observe that the stiffness decreases at a load little bit higher than the preload, because of loosening of the washers. This was also predicted by the mathematical description of the system (cf. Equation 3).

As we can see, the Elastiplus fixation had a dynamic stiffness of approximately 8,6kN/mm in the load range of 20–30 kN.

After fatigue tests static and dynamic stiffness varies within acceptable limits.
1.8.3. **Conclusions**

An alternative for floating slab track has been developed for which calculations and laboratory tests showed that by preloading a rail fixation, a low dynamical stiffness can be obtained allowing the same noise and vibration performance as a floating slab track, while keeping rail deflection limited to 4mm.

The following step has been to check the performance of the new design on the Brussels and Barcelona validation sites (see chapters 3.7 and 3.8).
1.9. **DESIGN OF MODULAR LOW COST NEW INTEGRATED TRACK SYSTEM (WP1.3.1, DEVELOPED BY CDM AND VBK)**

1.9.1. **Introduction**

The Sub-project was targeting the needs of Karlsruhe, which has also been the validation site of the outcomes of chapter 1.9 (see chapter 3.9).

1.9.2. **General context**

Karlsruhe has a 70km tram and light-rail network carrying 108 million passengers per year. The section located in Kaiserstrasse is the most critical section:

- Located within the pedestrian area of Karlsruhe
- Five tram lines and 3 light rail lines are running on this track in a ten minute frequency from 06:00 o’clock in the morning until 08:00 o’clock in the evening.
- During the off peak time there is still a 20 minutes frequency.
- As there are no alternative tracks, the maintenance is a very sensitive operation (problems in the past).

Furthermore, City of Karlsruhe is planning a light rail tunnel under this pedestrian district (best case scenario is assuming an inauguration not before 2015).

On one hand there is an urgent need to renew the tracks in the pedestrian area; on the other hand the same tracks will disappear when the light rail tunnel will start operating in 2015.

VBK would like to solve this problem by using removable prefabricated tracks. In general the Re-Modulix system aims to give an answer to the following major practical concerns:

- fast temporary track installation with possibility to reuse system components in other locations within the network.
- easy renovation of entire multimodal track elements (track and road surface).
1.9.2.1. **The Re-Modulix concept**

Based on a modular prefabricated track-system and a catalogue of requirements from VBK the design for a Re-Modulix system was developed.

The Re-Modulix system will be an embedded track system (ERS) delivered as a prefabricated concrete slab with final road covering (pavement) included. It allows the tracks to be installed in strategic critical points of a network in very short time period (e.g. crossings, access to strategic sites, by hospitals,). The slab includes all possible elements such as drainage elements, electrical boxes, etc.

![Figure 1.9.1: Examples of classical prefabricated track module installation with final road covering included.](image-url)
1.9.2.2. Design of Re-Modulix

The Re-Modulix concept is based on a prefabricated modular track system (Modulix) with adapted foundation layers. The removability is ensured by adding two PE-films:

- one between the prefabricated module itself and the lean concrete to prevent any cohesion between the slab and the foundation
- one under the lean concrete layer to allow the removal of the supporting beams and fixation concrete layer when the module has been removed

Figure 1.9.2: Cross-section of the Re-Modulix concept
1.9.2.3. Re-Modulix installation sequences

The system consists of modules with a length of 16.5m and intermediary pieces to place between 2 modules. In the Modulix system those modules have the same width and both tracks are installed at the same time. However in Karlsruhe a change was needed.

KaiserStrasse has a width of 5.870m. The sidewalk can not be used for the installation because of many obstructions like benches, lampposts, garbage-cans. Transport trucks must be able to drive to the unloading-point and a truck needs 2.5m width to drive on.

Therefore the installation will be done in 2 phases. In the first phase the track of side 1 is demolished (1.7.3). The old track at the other side is used to drive on. After the installation of the modules of side 1, side 2 is demolished during the second phase. The new track at side 1 is used to drive on. The modules of the first phase will be wider then the modules of the second phase (Figure). This allows trucks to drive on the wider modules during installation.

![Figure 1.9.3: Cross-section of the KaiserStrasse phase 1: one side of the old track is used to drive on; the other side is demolished and installed](image)

![Figure 1.9.4: Cross-section of the KaiserStrasse with installed modules of 2 widths](image)

The installation of phase 1 (see figures 1.9.5 and 1.9.6 below) begins by demolishing the old track and preparing the platform surface, i.e. a clean lean concrete layer with a PE-film covering it. The supporting beams (provided with the modules) are then placed on the lean concrete layer to support the different modules. The position of those beams is determined by the land surveyor (based on drawings).

The pieces of the welding zone are placed between the beams. After this the modules are installed on the beams. The rails are welded and the welding zones are completed. Subsequently the pieces of the welding zone are lifted and positioned using steel supporting beams. The concrete of the first phase is poured. The steel supporting beams are removed once the concrete curing is completed.

In phase 2 all these steps are repeated at the other side of the street. Finally the concrete of phase 2 is poured and the intermediary pieces between the modules are placed in the fresh concrete using steel support beams.
1. Excavation old track, placing beams on concrete.

2. Placing pieces welding zone between beams.

3. Placing modules on beams and welding rail.

4. Lifting pieces welding zone.

Figure 1.9.5: Re-Modulix concept – Installation sequence
5. Pouring concrete first phase.

7. Excavation old track, placing beams on concrete, placing pieces welding zone and modules, lifting pieces welding zone.


Figure 1.9.6: Re-Modulix concept – Installation sequence
1.9.2.4. **Removal and/or replacement of the modules**

To remove the modules, the jackets (elastic encapsulation) and rail are cut in the intermediary zone i.e. original welding area (phase 2). The intermediary modules between the two tracks as well as the main modules are then removed using the available anchors in the slabs. These anchors have to withstand the weight of the modules and the force needed to pull the modules out. To estimate this force tests are performed (see 3.2.)

![Phase 1: Finished platform](image1)

![Phase 2: Cutting in the intermediary modules (welding zone)](image2)

![Phase 3: Removal of the modules](image3)

Figure 1.9.7: Re-Modulix concept: removal and replacement of modules

This phase is followed by the removal of the intermediary slabs of the welding zone (phase 4) and the cleaning of the fixation concrete surface poured around the supporting beams (phase 5).

Again this removal should be done in 2 phases because of limited space (first one side, then other side).
Phase 4
Removal of modulix for welding zone

Phase 5
Excavating L2

Figure 1.9.8: Re-Modulix concept: removal and re-use of modules
1.9.3. Testing

1.9.3.1. Integration into the STUVA test circuit

The Re-Modulix system is based on an embedded rail system where the rail is completely put in an elastic encapsulation (rubber-jacket) and embedded in a concrete slab, ensuring fastening in all directions and completely decoupling the rail from the environment (electrical and vibration protection).

The slab and the jacket are designed to take over specified rolling stock axle loads. They also need to resist to road traffic (e.g. heavy truck loads, traffic at grade crossing). The behaviour of the Re-Modulix system and its elastic encapsulation is tested on the STUVA test circuit (using test samples of slab with rail and elastic encapsulation).

This test circuit allows testing tyres, shock absorbers, road surfaces, expansion joints and roadway markings under extreme conditions (temperature range + 60 °C to – 30 °C, axle load 10 t, maximum speed 100 km/h) in order to be able to simulate high traffic loads in a short time.

Two test slabs are fabricated. The same road finishing is applied as will be installed in Karlsruhe: basalt stones. The rail orientation is different for both of them. The dimensions were fixed during meetings at Stuva in Cologne.

The test was carried out the beginning of 2008. After this test it can be stated that the test slabs with basalt stones show excellent results.

Figure 1.9.9: Fabricated test slabs.
Figure 1.9.10: STUVA test circuit composition. List of partners and position of test slabs on the circuit.

Figure 1.9.11: Two different STUVA test slabs proposed: rail in the direction of the rolling surface and two rails perpendicular to the rolling surface.

Figure 1.9.12: Test bodies with Karlsruhe basalt stones on test circuit STUVA during test.
1.9.3.2. Small Removability Test

Because the modules are surrounded by concrete during installation, the modules have to be separated from the concrete to prevent that the concrete attaches to the modules. 2 possible solutions are contemplated: rubber and PE-film (plastic foil). To make sure that the PE-film doesn't melt by the hardening warmth of the concrete and to determine the force necessary to pull out the modules, a test is carried out.

The test involves the production of a small concrete block (representing the prefabricated module). This small block is surrounded with a separating material. Concrete is poured around it, simulating the concrete poured in reality. After the hardening the small block is pulled out the surrounding block and the force needed to do so, is measured.

It can be assumed that decompression complicates the pulling out. Therefore in some blocks a tube is inserted to make contact with the air and eliminate decompression.

![Diagram of test block small removability test](Figure 1.9.13: Plan test block small removability test)

3 test blocks are produced (See figure 1.9.14):

1. test block with plastic foil
2. test block with plastic foil and tube against decompression
3. test block with rubber, vaseline and tube against decompression

![Production 3 test blocks](Figure 1.9.14: Production 3 test blocks)
The force needed to push out the small cube of test blocks 2 and 3 was measured in the CDM laboratory.

5kN was needed to pull out the small block of the test block with plastic foil and tube against decompression.

The blocks came out undamaged. The test block with plastic foil gave the best results. These tests show that the force needed to remove the modules can’t be neglected and the anchors of the modules should be calculated accordingly. However small scale parameters may have influenced these test results. Therefore a big scale test with plastic foil is planned to compare and to simulate real scale.
The force needed to pull out the small cube of test block 1 (without tube, no possibility to push) was to be measured at UCL “Université Catholique de Louvain”, one of the Urban Track partners. With good results, an execution without decompression tube is preferable, because of the difficulty to implement this on site.

1.9.3.3. **Surface finishing**

The surface finishing is very important in a street like Kaiserstrasse. Therefore VBK requested to make a test piece (1m²) with basalt stones provided from them. This way the prefabrication could be tested and a first impression of the joints-stones and total finishing was possible.

![Prefabricated test piece with basalt stones](image.png)
1.9.4. **Conclusion**

A prefabricated modular and removable embedded track system is developed for the needs of Karlsruhe city. Therefore different tests were performed.

Due to problems encountered during a previous installation in Karlsruhe and the limited installation possibilities of the narrow street, the executive board of VBK decided, based on an internal risk analysis, to change the location of the test track. The installation took place a year later than originally planned. This decision caused postponement in the further design (see chapter 3.8).

The prefabricated modules with integrated surface finishing allow limiting the installation time and nuisance to surrounding inhabitants. Also nuisance caused by maintenance is reduced by the reduction of surface finishing repairs.

Reusable track systems comply with the current tendency towards recycling and care for the environment. This environmental friendly concept goes hand in hand with a reduction of installation costs when reusing the track system. This makes it an interesting concept for track owners that plan to change their network in the near future.
1.10. **AUTOMATIC INSERTION OF RAIL FASTENERS FOR METRO (WP1.3.2, DEVELOPED BY ALSTOM)**

This topic which was covered by Deliverable D1.11 and has been validated in Reims (WP3.13) as reported in chapter 3.13.

The automatic installation method is based on mechanising the pouring of the track slab and inserting the rail supports. This is made possible by combining a slipform paving machine and an automatic installation method for direct fixed rail supports based on APPITRACK method developed by ALSTOM for the construction of tramway tracks.

The installation of this direct fixed track consists in inserting, to their final position, the rail supports in the fresh concrete obtained by slip form paving. The use of total stations to guide the machines and the automatic insertion ensures accuracy in installing rails within the required tolerances.

The concrete slab is built and the rail supports are inserted automatically with no special topographical arrangement in the foundation slab. Automation of both tasks is governed exclusively by total stations placed along the route with reference to the theoretical layout and actual site measurements (vehicle and reference polygonal).

1.10.1. **Architecture Of The Civil Structure**

1.10.1.1. **Compatibility with civil structure cross-section**

Different cross-sections of civil structure can be met on metro lines. Hence the gauge of slipform paver and automatic insertion machine have to be checked so that there is no infringement between installation equipements and civil structure.

The different civil structure sections that are usually found are detailed below. The design of the slipform paver and the automatic insertion machine are based on these sections.

![Figure 1.10.1: Twin Bored Tunnel](image-url)
Figure 1.10.2: Twin Cut & Cover Tunnel

Figure 1.10.3: Single Bored Tunnel
Figure 1.10.4: Single Cut&Cover

Platform definition
Distance from the platform nose to the axis of the compatible track with the gauges of both slipform and automatic insertion machine.

Figure 1.10.5: Insertion machine gauge
1.10.1.2. Tunnel access

One of the major issue in the development of an automatic installation method is to feed the slipform paver with a concrete which is very dry (slump about 2.5cm) and consequently not pumpable.

The access to the tunnel, whatever cross-section, is depending on:

- Intervals and dimensions for machine access
- Intervals and dimensions for pouring concretes

The result of this tunnel access study shows that it is possible to use an automatic installation method inside a tunnel.
1.10.2. Track Design

1.10.2.1. Fastening system compatible with automatic installation

Typically the automatic installation method requires a standard fastening system however some verification must be done beforehand.

For example the fastening system must be designed to be hold by magnetic means. It must be able to transmit appropriate vibrations in order to be correctly inserted in fresh concrete.

1.10.2.2. Compatible fastening system with single elastic layer

This type of fastening system is installed in locations where no specific vibration mitigation provisions are required.

![Figure 1.10.7](image)

1.10.2.3. Compatible fastening system with double elastic layer (to be developed)

This type of fastening system is installed in locations where some specific vibration mitigation provisions are required.

![Figure 1.10.8](image)

As it is designed to attenuate the transmission of vibrations from the top of rail to the anchors, this is in contradiction with the effect aimed at during the construction phase.
Consequently specific provisions, implemented during the construction, must be taken in order to keep the vibration mitigation performance of the fastening system and to ensure it is compatible with the automatic installation.

The detailed development of such a fastening system is to be done.
1.10.2.4. Floating Slab

In locations where a high vibration mitigation is required, the installation of a floating track slab is necessary.

The design of this track system will be compatible with the automatic installation method. Especially the width and height of the track slab will take into account the gauge of the automatic insertion machine.

Figure 1.10.10
1.10.3. **Track Dimensioning**

Track design will take within geometrical constraints due to capabilities of insertion machine and mechanical loads due to metro operation.

![Diagram](image)

Figure 1.10.11

1.10.3.1. **Track reinforcement**

Reinforcement of the track slab, when required, is designed to hold the track on the civil structure and / or to allow for the track slab to withstand the operational loads.

The implementation of re-bars and lattice is compatible with the use of a slipform paver. However the arrangements of reinforcing lattice and bars have to be compatible with the insertion of rail fasteners to avoid any interfere between anchors and reinforcement.

1.10.3.2. **Recess**

The provision for recess in track slab is required because of the interface between track and other sub-systems such as power supply or signalling.

Recess have to allow for the slipform paver to pass through and are less than 2 cm above the concrete slab. They will be in the track axis.
1.10.3.3. Embedded sleeves

The installation of sleeves in the track slab is subject to interface between track and other sub-systems such as power supply or signalling.

Embedded sleeves can be on stand-by on top of the track slab; they will be protected and identified correctly to make them easy to find.

Some embedded sleeves need to end up in an inspection hole in the thickness of the track slab. This will be dealt with in exactly the same way as the drainage recess, reinforced if necessary.
1.10.4. **Track Drainage**

1.10.4.1. **Drainage**

The trackform must include provision for drainage. Drainage gradients are created with the slipform paving machine. A gradients of 1% is built to allow for water flow.

![Figure 1.10.14](image)

1.10.4.2. **Longitudinal drainage**

Drainage gutters are made on both sides of the track using the slipform paver by positioning removable metal sections in the required design shape.

![Figure 1.10.15](image)
1.10.5. **Handover and Acceptance Of The Civil Structure**

The site is handed over with the foundation slab fitted with topographical reference points, where the x, y and z coordinates are known.

Placed at about 100 m intervals, they serve as topographical references for the installation of the track.

Acceptance and visual and topographic inspection of the slab are carried out before any track activity:

- An initial visual inspection to check that the site is clean, that pockets, drainage systems and so on are installed correctly. Any cracking more than 1 mm deep must be dealt with.

- A second inspection, consisting of a field survey (slab position and levelling) every 10 m of straight track and every 4 m of curve.

- A third inspection to identify and check the electric sleeves leaving the platform, irregularities which may hamper the track concrete-laying machines such as cable pits, catenary foundations, drain inspection holes, etc.

The continuation of the work depends on acceptance of the compliant platform.

The control points must be included in the required tolerances:

For the record: Altimetry of the improved subgrade roof: 0/-3 cm (earthworks), checked prior to installing the foundation slab by the unit in charge.

For the record: Horizontality of the improved subgrade under a rule of 5 m: 0/- 1 cm

Altimetry of the foundation slab concrete: 0/- 2 cm

Lateral tolerance in the foundation slab plane: ± 5 cm

1.10.6. **Progress Of The Slipform Machine**

The plasticity of the concrete is a major consideration in the correct positioning of the concrete by the slipform paver (optimum slump 2 to 2.5 cm with Abram's cone).

The slipform paver moves forward at its optimum speed of 4 to 7 m/mn. The average volume of concrete per ml of slab is 0.5m3 which gives a minimum consumption of 2 m3 per minute.

Hence progress per 6 m3-lorry delivery of 12 ml in 6mn of one track slab.

The optimum turnaround of lorries or truck mixers is therefore 15mn minimum.

1.10.7. **Progress Of Insertion Machine**

The automatic insertion machine must insert the baseplates within 10 to 30 mn after the concrete is poured.

The automatic insertion machine has an insertion and progress cycle time of 1.10 min for a fastener spacing of 0.75 m, i.e. a cycle of 1.50mn/ml of track slab (0.70 ml/mn).
The progress of the slipform paver ahead of the automatic insertion machine is therefore a maximum of 20 ml of track slab (30 mn/1.5mn/ml = 20 ml).

The automatic insertion machine therefore sets the rate of progress for the slipform paver of 120 ml of track per 3-hour station of actual work except for an irregularity and special case.

Figure 1.10.16

1.10.8. Sequence Of Operations And Logistics

Implementing the automatic installation method involves the following sequence of operations and related means and supply chain:

<table>
<thead>
<tr>
<th>Operation</th>
<th>Plants and tools</th>
<th>Supply chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installing recess reservation</td>
<td>Classic manual equipment</td>
<td>Re-bars, Concrete forms</td>
</tr>
<tr>
<td>Slab track concreting</td>
<td>Slipform paver</td>
<td>Supply method of concrete</td>
</tr>
<tr>
<td>Automatic insertion of baseplates</td>
<td>Automatic insertion machine</td>
<td>Preparing and conditioning baseplates</td>
</tr>
<tr>
<td></td>
<td>Guiding of slipform paver</td>
<td>Handling and supplying baseplates</td>
</tr>
<tr>
<td>Post-concreting process (curing, etc.)</td>
<td>Curing compound Curing mats</td>
<td></td>
</tr>
<tr>
<td>Controlling baseplates insertion</td>
<td>Topographic tools</td>
<td></td>
</tr>
<tr>
<td>Start and end of shift</td>
<td>Classic manual equipment</td>
<td>Re-bars, Concrete forms</td>
</tr>
<tr>
<td>Installing rails</td>
<td>Handling tools</td>
<td>Handling and supplying rails</td>
</tr>
</tbody>
</table>
1.10.9. Conclusions

All design and construction aspects have been identified and addressed. Interfaces with the civil structure and other sub-systems have been taken into account.

Two major issues were identified i.e. the supply of concrete inside a tunnel and the fastening system with double elastic layer.

- The first issue can be overcome with an appropriate logistics.
- The second issue needs further investigations.

The automatic installation method implemented on tramway tracks can be transferred to the construction of metro tracks.

Such a method provides a gain in installation time and reduces the number of operation required to build a new track.