Transition zones between ballasted and ballastless tracks

A knowledge review

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Abstract

In today's railway facilities there are several types of track systems with different characteristics, which must interconnect in order to obtain a closed network. The area where a track system passes over into another track system is called a transition zone. The track systems' different characteristics chiefly consist of differences in settlement tendency and track stiffness. The transition zone is described as the weakest link in the railway track by Nyquist (2010). The thesis is a review of the knowledge concerning the construction of transition zones, as well as what impact the construction generates in regard to its design and maintenance.

The knowledge review of the transition zones include studies based on interviews, documents, previously conducted measurements, as well as site visits to the reference projects: Citytunneln in Malmö, Nya Årstabron in Stockholm, the Metro in Copenhagen and Drogdentunneln in Öresundsförbindelsen. A purpose-built transition construction from Austria, V-TRAS, has been studied based on an interview and document in the form of a concept description. Also a theoretical review and interview has been performed with a Doctor of Technology, who has conducted research of transition zones.

The result shows that Citytunneln has relatively well-designed transition zones, working as designed. There are settlement tendencies in the transition zones, as a consequence improvements have been proposed for preventing further deterioration of the existing condition. With today's design, the transition zones on Nya Årstabron show greater settlements and maintenance need, in comparison to the other reference projects. Regarding the transition zones in the Metro, two of the ten transition zones lack a construction for stiffness equalisation. The transition zones without the construction demonstrates significantly greater maintenance need in comparison to the other transition zones, which work well. Among all transition zones in the reference projects, the transition constructions in Drogdentunneln differentiate as the better, after a reconstruction was made. As of today, they are well adapted to the surrounding conditions, exemplified by the low maintenance need. The V-TRAS module is applied in both new and existing tracks, and can be adapted to existing conditions as well. It seems to work well, but it should be noted that the period of use is only two years. Finally, theoretical experiences of transition zones are presented. The gradual or abrupt designs of the change in track stiffness in the included reference projects are not to be recommended. Instead it is recommended to use the error function, with an S-shape to obtain a smooth transition in track stiffness.

In summary there are generally large differences between transition zones, in particular between transition zones with, respectively without an adapted design. It is found that a construction of the stiffness transition is important, especially as a preventive measure against settlements.

Keywords: ballasted tracks, ballastless tracks, maintenance, settlements, track stiffness, transition constructions and transition zones.

Sammanfattning

I dagens järnvägsanläggningar finns flera typer av spårsystem med olika egenskaper, vilka måste sammanlänka för att erhålla ett slutet järnvägsnät. Platsen där ett spårsystem övergår i ett annat kallas övergångszon och spårsystemens olika egenskaper består huvudsakligen av skillnader i sättningsbenägenhet och spårstyvhet. Övergångszonen har beskrivits som den svagaste länken i järnvägsanläggningen av (Nyquist, 2010). Examensarbetet är en kunskapssammanställning beträffande övergångszonernas konstruktion samt vilka effekter konstruktionen ger upphov till i förhållande till dess design och underhållsbehov.

Kunskapssammanställningen av övergångszonerna omfattar undersökningar med utgångspunkt från intervjuer, handlingar, tidigare utförda mätningar och platsbesök av referensprojekten: Citytunneln i Malmö, Nya Årstabron i Stockholm, Metron i Köpenhamn och Drogdentunneln i Öresundsförbindelsen. En specialbyggd övergångskonstruktion från Österrike, V-TRAS, har undersökts utifrån intervju och material i form av konceptbeskrivning. Även en teoretisk genomgång och intervju med en teknisk doktor som forskat i området övergångszoner har utförts.

Resultatet redovisar att Citytunneln har förhållandevis välkonstruerade övergångszoner som fungerar enligt design. I övergångszonerna finns tendenser till sättningar, varför förbättringsåtgärder har föreslagits för att befintligt skick inte ska försämras. Övergångszonerna på Nya Årstabron visar större sättningar och underhållsbehov jämfört med övriga referensprojekt, med dagens konstruktion. Gällande Metrons övergångszoner saknas styvhetsutjämnande konstruktion i två övergångszoner av de tio som finns i anläggningen. Övergångszonerna utan konstruktion visar på märkbart större underhållsbehov i jämförelse med övriga övergångszoner, vilka fungerar bra. Bland alla övergångszoner som undersökts mellan referensprojekten utmärker sig Drogdentunnelns konstruktioner som de bättre efter dess ombyggnad, vilka idag är välanpassade till anläggningen med lågt underhållsbehov i förhållande till övrigt spår. V-TRAS-modulen tillämpas i såväl nya som gamla anläggningar och kan anpassas till rådande förutsättningar. Den verkar fungera bra, men det bör uppmärksammas att användningsperioden hittills endast är på två år i trafik. Avslutningsvis redovisas teorin om övergångszoner, där konstruktionerna i anläggningarna som undersökts ej är att rekommendera, med hänsyn till dess stegvis eller abrupta utformning på styvhetsförändringen. I stället rekommenderas felfunktionen med formen likt ett ”S”, för att erhålla en jämn övergång i spårstyvhet.

Sammanfattningsvis finns det i allmänhet stora skillnader mellan olika övergångszoner och i synnerhet mellan en övergångszon som har, respektive saknar en anpassad konstruktion. Det konstateras att en konstruktion i övergångszonen är viktig, speciellt i förebyggande syfte mot sättningar.

Nyckelord: ballastfria spår, ballastspår, spårstyvhet, sättningar, underhåll, övergångskonstruktioner och övergångszoner.

Preface

This thesis is the final stage of the education in Civil Engineering specialising in Railway Construction at LTH School of Engineering at Campus Helsingborg.

The thesis has been written at the office of Sweco Rail AB in Malmö, Sweden. We thank Magnus Nilsson, Group Manager, for the opportunity to write the thesis at their office. We also would like to thank Michael Huy Than, Technical Manager Rail, for his efforts to put us in the right direction in his role as supervisor.

We would also like to thank Anders Wretstrand at the Department of Technology and Society, for his role as examiner.

We want to thank Frank Mika, Håkan Tirus, Mikael Lundgren and Thor Thorshaug for being available for interviews, providing material, as well as site visits.

Finally, we also thank Alexander Smekal, Lars-Erik Jelcander, Rick Scherstein, Björn Södergren, David Nyquist, Johan Jonsson, Stefan Knittel and Fredrik Jansson. They have contributed to the report through their contact network, interviews, and documents.

Malmö May 2014

Henrik Lund & Andreas Åswärdh

Contents

1 Introduction

1.1 Background

The superstructure of the railway track can be constructed in numerous different ways. The most commonly used solution is ballasted tracks. In addition to ballasted tracks there are also ballastless tracks, which were developed first in the 1970s in countries such as Germany and Japan. The reasons behind the development of ballastless tracks were primarily the demand for a track with less maintenance, as well as lower costs for maintenance (Esveld, 2001).

The actuality of transition zones is linked to a number of projects, for example the plans for constructing the first part of high-speed tracks in Sweden, Götalandsbanan. The pilot project is Ostlänken, Järna-Linköping, included in the national plan for the transport system 2014-2025 (Regeringen, 2014). It has recently been decided by Trafikverket that high-speed lines will consist of ballastless tracks, according to Forslund (2014). In Sweden the use of such systems is rare; Citytunneln and Nya Årstabron are two sites currently using ballastless tracks.

Concerning the maintenance in railway tracks, the transition zone is an area with greater need for maintenance. Nyquist (2010) points out the transition zone between ballasted and ballastless tracks as the weakest link in the track and recommended further studies in this particular area.

1.2 Aim of the thesis

The aim of the thesis is to analyse transition zones in ballasted tracks and ballastless tracks from a structure point of view, as well as study the differences in need for maintenance and what maintenance measures are taken.

1.2.1 Issues

- What is the purpose of a transition zone?
- Is there a standardised construction of the transition between ballasted and ballastless tracks?
- What types of designs and constructions are there?
- How is the maintenance of the transition zones performed?
- Does the need for maintenance differ between different transition zones?
- Does the need for maintenance differ depending on the traffic?
- What are the issues experienced in transition zones?

1.3 Delimitation

The thesis will only deal with structure points of view, maintenance and follow-up of the maintenance work of transition zones. Aspects and issues regarding economics will not be examined.

1.4 Definitions

Auxiliary rails:	Auxiliary rails can also be mentioned as additional or extra rails, all with the same function. Used for load distribution in transition zones.
Ballast box:	The ballast box is a framework filled with ballast as in traditional tracks to enable track construction in special cases were track movements are necessary. In this case it is placed at Nya Årstabron to enable movements of the bridge.
Floating sleepers:	A consequence of settlements that occurs when the sleeper is lifted from its supporting bed in the ballast and there is a gap between the ballast layer and the sleeper when it is unloaded. This allows the rail to bend, and the sleeper to bump onto the ballast when the train passes.
Light rail:	System of railways used for medium-capacity transportation in metropolitan areas.
Transition construction:	A construction in the transition zone for equalising the differential settlement and track stiffness
Transition zone:	The area where a track system passes over into another track system.

2 Methodology

The gathering of information concerning transition zones and the reference projects was performed through interviews. The interviews were conducted face to face, via e-mail, as well as by telephone and the communication program Microsoft Lync. Besides interviews, information was collected by literature review.

2.1 Literature review

The initial phase consisted of literature review, in order to increase the knowledge of the structure in ballasted and ballastless tracks, as well as maintenance aspects of both systems. This was performed for understanding the need of transition zones.

2.2 Methods of interviews

Interviewing is used in a wide variety of contexts and can be performed in different ways. The most common interviews are those we listen to on radio and television. Most of us have sometime been the interviewee or the interviewer. We get called to interviews when we are searching for jobs, and interviewed when visiting the doctor's office. The list can be made very long for occasions when we are interviewed, as well as professionals performing interviews as an instrument for collecting information. Also, it is important that the interviews are formulated in such a manner they can be used as a collection method for data. It is further required that the data collection can be critically examined afterwards in order to answer the following questions: Did the interviewer ask the interviewee the required questions? Does the questions asked by the interviewer reflect what have been said during the interview and the interviewee's perception (Lantz, 2007)?

A well-conducted interview provides data satisfying certain requirements for usability. In scientific contexts it is often mentioned that:

- the method must provide reliable results (the requirement of reliability),
- the results must be valid (the requirement of validity) and,
- it shall be possible for other to critically examine the conclusions (ibid.).

There are various ways to form an interview; the forms are usually described in terms of differences in the structuring degree. An interview can be completely open, meaning that the interviewer asks an open question to the interviewee, who is free to explicate their thoughts. The opposite of the completely open interview is the fully structured interview, where pre-formulated questions are asked in a predetermined order and the interviewee answers the pre-defined responses (ibid.).

2.3 How the interviews have been performed

The interviews have been of open character. A number of pre-formulated questions were asked and the interviewee then had the opportunity to freely explicate their thoughts. We used this method to not only rely on the prepared questions and miss important information. We also wanted to minimize the risk of the person in question using other references, but would respond based on their own experiences.

2.4 Survey groups

Mikael Lundgren is head of railway maintenance at Øresundsbro Konsortiet, the corporation administrating the railway on Öresundsförbindelsen. He was interviewed at the offices of Øresundsbro Konsortiet, Copenhagen concerning the design, structure, and the maintenance of the transition zones in Drogdentunneln. Furthermore, he provided drawings of the construction of the transition zones. As a complement to the interview, a site visit to Drogdentunneln on Pepparholm was made for observing the transition zones.

Frank Mika, Civil Engineer, Technical Support for Construction and Design, and Håkan Tirus, Track Engineer, employees at Trafikverket, were interviewed at Trafikverket's offices in Solna, Stockholm regarding their knowledge of the transition zones on Nya Årstabron. They provided drawings of the bridge as well as the transition zones. As a complement to the interview, a site visit to Nya Årstabron in Stockholm was made for observe and discuss the transition zones.

Stefan Knittel is Managing Director at Rohmberg Rail, Austria. He was interviewed via e-mail concerning his knowledge of transition zones and provided material of a transition zone construction module, developed by Rohmberg Rail. Knittel was asked questions about the transition module.

Johan Jonsson, Doctor of Technology is currently employed by Trafikverket in Gothenburg and works with computational mechanics and has also been involved in research of transition zones. He was interviewed via Microsoft Lync concerning his theoretical knowledge of transition zones.

Thor Thorshaug is Track Manager at Metro Service and was interviewed in Ørestad, Denmark, concerning the maintenance of the Metro and regarding his knowledge in the construction of transition zones. Also we got a visit to the maintenance facilities in Metro Service for a better understanding of the maintenance on the trains and components in the track.

3 Theory

3.1 Description of ballasted tracks

The following descriptions clarify the properties of ballasted tracks, regarding the part and importance of ballasted track in the transition zones.

Ballasted track, also known as conventional track or classical track, is the track construction currently dominating in railway tracks. In general, ballasted track consists of a framework of rails and sleepers, which is supported on ballast. The ballast layer is in turn supported on a layer of sub-ballast, where the latter forms a transition layer to the formation/subgrade. The rails are held in place on the sleepers through a fastening system. Figure 1 below illustrates the cross section of an embankment (Esveld, 2001).

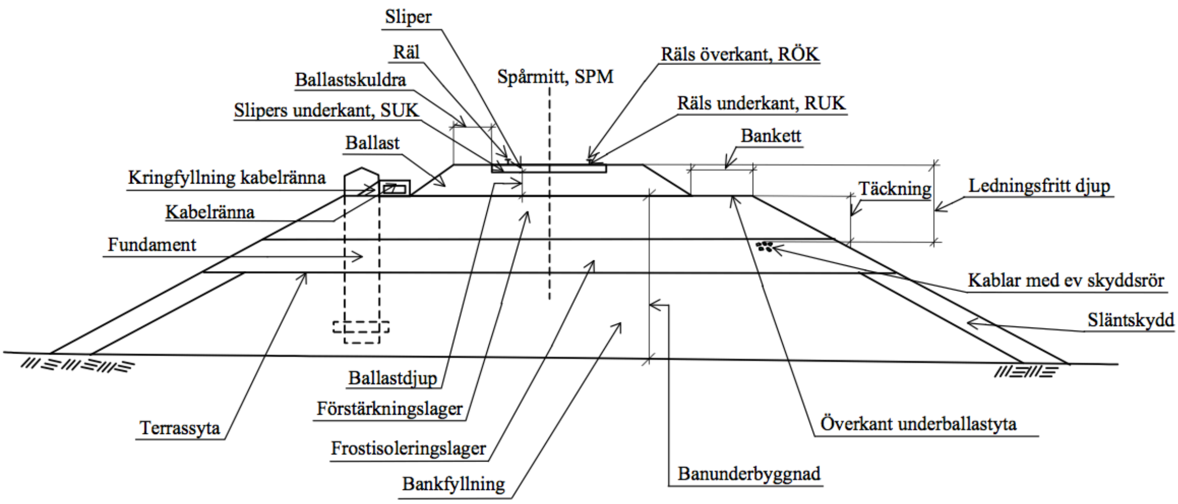

Figure 1. *Railway embankment, cross section of the principle of ballasted track structure* (Banverket, 2012)

Since the early days of the railways, the principle of the ballasted track has not changed considerably. Although, after the Second World War the following developments are worth mentioning:

- continuously welded rail,
- concrete sleepers,
- heavier rail-profiles,
- elastic fastenings,
- mechanisation of maintenance, and
- advanced measuring equipment and maintenance management system (Esveld, 2001).

Consequently, the superstructure of ballasted tracks can still withstand high demands, exemplified by the French TGV-trains (high-speed trains) (ibid.).

Opposed to ballasted tracks there are also ballastless tracks, further design details and advantages of ballastless tracks, see paragraph 3.2 Description of ballastless tracks. Advantages with ballasted tracks compared to ballastless tracks are:

- proven technology,
- relatively low construction costs,
- simple replacement of track components,
- relatively simple correction of track geometry (maintenance),
- small adjustments of track lay-out possible (curves),
- good drainage properties,
- good elasticity, and
- good damping of noise (Esveld, 2001).

3.1.1 Formation

The formation mainly consists of slopes, steeps, ditches, etc. on which the sub-ballast is supported. Sufficient strength and consolidating are two requirements the formation need to meet. Also, the formation needs to have an adequate bearing capacity in each and every case. Further requirements are qualities neutralising settlements, such qualities include good drainage properties for rainwater and melted snow and ice on/in the ballast bed. In case these requirements are not met by the formation/sub-ballast, actions must be taken. Such actions include digging drainage ditches, as well as consolidating the soil, for example piling (ibid.).

3.1.2 Ballast bed

The ballast bed (ballast layer) consists of a layer of crossed stone, macadam, which through internal friction absorbs considerable compressions, but not tensile stresses. Thus, the vertical bearing capacity of the ballast bed is great, whilst the capacity is considerably less in the lateral direction. The most important properties of the ballast are hardness, good resistance to wear, and good dispersal of the grading. In addition, the particles must be cubical and have sharp edges. The ballast bed should have a thickness such that the formation is loaded as uniformly as possible. The optimum thickness is usually 25-30 centimetres, measured from the lower side of the sleeper (ibid.).

Finally, it is of great importance to keep the ballast clean from contamination, which may arise from internal wear between the grains. Weathering of the ballast or pumping of fines can form sludge and decrease the bearing capacity, as well as the drainage properties. The latter is important because it can lead to gathering of water in the ballast, which may freeze and induce freeze-thaw weathering (ibid.).

3.1.3 Rails

3.1.3.1 Function

The rail can be seen as the most important component of the track and has a number of functions, as presented in the bulleted list below, it:

- Accommodates the wheel loads and distributes these over the sleepers and supports.
- Gives the wheel support in lateral direction, any horizontal crosswise forces on the rail head is transferred and distributes these over the sleepers and supports.
- Gives a smooth running surface and distributes acceleration and breaking forces through adhesion (ibid.).

Figure 2. *Rail profile* (Rail, 2014)

- Rail head – the form must be such that good contact with the wheel tire profile is ensured. The dimensions of the rail head must be sufficient to provide a high wear margin.
- Rail web – the thickness of the web is dictated by the demands on adequate stiffness against bending and buckling as well as when the web is affected by corrosion.
- Rail foot – the width of the foot must be great to provide stability, load distribution to the sleeper and the required moment of inertia in the lateral direction (Esveld, 2001).

3.1.4 Sleepers

For ballasted tracks, the rails rest on sleepers, which are a part of the superstructure. There are several types of sleepers; timber, concrete and steel sleepers. The two former types of sleepers are the most commonly used (ibid.).

Concrete sleepers are not as exposed to the climate as timber sleepers, as well as much longer service life under certain conditions. The conditions include good quality of the formation, ballast, rails and welds (ibid.).

The general functions and requirements of the sleepers are presented in the bulleted list below.

- Provide support and fixing possibilities for the rail foot and fastenings.
- Sustain rail forces and transfer them as uniformly as possible to the ballast bed.
- Preserve track gauge and rail inclination.
- Provide adequate electrical insulation between both rails.
- Be resistant to mechanical influences and weathering over a long period of time (ibid.).

3.1.5 Fastening system

The purpose of the fastening system, or just fastening, is to connect the rail to the sleeper. There is a wide range of fastenings in use. The choice is largely dependent on the properties and construction of the sleepers. Generally, the sleeper comes with pre-fastened fastenings (ibid.).

The general functions and requirements of fastening systems are to:

- Elastically absorb loads on the rails and transfer these to the sleeper.
- Dampen vibrations and impacts from the traffic as much as possible.
- Maintain track gauge and rail inclination within certain tolerances (ibid.).

For description of an applied fastening system in connection to transition zone, see 3.2.2.2 Direct rail fastening system.

3.2 Description of ballastless tracks

Ballastless tracks, also known as non-ballasted tracks, and slab tracks are often used as synonyms due to similar design, but as a matter of fact there are differences between them. Slab track is an expression for a stringer meaning of constructions with the superstructure of the same concrete cast, which is not the case for constructions made of prefabricated two-block sleepers, or frames of concrete disposed on an asphalt layer. Then there is ballastless track. The appellation ballastless track tells us the superstructure lacks ballast with bearing function, but the construction is related to the track with other functions to keep the rails in place (Jänsch & Wassmuth, 2006).

Most of the current railways are made of ballasted track, as described above in paragraph 3.1. However, recently more applications tend towards ballastless tracks. The reason for this development is the advantages presented by ballastless tracks. The advantages include lower maintenance, higher availability, lower structure height and lower weight. Apart from these advantages ballastless tracks have proven to be very competitive from an economic point of view, life cycle studies have shown (Esveld, 2001).

Generally, the problem with ballasted tracks has been and still is the slow deterioration of the ballast material, caused by the loads from the traffic. Due to the characteristics of the ballast material, consisting of loose granular material, where the grains wander, wear and break up. In turn this causes increasing geometrical unevenness and clogging of the ballast bed by fine particles, which cause drainage problems. Thus, the ballasted track needs regular maintenance to restore the track alignment. In contrary, given a good foundation, the ballastless track provides far greater lateral and longitudinal stability, and differences in the track alignment are reduced and less likely to occur (ibid.).

For further information regarding differences in settlement tendency between ballasted and ballastless tracks in transition zones, see paragraph 3.3.2 Description of the problem.

3.2.1 System requirements

The system requirements for the ballastless tracks are specific regarding the superstructure, in contrast to the requirements on the permanent way, which vary per country. These requirements include applications in tunnels, embankments (the substructure) and bridges (ibid.).

When it comes to high-speed trains, there will be a considerable increase in the dynamic forces because of deviations in track geometry and alignment. Therefore, measures have to be taken to prevent progressive deterioration of the track, improvements to passenger comfort and to lessen the need for maintenance. To satisfy these requirements the ballastless track systems are judged based on the measures mentioned below:

- the use of standardised construction elements,
- rail fastening systems that are adjustable in vertical and lateral direction,
- repair and construction friendly,
- possibility to install noise absorbers,

- easy access for rescue services,
- labour-saving construction work, and
- maximum availability (ibid.).

3.2.1.1 Requirements for the substructures

The requirements for the substructure of the ballastless track are usually very high, because of the limited ability to make adjustments to the track geometry after the construction is completed. Consequently, it is of outmost importance to try to avoid any settlements (ibid.).

E.g. in Germany a lot of work has been carried out to stabilise the embankment through improving the ground by compacting or hydraulic stabilising, and then there is a frost-protection layer of granular material (ibid.).

Over the abovementioned layers is a concrete roadbed or asphalt-concrete layer, which depends on the system of ballastless track. On top of this the concrete slab is constructed. Ahead of the ground improvements and preparation of the embankment, a geotechnical investigation into the actual ground conditions is carried out. By using a ground probe, the necessary assessment of the geotechnical conditions is carried out at least every 50 metres (ibid.).

In areas where the soil has low bearing capacity and thus the quality of the ground is not satisfactory, improvements have to be made to achieve an adequate modulus of elasticity. This is achieved through dynamic compacting and by mix-in-place ground-improvements with e.g. chalk and cement or by ground-replacement. Other methods for strengthening the soil are deep mixing (mixing the material already present in the soil with a liquid or dry mortar based on cement, limestone etc.), grouting (injecting liquid mortar that hardens), and piling (ibid.).

These extensive efforts to improve the soil have been carried out in countries such as Italy, Japan and the Netherlands. The two latter have encountered subgrades consisting of weak soils, which have resulted in very low critical speeds, far below the intentional operating speed. In such instances the improvements are inevitable (ibid.).

Below follows a short description the advantages of ballastless tracks in tunnels and bridges. Consequently a transition zone is often located in close proximity to the tunnel or bridge.

3.2.1.2 Requirements in tunnels

In general ballastless tracks are very suitable for use in tunnels. One of the advantages when applying ballastless track in tunnels are the reduction of the required cross-section, dependent on the type of ballastless system. Cases where ballasted tracks are preferable are in tunnels with geological unstable formations, because of the risk for settling, earth slides, and the appearance of wells (ibid.).

Further requirements in tunnels can be read about in Profilidis (2006), Esveld (2001) and Lichtberger (2005).

3.2.1.3 Requirements on bridges

Bridges provides a solid foundation for applying ballastless track on, but also acts as a discontinuity. Therefore, ballastless track across bridges can cause problems if certain characteristic behaviours of the bridge are not carefully accounted for. This is caused by changes in temperature, which in turn causes of longitudinal movements of the bridge-structure. Furthermore, the loading caused by the traffic makes the spans of the bridge to bend and the edges to twist over its supports (Esveld, 2001).

Further requirements on bridges can be read about in Profilidis (2006), Esveld (2001) and Lichtberger (2005).

3.2.1.4 Requirements on earth structures

The use of ballastless track on earth structures requires special attention because of the risk of settlements. Adjustments in the fastenings are carried out to compensate for settlements. It is only possible to make adjustments at this point due to the structural reasons. Before construction of ballastless tracks the settlement behaviour has to be investigated comprehensively (Lichtberger, 2005).

3.2.2 Systems of ballastless tracks

The current application of ballastless track is mainly on high-speed lines, light rail, and civil structures. Today there is a great range of design of ballastless track systems, and each system has its specific features. Table 1, on the following page, highlights the existing different types of ballastless track.

Table 1. *Summary of the possible construction methods of ballastless tracks* (Esveld, 2001)

<table>
<tr><td colspan="6">BALLASTLESS TRACK SYSTEMS</td></tr>
<tr><td colspan="4">DISCRETE RAIL SUPPORT</td><td colspan="2">CONTINUOUS RAIL SUPPORT</td></tr>
<tr><td colspan="2">With sleepers or blocks</td><td colspan="2">Without sleepers</td><td colspan="2"></td></tr>
<tr><td>Sleepers or blocks embedded in concrete</td><td>Sleepers on top of asphalt-concrete road bed</td><td>Prefabricated concrete slabs</td><td>Monolithic in situ slabs (on civil structures)</td><td>Embedded rail</td><td>Clamped and continuously supported rail</td></tr>
<tr><td>Rheda
Rheda 2000
Züblin
LVT</td><td>ATD</td><td>Shinkansen
Bögl</td><td>Paved-in track
On civil structures</td><td>Paved-in track
Light rail
Road crossing
DeckTrack</td><td>CoconTrack
ERL
Vanguard
KES</td></tr>
</table>

Low flexural stiffness in a ballastless track means the track stiffness only depends on the bearing capacity and the stiffness of the soil, see table 2 below. Regardless of design of the superstructure, either prefabricated or monolithic slabs, the superstructure can hardly be bended. A flexural stiff and reinforced slab can, when it comes to weak and soft soils act as a bridge across weaker spots and local deformations in the substructure (Esveld, 2001).

Table 2. *Division between superstructures with high and low flexural stiffness* (Esveld, 2001)

<table>
<tr><td rowspan="2">BALLASTLESS TRACK SYSTEM</td><td colspan="2">Flexural stiffness</td></tr>
<tr><td>Low</td><td>High</td></tr>
<tr><td>Sleepers or blocks embedded in concrete</td><td colspan="2"><-------------------------></td></tr>
<tr><td>Sleepers on top of asphalt-concrete road bed</td><td colspan="2"><-----></td></tr>
<tr><td>Prefabricated concrete slabs</td><td colspan="2"><----------------></td></tr>
<tr><td>Monolithic insitu slabs (on civil structures)</td><td colspan="2"><-------------------------></td></tr>
<tr><td>Embedded rail</td><td colspan="2"><-------------------------------></td></tr>
<tr><td>Clamped and continuously supported rail</td><td colspan="2"><-------------------------></td></tr>
</table>

The systems of the included reference projects are sleepers or blocks embedded in concrete; LVT is the ballastless track system in Drogdentunneln, the Metro and Citytunneln, and the direct rail fastening, Vossloh DFF 300, ballastless track system is used on Nya Årstabron (ibid.). Both systems are described in more detail in the paragraphs below.

3.2.2.1 Low Vibration Track - LVT

The LVT-system is an independent block system made of single concrete blocks, in a twin block sleeper system. Underneath the block there is a resilient pad and around them a rubber boot, see figure 3 below. The block, pad and boot are then surrounded by unreinforced concrete. As far as the rail fixation is concerned, no special demands are made, and elastic pad is simply used. The two elastic components are matched to each other for each specific project, to receive dual-level elasticity. The concept with two elastic layers separated by an intermediate mass, is designed to attenuate vibrations. The stiffness of the pads in the LVT-system is chosen to meet the technical requirements of each project. The LVT-system comes in different embodiments, presented below (Sonneville, 2012; Jansson & Nielsen, 2012).

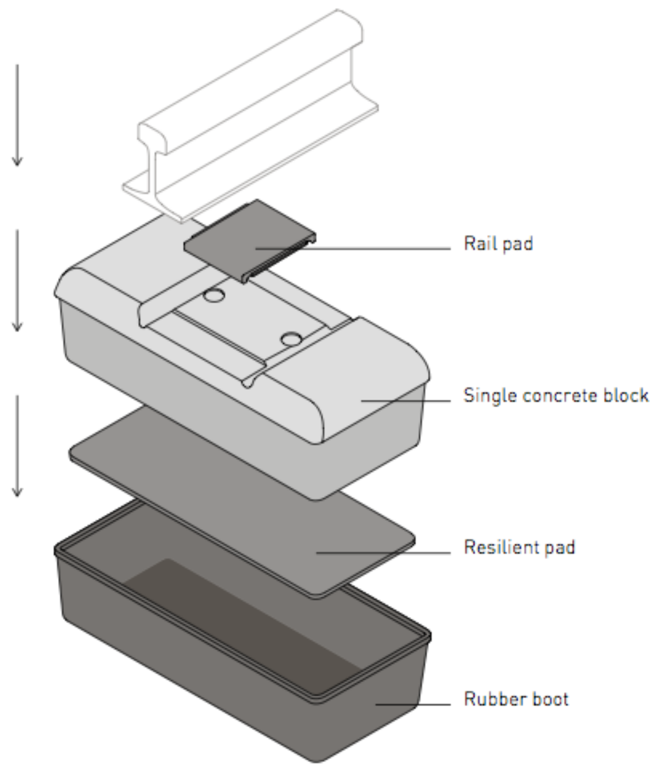

Figure 3. *The LVT-system* (Sonneville, 2012)

LVT standard (LVT)

The standard LVT is used on high-speed sections, metro systems and heavy freight lines. Figure 4 below illustrates the dimensions, in mm, of the LVT standard system (ibid.).

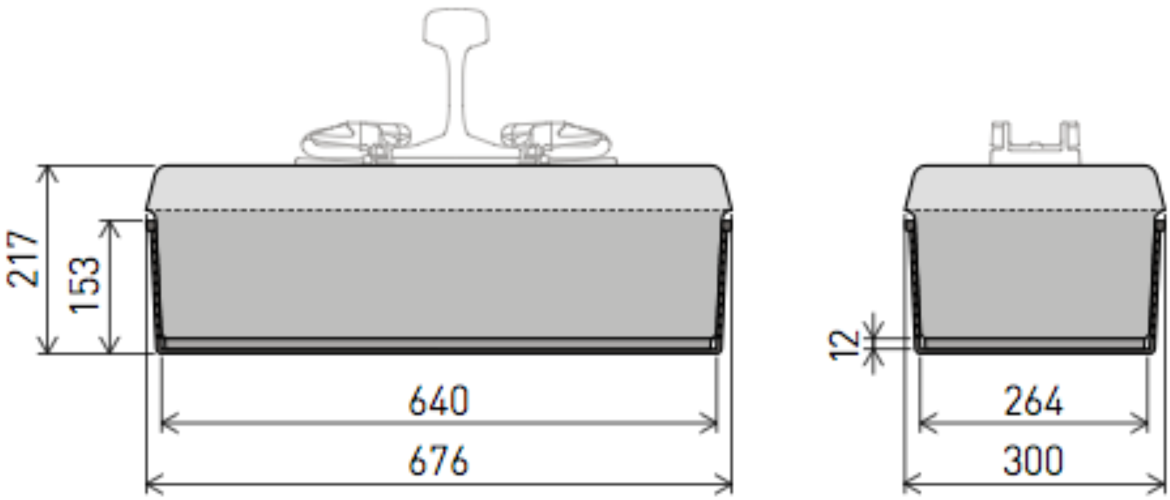

Figure 4. *The LVT standard system* (Sonneville, 2012)

LVT High Attenuation (LVT HA)
The LVT HA system is fitted with a larger block and softer pad, which was produced to fulfil higher demands of noise and vibration attenuation in urban centres. The combination of wider (additional mass) block and softer pad results in a lower natural frequency than the standard LVT. Apart from the standard LVT, Citytunneln uses LVT HA as well. Figure 5 below illustrates the dimensions, in mm, of the LVT HA system (ibid.).

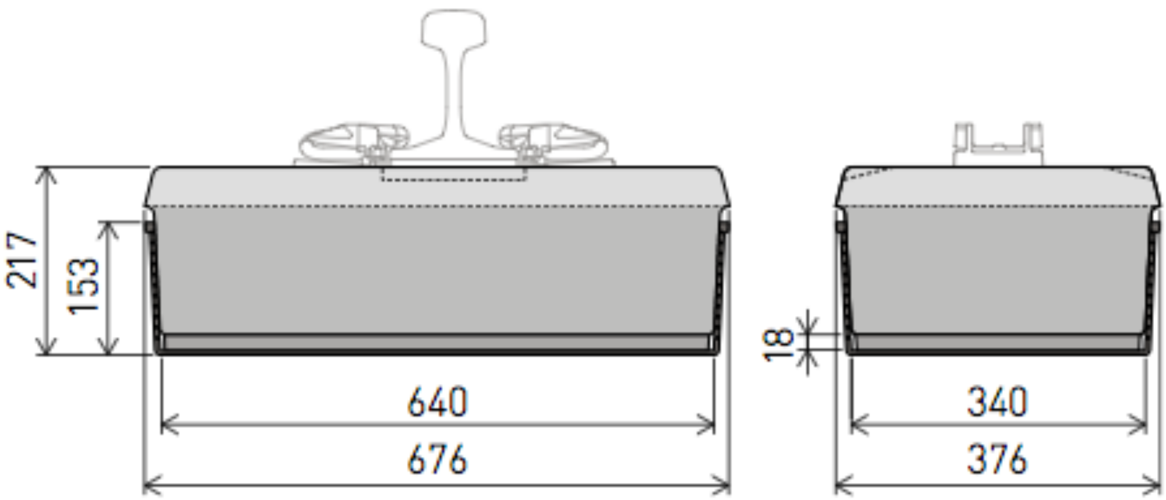

Figure 5. *The LVT HA system* (Sonneville, 2012)

Both LVT and LVT HA are available as LVT low profile (LVT LP), which is used in cases where the structure gauge is restricted (ibid.).

3.2.2.2 Direct rail fastening system
The reference project Nya Årstabron in Stockholm uses a direct rail fastening system, the Vossloh system described below.

Direct rail fastening systems are applied on civil structures, such as bridges and continuous monolithic slabs without sleepers. The fastening system is bolted directly onto the concrete, steel deck or floor. Application of direct rail fastenings instead of sleepers in a ballast bed means the civil structure, e.g. the bridge, could be made lighter (Esveld, 2001).

There are also fastening systems allowing minor adjustment of track alignment, vertically and horizontally, e.g. the Vossloh DFF 300 applied on Nya Årstabron, see figure 6 below, which can be used as an alternative to direction of the track. The fastening system can be adjusted 60 mm in height and 46 mm in track gauge. The advantage, also used in ballasted tracks, is that the track position can be adjusted without disturbing the ballast. A track direction means that the settlement progress in the ballast reboots, to a certain extent, which always involves initial track condition deterioration (Nyström & Prokopov, 2011; Vossloh Fastering Systems, 2014).

Figure 6. *Adjustable Vossloh DFF 300* (Vossloh Fastening Systems, 2014)

3.2.3 Maintenance aspects

In general ballastless tracks are expected to have lesser need for maintenance than a conventional ballasted track. This has proven to be the case in the constructed sections of ballastless tracks in Germany. During observed period of time the track quality has proven to be good, even in a longer perspective. Further observations include improved passenger comfort and higher availability for the ballastless track in comparison to ballasted track (Esveld, 2001).

A stiffer slab leads to a more stable track, which in turn considerably lessens the need for maintenance and in some cases almost makes the need for maintenance redundant. The general experiences from using ballastless tracks are very promising in regards to maintenance. Due to the limited period of time the systems have been used, it is too early to draw any empirical conclusions concerning the deterioration of the ballastless tracks (ibid.).

The German experiences with ballasted tracks date back to the 1970s when the pilot-project at the railway station in Rheda was completed. When it comes to this track system, the general maintenance only includes changing the synthetic rail pad and preventive rail grinding. The latter was carried out to remove rail irregularities and smoothening out the rail surface. After grinding the rail the production of noise was considerable decreased, as well as halting the development of corrugations, head checks. Also damages to the rail surface by imprints were prevented (ibid.).

Due to the lower dynamic forces in the ballastless track failures such as dents close to welds or close to insulated rail joints will be significantly reduced. The approximated cost for maintenance of the Rheda-system amounts to only 10 per cent of the cost for maintaining ballasted track (ibid.).

3.3 Description of transition zones

The purpose of using transition zones between ballasted tracks and ballastless tracks is to get a smooth transition by gradually increasing or decreasing the track stiffness. The main reason for its use is to prevent settlements (Nyström & Prokopov, 2011).

Transition zones are usually located between

- different types of ballastless tracks, and
- ballasted tracks and ballastless tracks.

Each transition zone between ballasted tracks and ballastless tracks represents a possible weakness in the track, where each change may cause increased dynamic forces. When the dynamic forces increase, they affect the track position and will most likely lead to settlements, which worsen over time, especially with substandard or no maintenance (ibid.).

Regarding the construction, there are many different types of solutions for the transition. The chosen construction depends on performed studies on e.g. geotechnical results (ibid.).

The paragraph 3.3.1 below takes a closer look at a number of different methods affecting the track stiffness and smoothening out the differences in track stiffness in the transition construction. Also, methods for lessening and smoothening out the tendencies for settlements are described.

3.3.1 Design of transition zones

Methods for increasing the track stiffness are for example:

- longitudinal auxiliary rails,
- sleepers,
    - longer sleepers and
    - reduced sleeper distance,
- gradually increased depth/width of concrete against ballasted track, and
- glued ballast (Jenks, 2006; Nyström & Prokopov, 2011).

3.3.1.1 Longitudinal auxiliary rails

Installation of auxiliary rails, also known as additional rails, often exists in transition zones between ballasted and ballastless tracks. The auxiliary rails can either be installed between the running rails, or on the field parallel to the track to increase the stiffness in the ballasted track panel, see figure 7 below. The purpose of this method is to improve the load distribution on the ballast and spread the change of stiffness in transition zone. Additionally, guard rails are often placed in transition zones on bridges. With the right phasing to the sleepers, the guard rails also work as auxiliary rails (ibid.).

Figure 7. *The transition zone at the entrance to Drogdentunneln, with auxiliary rails and longer sleepers.*

3.3.1.2 Sleepers

The influence of the sleeper to track stiffness is primarily due to the surface support against the ballast. An increased surface support will give higher track stiffness and decrease the risk for settlements and track mode decomposition in the ballast layer by decreased surface pressure between sleeper and ballast. Two methods for increasing track stiffness using varying designs of sleepers are presented below (Jenks, 2006).

Longer sleepers

One of the oldest and most widely used methods to increase track stiffness, is with gradually longer sleepers on the ballasted side of the transition, see figure 7 above (ibid.).

The longer sleeper increases the track stiffness by the larger bearing area, provided the ballast has a uniform density. The effectiveness of this method is dependent on constant density of the ballast from the rail seat to the end of the sleeper. This might lead to widening of the embankment width in case of e.g. narrow bridges or tunnels (ibid.).

Reduced sleeper distance
Normally the applied sleeper distance is 0.6 metres. With a reduced distance the sleepers surface support increases, which in turn achieves higher track stiffness (ibid.).

3.3.1.3 Gradually increased depth/width of concrete against ballasted track

Another method for increasing the track stiffness is to install an approach slab. The approach slab is a reinforced concrete slab, installed as a structural element in the ballasted track substructure. The ballastless tracks can have a reinforced and tapered concrete slab designed to gradually increase the stiffness and the effective distance is about six metres. This resembles an inclined plane. There can also be an approach slab, cast in one piece, with the shape of a downward staircase against the ballasted track to attain the same ramping effect (ibid.).

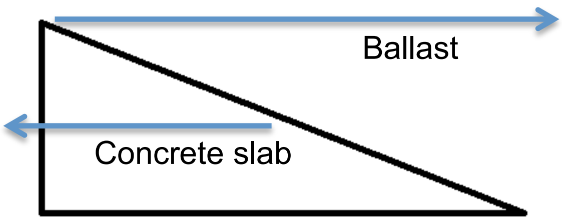

Figure 8. *Inclined plane.*

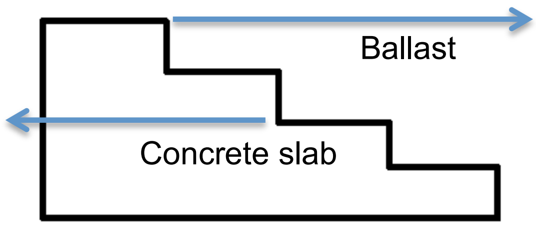

Figure 9. *Downward staircase.*

3.3.1.4 Glued ballast

In Germany, glued ballast is applied in the transition zones between ballasted and ballastless tracks, and sometimes even in ballasted tracks next to turnouts. The purpose is to reduce the risk of stone spatter (which especially increases in transition zones and turnouts) and mainly to minimize the tendency of settlement. It is possible to perform adjustment of the track alignment, but with the consequence to regluing the ballast after the process (Nyström & Prokopov, 2011).

Figure 10. *Glued ballast* (Xin, Kumar & Gao, n.d.)

Methods for decreasing the track stiffness are for example:

- under sleeper pads (USP),
- ballast mat (BM), and
- under rail pads (URP).

3.3.1.5 Under sleeper pads

To reduce dynamic loads and ballast deterioration, rubber mats can be placed between sleepers and ballast. A technique to reduce the track stiffness was developed in Japan in the 1970s for the Shinkansen high-speed network, where mats had a shape designed to achieve a specific spring rate (Jenks, 2006).

Figure 11. *Under sleeper pad in red colour* (Tiflex 1, 2014)

3.3.1.6 Ballast mat

Ballast mats are used for the same reason as for the USP. Due to the load distribution in the ballast layer, the flexibility must be significantly greater if there would be a difference to the total track stiffness. Normally, they are primarily used to decrease degradation rate in ballast, and as isolated element for high frequently vibrations (Nyström & Prokopov, 2011).

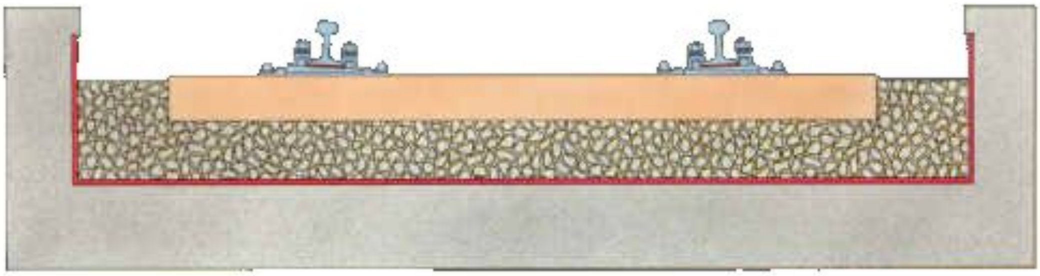

Figure 12. *Ballast mat in red colour* (Tiflex 2, 2014)

3.3.1.7 Under rail pads

To reduce the track stiffness on the stiffer side of the transition, elastomeric pads can be placed between rail and rail seat. For the best effect, the pad stiffness should be equal to the track modulus gradually increasing or decreasing approach in the track. The pads can also be customised according to the damping requirements, which attenuate high-frequency impact loads. (Nyström & Prokopov, 2011).

In case of ballastless track in concrete, it should be kept in mind that deflection of concrete is negligible. With wood or composite sleeper decks, the compression might be a significant part of the total rail deflection. The material stiffness is important concerning the selection of pads (Jenks, 2006).

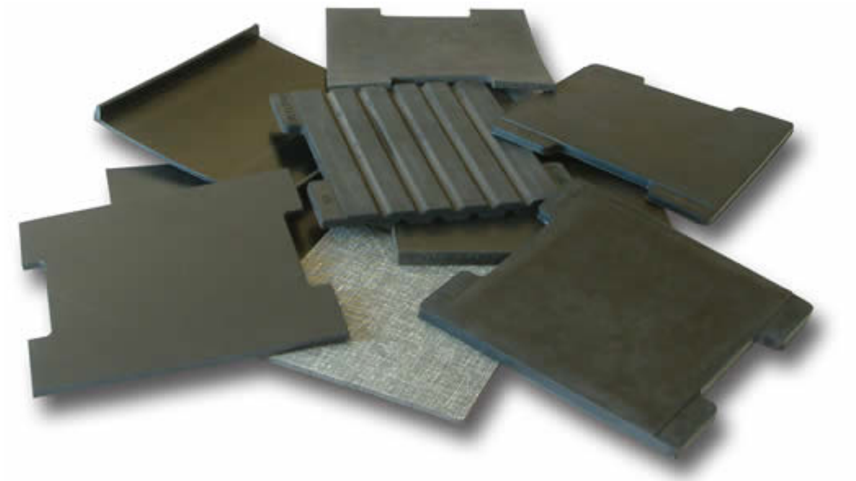

Figure 13. *Under rail pads* (Tiflex 3, 2014)

3.3.2 Description of the problem

The main issue in the transition zone is to minimize a simultaneous change in stiffness and settlement tendency. If the change in vertical stiffness where to happen abruptly, it would cause a disruption in the gait of the vehicle, which in turn would lead to differential settlements, according to the figure 14 below. The differential settlements are caused by the change in track deflection, and the difference in tendency to settle between the ballasted and ballastless track (Nyström & Prokopov, 2011).

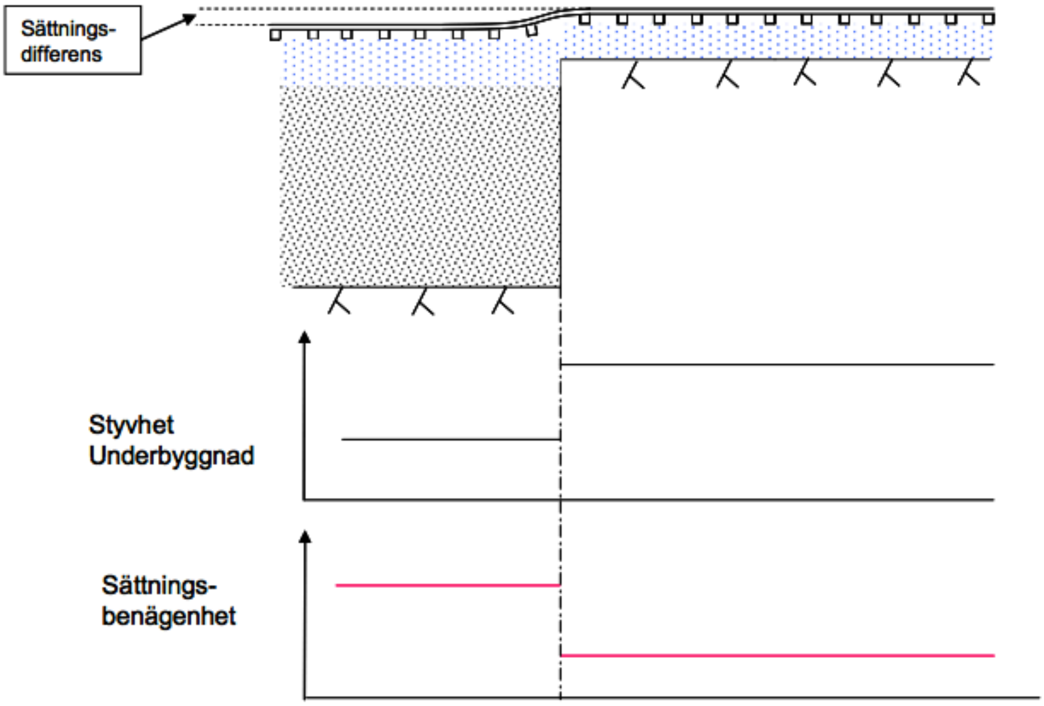

Figure 14. *Transition constructions, basic issues. The upper arrow points out the differential settlement, whilst the middle shows the subgrade stiffness and the lower graph shows the settlement tendency* (Nyström & Prokopov, 2011)

3.3.2.1 Differential settlement

The differential settlement tendency between the two types of tracks will lead to that the vertical track level drops more rapidly in the track with the higher tendency to settle, under the influence of traffic loads. With time there will be vertical track irregularities until the levelling of the track has stopped (ibid.).

The tendencies for differential settlement are especially pronounced in the transition between ballasted and ballastless tracks on embankments due to the construction of the ballastless track is made to have small tolerances for settlements. The settlement progress is particularly noticeable in newly constructed tracks since the soil and subgrade has not been compacted by traffic loads. Subsidence of the settlements lessens with time as the traffic dependent settlements stop (ibid.).

The vertical track irregularity in the transition will occur even if the suspension characteristics of the track are unchanged. Due to subgrade variations, both natural and constructed, the track degradation will increase because of the dynamic forces, which arise as a result of track irregularities, as well as changes in track stiffness (ibid.).

3.3.2.2 Differential track stiffness

The track stiffness varies depending on the track construction, substructure and soil quality. As mentioned earlier, an abrupt change in vertical track stiffness will give rise to a disruption of the vehicle gait due to the change in track deflection. Despite of perfect track alignments the change in vertical track stiffness will result in a response from the vehicle. The response causes supplementary dynamic forces, which in turn may influence the track degradation, comfort experience, and cause increased vibrations, to name a few. The accelerated track degradation in the transition zone will in time result in deteriorated track alignment, which in turn causes increased dynamic forces and further acceleration of the degradation process (ibid.).

The modulus of subgrade reaction is a measure of the subgrade stiffness at the lower edge of the sleeper, specified as the ratio between the contact pressure against a medium, e.g. soil, and indentation the pressure causes. The modulus is mostly used as a measure when calculating settlements under a fundament on soil. It is almost being considered a spring constant depending on the size of the load and propagation (Nationalencyklopedien 1, 2014).

It is noticeable that the stiffness below the sleeper can, in extreme cases vary in the order of a factor ten. The variations in stiffness are equalised by the characteristic load distribution of the track through the flexural stiffness in the rails, and the flexibility provided by the URP, USP etc. (Nyström & Prokopov, 2011).

The flexural stiffness of the superstructure is thus of great importance regarding to the variation of track stiffness. A higher resilience in the superstructure leads to smaller variations in track stiffness (ibid.).

4 Result

4.1 Reference projects

4.1.1 Drogdentunneln – Öresundsförbindelsen

Table 3. *General facts about Drogdentunneln.*

Commissioning year	2000
Number of transition zone(s)	4
Number of transition construction(s)	4
Number of track(s)	2
Maximum train velocity (km/h)	200
Track kilometre(s)	34
Ballastless track system	LVT
Fastening system(s)	Pandrol fast-clip
Tunnel length (m)	4050
Bridge length (m)	7845
Maximum axle load (tonnes)	25

The train connection between Sweden and Denmark consists of Öresundsförbindelsen, which is both bridge and tunnel, Öresundsbron and Drogdentunneln. The railway runs beneath the road on the bridge and parallel to the road in the tunnel.

The traffic on the railway tracks is in form of international freight trains and high frequent passenger trains as Öresundstågen and to a lesser extent SJ2000. In the year 2012 the amount of freight crossing the bridge-tunnel was 5.8 million tonnes, whilst the amount of passengers were a record 11 million, which translates into 30 000 persons every day. The demand for railway transport across the bridge-tunnel will increase in the coming 20-30 years, which will put the railway under increased pressure. According to Lundgren (2014), the service life of the tunnel is set to 100 years (Skønnemand, J 2013; Trafikverket 2013).

The connection is administrated and owned by Øresundsbro Konsortiet, and the responsibility for maintenance extends to Kastrup. Øresundsbro Konsortiet is Swedish-Danish company founded in 1991 through an agreement between the governments of Denmark and Sweden (ibid.).

4.1.1.1 Design and construction

The railway on the bridge is traditional ballasted track, whilst in the tunnel a ballastless system is applied (Vägen över Öresund). The system of ballastless track used is LVT from Sonneville (Appendix 5; Appendix 6).

In total there are four transition zones between ballasted tracks and ballastless tracks. Two of the transition zone are located on the Pepperholm isle and consists of the switch from the ballasted track on the bridge to the ballastless track in Drogdentunneln. The two remaining transition zones are located on the artificial peninsula in Kastrup and make the switch back to ballasted track out from the tunnel. Initially the change from ballast to ballastless track was made without any transition construction, the consequence of this is described in more detail in paragraph 4.1.1.2 Maintenance (ibid.).

In terms of the design of the four transition zones, all but one are designed in exactly the same way. The transition zone not designed in the same way is situated in close proximity to a turnout, and was shortened due to a lack of space. Below follows a closer description of the design and differences (ibid.).

Transition zone 1, 3 and 4 are 20 700 mm long, according to appendix 6, and are constructed with a constant sleeper distance of 600 mm with 24 sleepers, which equals the length in total to 14 400 mm. The track stiffness in the transitions is increased through longer sleepers. Closest to the ballasted section lay ten SP90 concrete sleepers, measuring 3 000 mm, and thereafter lay fifteen SP90 concrete sleepers, measuring 3 500 mm. In addition to the longer sleepers there are auxiliary rails. The auxiliary rails are UIC60 and the length is 20 800 mm. Aside from the construction elements above, the transition constructions include different types of fastenings, see table 4 below. To determine which types of fastenings to apply, a number of tests were performed. The track stiffness is greater in the ballasted track than the ballastless track, measurements show. The change in fastenings is to change the stiffness gradually, to accommodate a more smooth transition rather than an abrupt change. The difference between the fastenings is based on tests were the baseplate pad, rail pad and toe load varied (Pandrol 1, 2004; Pandrol 2, 2004; Appendix 6).

Table 4. *The table displays the chosen fastenings for the transition zones in Drogdentunneln* (Appendix 5; Appendix 6)

Sleeper	Fastening
Standard concrete sleeper	Pandrol Fastclip
Concrete SP90 3,000 mm	Pandrol VIPA SP 1:40, dyn. 46
Concrete SP90 3,500 mm	Pandrol VIPA SP 1:40, dyn. 38
LVT block	Pandrol Fastclip

As mentioned, transition zone 2 is the odd one out, the length of this zone is 12 900 mm according to appendix 5. It consists of six 3 000 mm long SP90 concrete sleepers followed by six 3 500 mm long SP90 concrete sleepers. The transition zone 2 is generally constructed in the same way as the other three, as in gradually longer sleepers approaching the ballastless track. Further, the auxiliary rails are UIC60 and measure 12 600 mm in length. Aside from the construction elements above this transition construction includes different types of fastenings as well, see table 4 above (Appendix 5).

4.1.1.2 Maintenance

As described in the introductory section above, Øresundsbro Konsortiet administrates the connection and conducts track maintenance. As Øresundsbro Konsortiet stands under both Swedish and Danish ownership, they observe both regulations from Banedanmark and Trafikverket, the respective country's railway authority. According to Lundgren (2014) Øresundsbro Konsortiet observe the sharpest regulation. Furthermore, Lundgren (2014) told the track is inspected three times every year in accordance with Banverket 2 (2012).

Lundgren (2014) stated, that as of the date the interview was conducted 50 per cent of the rails in the tunnel have been grinded since the commissioning year. Also, due to heavy freight trains, head checks occurred on the peninsula in Kastrup, which led to grinding the rails in sensitive areas in accordance with the rail profile for 30 tonnes axle load as used on Malmbanan in Sweden (Iron Ore Line). After the regrinding the occurrence of problems as head checks were solved (Lundgren, 2014).

Initially, problems with rail corrosion were experienced, most probably due to the higher percentage of salt from the Sound. The salt is pushed into the tunnel by passing trains and does not vanish through rainwater or wind as it would in an open area. The problem solved itself in a natural way by creating a protective layer covering the rails against the salt (ibid.).

In 2008 a sampling was made to inspect the slabs in the tunnel. The sampling was executed through lifting up the slabs and inspecting them. The slabs were satisfactory, no cracks or fractures were found. Specific inspections of the transition zones were performed in the first few years after commissioning due to greater stresses in this particular area (ibid.).

Further, Lundgren (2014) expressed his satisfaction regarding the maintenance of the transition zones, which will be tamped for the first time this year since the transition construction was built, eight years ago. Initially, there were no constructions for equalising the track stiffness at all. The switch from ballasted to ballastless track was abrupt, which led to that the maintenance demanded tamping three times in the first four years after commissioning. The main reason for tamping was to reduce settlements in the transition. Lundgren (2014) stated that there was too much maintenance, which was the reason for rebuilding the transition zone with a smoother transition construction. The table 5 below shows that adjustments of the track alignment should be carried out every third year, due to that Drogdentunneln is in its 14th year of service (ibid.).

Table 5. *Guideline values for maximum allowable differential settlements in longitudinal direction of the ballasted track* (Trafikverket 2, 2013)

Years after commissioning	Number of adjustments of track alignment on the same place	Settlement, mm. (totally per year/sum over the period/total)
1 – 4	Twice a year	12/48/48
5 – 10	Once a year	6/36/84
11 - 40	Once every third year	2/60/144
Output value for dimensioning: maximum 144 mm in 40 years		

Finally, Lundgren (2014) added that since the construction of the transition zones there have not been any major problems worth noting.

No information was received regarding differences in maintenance between the three identical transition zones and the odd one out.

4.1.2 Citytunneln

Table 6. *General facts about Citytunneln.*

Commissioning year	2010
Number of transition zone(s)	8
Number of transition construction(s)	8
Number of track(s)	2
Maximum train velocity (km/h)	160
Track kilometre(s)	28
Ballastless track system	LVT/LVT HA
Fastening system(s)	Pandrol fast-clip
Tunnel length (m)	6000
Maximum axle load (tonnes)	25

Citytunneln is a railway tunnel under central Malmö. The construction of the tunnel was initiated in the spring of 2005 and was completed for traffic in December 2010 (Helmersson, 2014).

Citytunneln project consists in total of 17 kilometres railway, 11 kilometres of which are double tracks from Malmö Central station (Malmö C) to Öresundsbron, and the remaining 6 kilometres is single track eastwards towards Trelleborg and Ystad (ibid.).

The double track railway starts under Malmö C in two 6 kilometres long parallel tunnels, and move upwards to the surface that continues above ground towards Öresundsbron, see figure 15 below. The project involved the expansion of the railway station Malmö C with an underground section and the building of a new underground station at Triangeln in the central Malmö, as well as a new station above ground in Hyllie (ibid.).

The number of travellers boarding Malmö C in 2013 was 34 000 every weekday. The corresponding number for Triangeln and Hyllie stations was 19 000 respectively 15 000 (Skånetrafiken, 2013).

The two parallel tunnels are constructed with ballastless track, LVT and LVT HA, and on either side of the tunnel is ballasted track where transition zones are constructed. The change from ballasted to ballastless tracks are made through transition constructions, which is described in more detail the paragraph 4.1.2.1 below (Jansson & Nielsen, 2012).

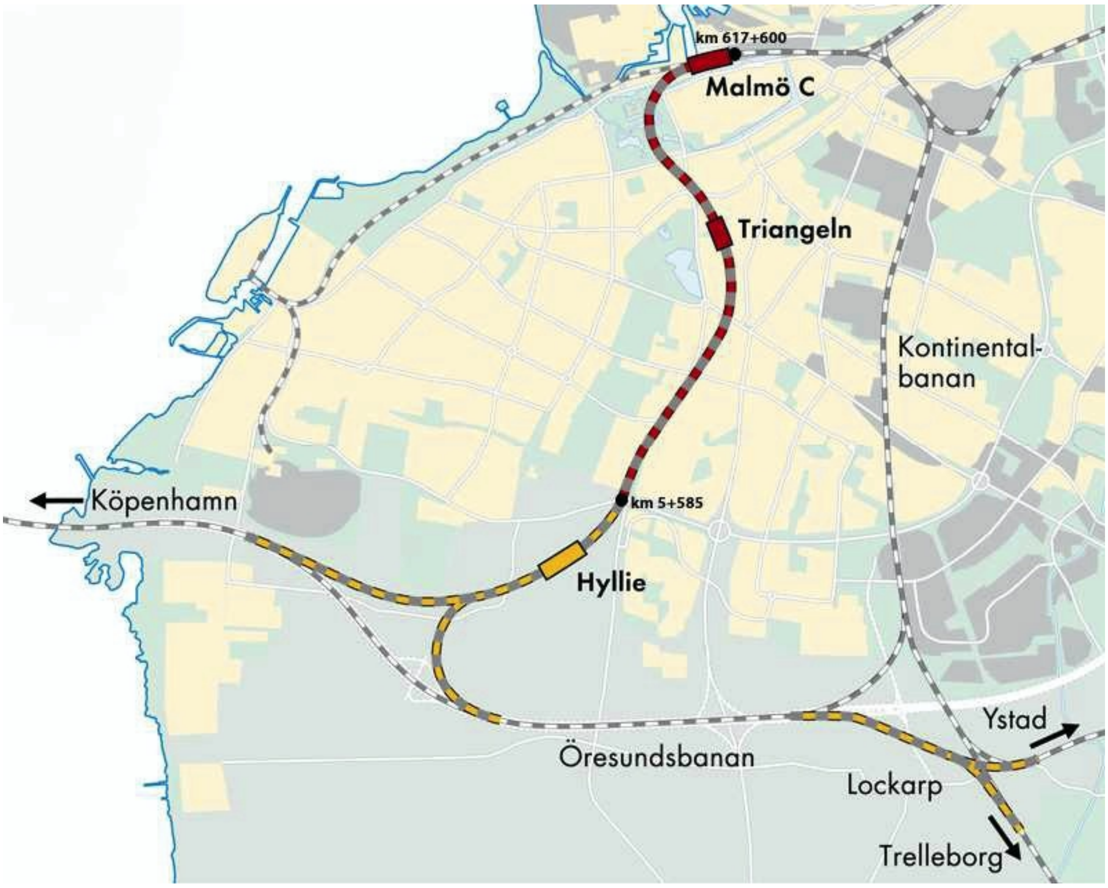

Figure 15. *Map of the city tunnel in Malmö where the red line shows the tunnel* (Jansson & Nielsen, 2012).

4.1.2.1 Design and construction

Design of the transition zones
In total there are eight transition zones in or in close proximity to the tunnel. The transition zones are not all designed in the same way. The four tracks at the entrance to the tunnel at Malmö C have four transition zones from ballasted track to ballastless track and all four have the same design. Malmö C is constructed with standard LVT, whilst the tunnel from Malmö C to Hyllie is constructed with LVT HA. Therefore, there are two additional transition zones, one at turnout 696 and another one at turnout 698, see figure 16 below (Appendix 3; Appendix 4).

Finally, the two remaining transition zones are located just before the turnouts 451 and 453 on the Hyllie-side of the tunnel. These two transition zones are constructed in the same way. The design includes two consecutive transition constructions; the first is LVT HA to LVT and the second LVT to ballasted track (ibid.).

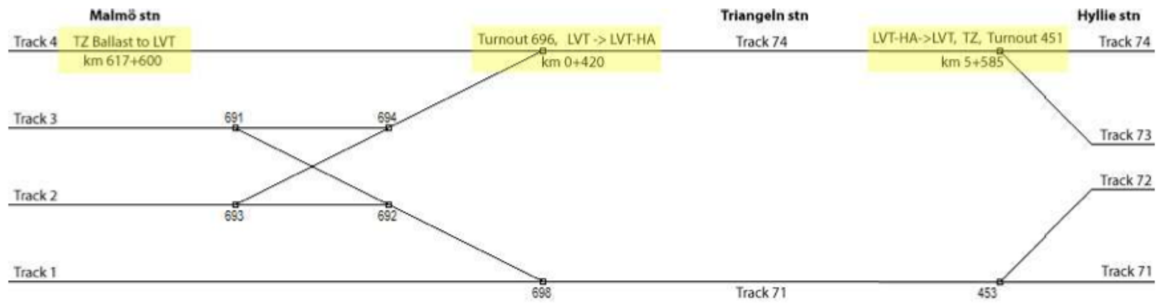

Figure 16. *Schematic view of the tracks in Citytunneln* (Jansson & Nielsen, 2012)

All transition zones from LVT/LVT HA to ballasted track are designed very similarly. The length is approximately 19 metres (18 850 mm) and includes auxiliary rails, as well as USP for the stiffness transition, see Appendix 4. At the ballastless track end, there are nine LVT twin blocks with auxiliary rails. After, there are sixteen T1-sleepers with USP and auxiliary rails. Finally there are four T2-sleepers with USP, but without auxiliary rails, which marks the end of the transition zone. The sleeper distance used throughout the zone is 650 mm (Appendix 4).

The transitions from LVT to LVT HA are designed with varying distance between the twin blocks, as well as varying the block stiffness throughout the total length of 24,000 mm. The varying distance between the twin blocks are combined with the pad stiffness variation to achieve the desirable stiffness transition (Appendix 3).

4.1.2.2 Maintenance and measurements

Rail deflection
According to Jansson & Nielsen (2012), large rail deflections were measured for the LVT section in the block closest to the transition. The rail deflection is small in the T1 section in the ballasted track, except at the transition from LVT to T1 sleepers. The deflection was at its maximum in the sleeper closest to the ballastless track (Jansson & Nielsen, 2012).

The rail deflection is greater for the sleepers with USP than sleepers with no USP (which is on ballasted track). No significant difference in deflection was detected between X31- and X61-trains (ibid.).

Due to the difference in rail deflection between the LVT section and the T1 section, as well as the greater deflection of the sleepers closest to the ballastless track, Jansson & Nielsen (2012) state, the design of the transition construction is not optimal (ibid.).

Sleeper and block accelerations
Measurements show that sleeper acceleration is low in the ballasted track, whilst they are large in the LVT section (ibid.).

Track stiffness
Measurements performed with the Rolling Stiffness Measurement Vehicle (RSMV) point out obvious different sections with varying track stiffness. According to the different types of track system, Jansson & Nielsen (2012) state, this is the possibly reason for different stiffness in different section, e.g. ballasted and ballastless track, as well as varying types of rail pad/USP (ibid.).

The transition zone at the tunnel entrance to the Malmö C is extremely short, which in turn leads to increased need for maintenance due to the additional dynamic forces caused by the passing trains (ibid.).

The length of the abovementioned transition zone is 19 metres. Measurements of the stiffness in the transition zone were performed, which show a sharp fall in track stiffness in five metres. Additionally, the two auxiliary rails in the transition zone connect the sleepers closest to the LVT to the concrete slab. The arrangement improves the load distribution, but also leads to a step change in the transition (ibid.).

On the Malmö C-side of the tunnel, there is a transition from LVT to LVT HA. The transition zone seems smooth as well as the stiffness in the turnout, which match well with the surrounding track (ibid.).

On the Hyllie-side of the tunnel, there is a transition from LVT HA to LVT to ballasted track, and the turnout on ballast. There is a sharp change in stiffness about 20 metres before the change in the transition zone from LVT to ballast (ibid.).

Sleeper settlement measured for unloaded track

The section in ballast with USP shows the highest value of sleeper settlement. During the first months of operation the contact with ballast stones causes the USP to permanently deform. Jansson & Nielsen (2012) regards this as a possible explanation for the high value of sleeper settlement, according to measurements (ibid.).

In the beginning of the LVT section there seems to be an uplift of the track. Possibly, it can be explained by the rail bending over the end of the ballastless track, caused by the settlement in the ballasted track with USP.
The four sleepers on USP without auxiliary rails, experience the highest settlement values. The abovementioned causes problems with accessibility for ballast tamping (floating sleepers) (ibid.).

Jansson & Nielsen (2012) raise a note of caution to damage the LVT system with auxiliary rails, which could cause uplift of the LVT blocks. They suggest removing the auxiliary rails and only use USP in the transition zone. Also, they suggest retamping the ballasted track and then evaluate the consequences by repeated track geometry measurements before the change would be permanent (ibid.).

Jansson & Nielsen (2012) concludes that the two types of ballastless track, LVT and LVT HA, and the transition zones as well, generally work as designed according to track stiffness measurements. Further, they recommend designing longer transition zones to get a lesser variation of track stiffness (ibid.).

4.1.3 Copenhagen Metro

Table 7. *General facts about Copenhagen Metro.*

Commissioning year	2002
Number of transition zone(s)	10
Number of transition construction(s)	8
Number of track(s)	2
Maximum train velocity (km/h)	80
Track kilometre(s)	36
Ballastless track system	LVT
Fastening system(s)	Vossloh SKL 14 on the line Vossloh SKL 12 in turnouts
Maximum axle load (tonnes)	10

The Metro in Copenhagen is a rapid transit system in the Danish capital. The first stage was inaugurated in the autumn 2002, which is 11 kilometres long and include two lines with 11 stations. The Metro is one of the most modern rapid transit systems in the world with completely remote and driverless trains. The underground stations include glass walls by the platform edge, which automatically opens in the exact point where the doors from the train open when the train has stopped (Nationalencyklopedien 3, 2014).

The first stage of the Metro extends between the island Amager to the neighbourhood Nørreport and linking the town’s centrum with other new neighbourhoods, e.g. Ørestad (ibid.).

Today there is an expansion of the Metro, which continues till total 21 kilometres with 24 stations where half of the rapid transit system is under ground (ibid.).

4.1.3.1 Design and construction

In total there are ten transition zones between ballasted track and ballastless track. Out of these ten transition zones, eight are made with a transition construction. The two remaining transition zones do not have any construction at all for smoothening out the stiffness difference. These two transition zones are located at Islands Brygge station (Thorshaug, 2014).

The track is provided with the fastening system Vossloh 14 on the line and Vossloh 12 in turnouts. The fastenings are able to adjust in both vertical and lateral direction (ibid.).

4.1.3.2 Maintenance

According to Thorshaug (2014), problems with settlement have only been experienced in the two transition zones at Islands Brygge. The settlements cause more maintenance measures in this area. However, Thorshaug (2014) does not see this as a problem, but agreed it causes greater need for maintenance (ibid.).

4.1.4 Nya Årstabron

Table 8. *General facts about Nya Årstabron.*

Commissioning year	2005
Number of transition zone(s)	4
Number of transition construction(s)	4
Number of track(s)	2
Maximum train velocity (km/h)	120
Track kilometre(s)	1.6
Ballastless track system	Direct rail fastening
Fastening system(s)	Vossloh DFF 300/Pandrol e-clip
Bridge length (m)	833
Maximum axle load (tonnes)	22,5-25

Årstabroarna in Stockholm are two parallel railway bridges connecting the locations Södermalm with Årsta (Axelsson & Helmersson, 2014).

Gamla Årstabron was built 1925-29 and included two tracks connecting Stockholm C. The bridge is 753 metres in length and is made as an arch bridge with reinforced concrete (ibid.).

Nya Årstabron was built 2000-05 and is located 45 metres from the old bridge and has two railway tracks, as well as a pavement for bike path and service road. The bridge is made of prestressed concrete with a length of 833 metres and the width 19.5 metres. The traffic consists by long-distance trains, commuter trains and freight trains (ibid.).

Nya Årstabron is generally trafficked by northbound trains, whilst on Gamla Årstabron the trains are southbound (ibid.).

The two bridges are part of Västra stambanan, the main railway line connection between Gothenburg and Stockholm (Nationalencyklopedien 4, 2014).

4.1.4.1 Design and construction

The system of railway construction divides on the bridge. On either side of the bridge lays traditional ballasted track, which extends a few metres onto the bridge on both the north and south abutment. The ballasted track lying on the bridge is put in a ballast box on both ends to accommodate movements of the bridge through the dilatation device (Nationalencyklopedien 2, 2014).

The system of ballastless track on the bridge is, according to Mika (2014) and Tirus (2014), the direct rail fastening system Vossloh DFF 300, see paragraph 3.2.2.2 figure 6. They further told, the system is a special solution made for Nya Årstabron and that Vossloh projected the ballastless track on the bridge.

Figure 17. *The transition zone on the north side of the bridge, illustrating the design with the associated guard rails, dilatation device, ballast box and direct rail fastening system.*

In total there are four transition zones between ballasted track and ballastless track. Two transition zones are located on the bridge in close proximity to the north abutment, and the other two are placed similarly on the south side of the bridge. All transition zones are designed in the same way. The design only includes guard rails, which also act as auxiliary rails. Besides the auxiliary rails there is not any known construction made to smooth out the track stiffness. Despite researching, interviewing and gathering of information no further material regarding the stiffness transition was received (Appendix 1; Appendix 2).

The following measures are all according to drawings, see Appendix 1 & Appendix 2.

The switch from ballasted track to ballastless track, on the south side of the bridge, is made 14.215 metres from the abutment on the bridge, which also corresponds to the length of the ballast box. The guard rails on both tracks are 15.2 metres long with additional laces of the guard rails measuring 5.05 meters.

The corresponding switch from ballast to ballastless track on the north abutment is made 20.746 metres onto the bridge, which is the length of the ballast box as well. The guard rails on the north side differ in length due to the nature of the track, located in a curve. The length of the guard rails on the outer track is 14.5 metres, whilst the inner rails measure 14.3 metres. Additionally, the laces of the guard rails measure 5.05 metres on the north side as well.

4.1.4.2 Maintenance
To obtain the state of the tracks on the bridge, safety inspections and measurements of the track alignment are executed six times every year. However, no recurring measurements of dynamic forces or the track stiffness are performed. The bridge is dimensioned for a service life of 120 years and salt (chlorides) is the worst enemy of the concrete (Mika, 2014; Tirus, 2014).

Settlements were observed through the rail deflection when trains were passing the transition zone. Tirus (2014) pointed out that tampering could be performed, but it would only be a very temporary solution. Other observations included the existence of fines in the ballast box, see figure 18.

Figure 18. *Transition zone on the north side of the bridge, illustrating the existence of fines and water collection in the ballast box.*

The German way of dealing with the ballastless tracks after the end of the service life is simply to construct a new track, if needed. If the system functions still are satisfactory at the end of the expected service life, it is unnecessary to replace it (Mika, 2014).

The main maintenance consists of tamping in the ballast box due to the transition construction. Additionally the ballast is complemented every third year and the track alignment has been adjusted with different periodicity, last year the alignment was adjusted twice (Mika, 2014; Tirus, 2014).

Finally Mika (2014) pointed out the importance of communication between the constructor of bridges and track engineers to consider the need of transition constructions. This because the transition zone is a sensitive area of the track and can lead to a greater need for maintenance, if not designed according to the soil conditions and track properties.

4.2 Other experiences

4.2.1 Universal transition module – V-TRAS

The Rohmberg Group has developed a new construction for the transition zones between the traditional ballasted tracks and ballastless tracks. The construction is called *Universal transition module V-TRAS* (Rohmberg Rail, 2013).

4.2.1.1 Design and construction

The construction was developed during 2011-12 and is currently used on two locations, Dornbirn in Austria and Asfordby in England. The application of the construction is at this moment in time discussed for use in a number of other countries such as South Africa, Canada, Germany and Switzerland (ibid.).

Regarding the design of the universal transition module itself, it is designed in form of a ramp structure. The structure is supported on respective bearings at the end of the ballastless track and laid floating in the ballast bed end, according to the figure 19 on the following page (ibid.).

Figure 19. *The universal transition module V-TRAS pictured as it is provided and supported on the massive end of the ballastless track and floating in the ballast bed* (Rohmberg Rail, 2013).

According to Knittel (2014), the universal transition module V-TRAS is not only possible to use on embankments, but also on bridges, at the abutment in beginning of the bridge construction. V-TRAS is adaptable for use in small, normal and wide track gauge, and along with light rail systems. The construction is designed for 25 tonnes axle loads and to be used in both new constructions and for rearmaments of existing tracks. Knittel (2014) also estimated the theoretical service life to be at least 30 years (ibid.).

As the figure 20 below shows, the structure consists of two massive longitudinal steel beams. The beams run centrally under the sleepers in the same way the rails do. The length of the beams are not standardised, but are determined in accordance with the specific requirements of each project. If needed, a number of V-TRAS modules can be arranged one after the other to meet requirements set by each project (ibid.).

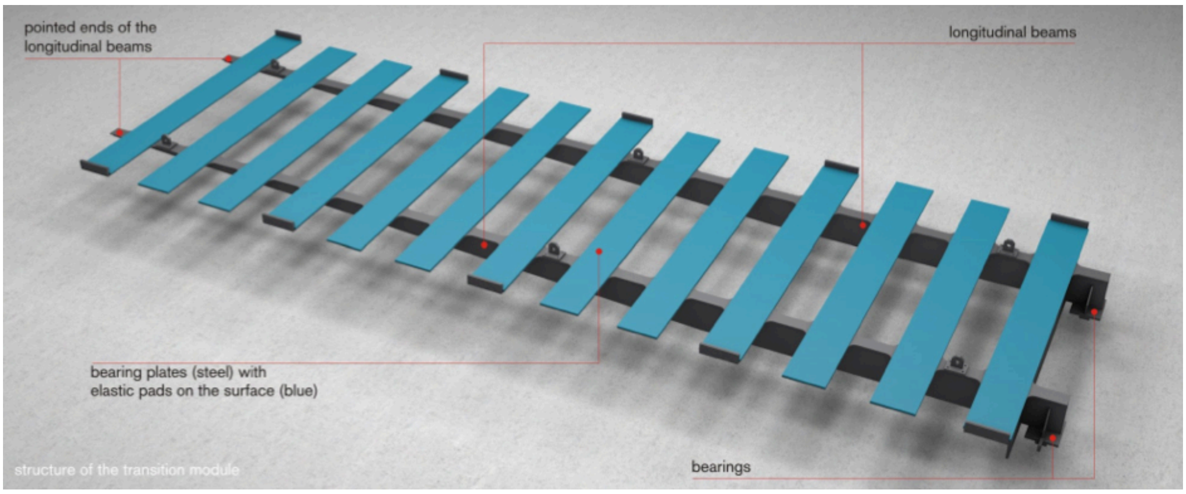

Figure 20. *The structure of the universal transition module V-TRAS* (Rohmberg Rail, 2013)

The two steel beams are constructed with supporting plates, whose form corresponds to the base of a standard ballast concrete sleeper. As the figure also illustrates, the distance between the supporting plates corresponds to the sleeper distance (ibid.).

On the supporting plates elastic USP are attached, both figures above show the pads in blue colour. The stiffness, damping properties and elasticity of the USP can be determined to suit the specific demands of the stiffness transition in accordance with the requirements of each project (ibid.).

The fixation points of the supporting plates on the longitudinal steel beams are exposed to abrasion of gravel. To counter the abrasions a resilient coating or optionally elastic pads can be fitted at the fixation points (ibid.).

4.2.1.2 Maintenance

Settlements are treated in the same technique as in regular ballasted tracks. The construction does not influence the tendency for track settlements. The maintenance is generally performed for comfort purposes and is dependent on the track conditions as in standards, velocity, axle loads, etc. Despite the limited time of use, nothing suggests changes in the track condition (Knittel, 2014).

Furthermore, Knittel (2014) states, the lateral displacement of the construction is less than for a normal ballasted track, due to the anchoring depth of the V-TRAS construction in the macadam.

4.2.2 Theoretical experiences

An important issue when dealing with the construction of transition zones is which sudden change in track stiffness should be allowed without taking actions for smoothing out the change. It is also important to have in mind that due to the flexural stiffness of the rails, the track will to a certain degree automatically smooth out the difference. Therefore, a step-by-step change in stiffness measured in the supporting points of the rail will result in a gradual change in track stiffness (as perceived by the vehicle) through an equalisation length, dependent on the flexural stiffness of the rails and the substructure stiffness. Thus, the sudden change in stiffness is actually over a few metres. When the change in track stiffness is great, a transition zone is required. The principal functional requirements are what length and shape the transition zone will have to accommodate the change and minimize the vehicle response (Nyström & Prokopov, 2011).

Based on theoretical models and research, which Jonsson (2014) has been involved in, he says that the theory is simple, and explains that the track could be treated as a spring/mass-system.

The main issue in transition constructions is the change in acceleration (jerk) in the transition zone, which leads to greater dynamic forces. The change in acceleration is highest when the derivative of the acceleration goes towards the infinity (Jonsson, 2014).

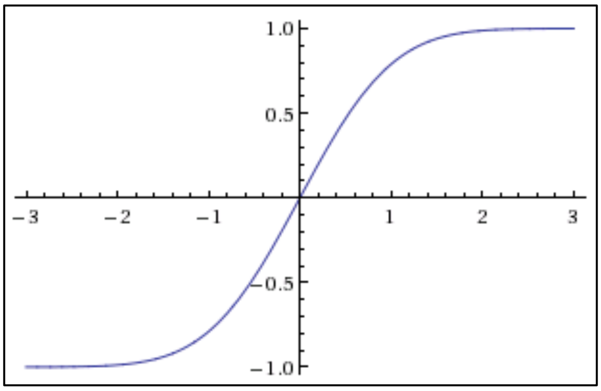

Figure 21. *Error function, S-shape.*

To reduce the change in acceleration in the transition zone, Jonsson (2014), recommended designing the characteristics of the stiffness transition in accordance with especially the error function. Figure 21 above illustrates the graph. Other functions he recommended were cycloid and versed sine. Jonsson (2014) also strongly dissuaded from using an abrupt and linear change in track stiffness.

As described in paragraph 3.3.2 ‘Description of transition zones’ an abrupt change would cause a disruption in the vehicle gait, which is in turn due to the jerk from the change in stiffness. A possible solution to reduce the jerk is to design the stiffness transition with a shape of an S. The error function or the similar cosine, hyperbolic, cycloid and inverted sine satisfy the stiffness variation via the smoother S-shape. Observe figure 22 on the following page for a comparison of the stiffness variation functions (ibid.).

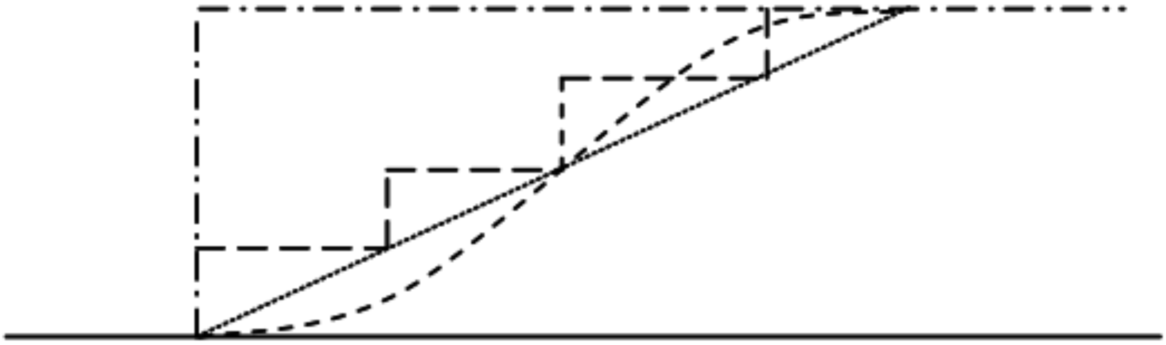

Figure 22. *Example of change of track stiffness functions, those included are abrupt, step-by-step, linear and cosine* (Nyström & Prokopov, 2011)

Jonsson (2011) concludes: the variation of stiffness is of great importance, as well as that the third derivative of the zone is governing. Jerks in the third derivative should be avoided and S-shape is favourable to minimize force variance. Additionally, Jonsson (2011) reveals the transition zones can be as short as 10 metres for speed up to 100 m/s.

Regarding other factors influencing the dynamic forces in the track, Jonsson (2014) pointed out the importance of the soil conditions. Finally, the track irregularities could be used as an indirect indication of stiffness differences, he said.

5 Discussion

5.1 The importance of transition constructions

The transition zones at Islands Brygge in the Metro have experienced greater difficulties with settlement than the other transition zones, which have led to more frequent inspections and maintenance. Despite the consciousness about the extra maintenance, Thorshaug (2014) did not consider this a problem, because of his cognisance about the problem and his opinion of time and resources to fulfil the maintenance.

According to the transition zones with more maintenance and the knowledge we have gained, we would although recommend to consider the Islands Brygge with a designed construction in the transition zones for stiffness equalisation. Possibly it will reduce the need for maintenance and save work time in track. Even though it is not a problem today, you never know when a new problem occurs in track, especially with account for the Metros expansion. Suddenly, and perhaps the time is not enough to fulfil the maintenance in Islands Brygge?

Also we would like to highlight the success of reconstructing the transition zones in Drogdentunneln as an exemplary example to the difference between transition zones with, and without transition constructions. For further discussion, see paragraph 5.4 ‘With or without transition construction’, below.

5.2 Floating sleepers (settlement)

Floating sleepers are a recurring phenomenon, present in several of the reference projects. We have personally observed the phenomena on Nya Årstabron and Drogdentunneln, as well as taken note of measurements performed in Citytunneln, which have drawn attention to this.

According to the measurements performed in Citytunneln at Malmö C, the rail deflection is greatest in the ballasted track, more specifically the sleepers closest to the ballastless track. The possible consequences of this are rail fatigue and wearing of the ballast, which may lead to additional maintenance, e.g. tamping and ballast complementing, as well as shortening the service life of the track components.

The abovementioned is especially visible in the transition zone at Nya Årstabron. The wearing of the ballast is the probable cause for fines rising to the surface and affects the bearing capacity negatively, as well as impairing the drainage properties. To reduce the need for maintenance caused by the settlements, we recommend, based on the impressions we got, to investigate the transition zones on Nya Årstabron including geotechnical knowledge and evaluate how the transition construction relate to limits of readings. This is of importance to detect and document possible settlements for an eventual strategy to radical actions. In case the settlements go undetected, the problem could worsen and be a risk for serious damage to track.

5.3 Length of the transition zone

The length of the transition zone is solely dependent on how the equalisation of the track stiffness is constructed. Jansson & Nielsen (2012) conclude, the transition zones at Malmö C is extremely short, and specify this as a reason for the increased need for maintenance in this area.

It is certainly correct that a longer transition zone with the same design elements would possibly result in an easier way to equalise the track stiffness, and in the end decrease the need for maintenance. However, Jonsson (2014) specifies, the length of a transition zone could be as short as 10 metres, given an optimal design. Since the length of the transition zone depends on how the stiffness equalisation is designed, the transition zone at Malmö C could most likely be considerably shorter and still give a smoother transition. Therefore, the solution might not only be to extend the transition zone, but rather to apply a different design of the transition construction to decrease the maintenance.

Despite the length of the transition zone is 19 metres, there is a sharp change in track stiffness on a distance of five metres, which recalls of an abrupt change in stiffness. This also suggests another design of the transition zone might be a more suitable, rather than lengthening the zone.

The abovementioned proposals may not be in question, due to Jansson & Nielsen (2012), which have evaluated the design as good, relative the measurements and design. We agree the transition construction is pleasing enough, and think it would be unnecessary changing something if already in function. Although, the facts mentioned should be kept in mind for possible reconstructions in the future.

5.4 With or without transition construction

The case of Drogdentunneln indicates the transition zone did comply with the requirements set by Trafikverket, even before the reconstruction of the transition zone. After the transition construction was redesigned, the need for maintenance decreased dramatically. It should be noted the governing documents only have been in effect since 2013, and might as well have been different prior to 2013.

With the new construction of the transition zone, the speed of settlement development has decreased considerably, and resulted in a reduction in the tamping frequency. Whilst visiting the site of the transition zones on Pepparholm, we observed tendencies for settlements and floating sleepers, but as mentioned in the result, the track will be tamped this year for the first time since 8 years.

The difference between the maintenance before, respectively after the construction of the transition zone is significant. This clearly shows the need and effect for an action for equalising the track stiffness. Additionally, the constructed transition zone in Drogdentunneln satisfies the requirements set by Trafikverket, with good margin.

5.5 Standardised transition construction

As far as we are knowledgeable, the application of transition constructions is evaluated for each case through geotechnical investigations of the soil condition. Different track systems, as ballasted and ballastless track are also accounted for. When comparing transition zones, we have not to this date, experienced identical stiffness equalisation methods in transition zones. It is however common to combine different types of solutions, which vary to give the required effect for stiffness equalisation. The closest to a standardised construction we have seen is the V-TRAS universal transition module, but even V-TRAS has to be adapted after the conditions prevailing at the location in question.

Knittel (2014) highlights V-TRAS as a well-functioning construction, which has its application in a wide variety of transition zones. The maintenance mainly consists of actions for increasing the comfort in relation to track technical standards. On this basis, we interpret the need for maintenance as low. The focus seems only treat minor actions or applications, as increasing the comfort in relation to the trains and the track properties.

We find the V-TRAS construction as an interesting solution with its wide range of applications because, according to Knittel (2014), the construction currently works well and can be applied for many types of transition zones. V-TRAS also seems to be very adaptable and relatively easy to maintain, which is performed by the same techniques as in regular ballasted tracks.

Although, it should be considered the construction only has been used for a period of two years, which is a very short period of time in railway contexts. It is thus difficult to conclude how well the construction will function in the coming years. We suggest that the solution should be followed up continuously in the next few years for an eventually application in future, if V-TRAS has been more established and of use in traffic etc. It is, at this moment in time too early to draw any final conclusions regarding its use.

5.6 Practice of theory

The construction of the transition zones we observed is constructed with an abrupt, gradual or linear shape, based on our assessment. We came across the constructions working well, and less well. We have taken note of transition constructions that easily complies with the requirements for maintenance, demonstrated by the gradual change in stiffness in Drogdentunneln. Additionally, we have noted other constructions with a more abrupt change in stiffness, where the maintenance not seems to be sufficient, as for example the case with Nya Årstabron.

Jonsson (2014) explained that an abrupt, gradual or linear rate of change on the track stiffness is not good. Instead he recommends a stiffness change as the error function, alternatively versed sine to minimize the affect the dynamic forces have on the tendency for settlements in the transition zones.

Considering the theory Jonsson (2014) presents, we agree the significance of the change function to minimize the acceleration, and would recommend the application of these constructions. While we agree, we also contemplate on why these methods for changing the stiffness not have been applied in the transition zones we observed when researching and visited the sites of the reference projects. We consider the construction design with for example the error function, might be too advanced or expensive to construct, and that the transition zone not will be economically viable. However, we do not possess the knowledge regarding the construction/maintenance work, or the cost for such a construction, why we cannot point out a qualified conclusion of the adequacy to such a transition construction.

6 Conclusions

The transition construction is made as an action for equalising the stiffness between tracks with different stiffness and tendencies for settlements. The transition construction shall be constructed to lessen the dynamic forces in the transition zone.

We can conclude, there is no standardised construction made to fit all transition zones, due to the wide variety of aspects needing to be accounted for. It is only the soil conditions and creativity setting the limit for choosing transition construction.

The main maintenance methods used in transition zones are similar to those used in regular tracks today. In a well-constructed transition zone, the need for maintenance shall not differ significantly from the maintenance in regular tracks. A less well-constructed transition zone requires more maintenance in relation to the regular track.

The transition construction dictates how dynamic forces grow. Greater dynamic forces are the main reason for settlements, and lead to a more rapid track deterioration.

It is important to account for the current conditions, in particular the soil condition and the difference in stiffness between track systems. Also, it is important with communication and a high awareness between involved parties before the construction is made, as well as maintenance methods.

To build an effective transition zone, the geographical placement of the transition zone should be examined thoroughly and placed where the settlement tendency is lowest.

7 Recommendations for future studies

- The transition zones we have studied mainly use a gradual or linear change in track stiffness. In the paragraph 4.2.2 Theoretical experiences, Jonsson (2014) recommends the change to be built according to the error function. Therefore, we recommend further studies of how such a change in track stiffness would be applied in reality.
- The V-TRAS module is an interesting solution, but because of the short period of use we recommend follow-up and application.
- The transition zones we have studied have 200 km/h as the maximum velocity. With higher speeds, the dynamic forces increase, therefore, we recommend further studies of transition zones in high-speed lines as well as the difference of transition zones in low respectively high speeds.

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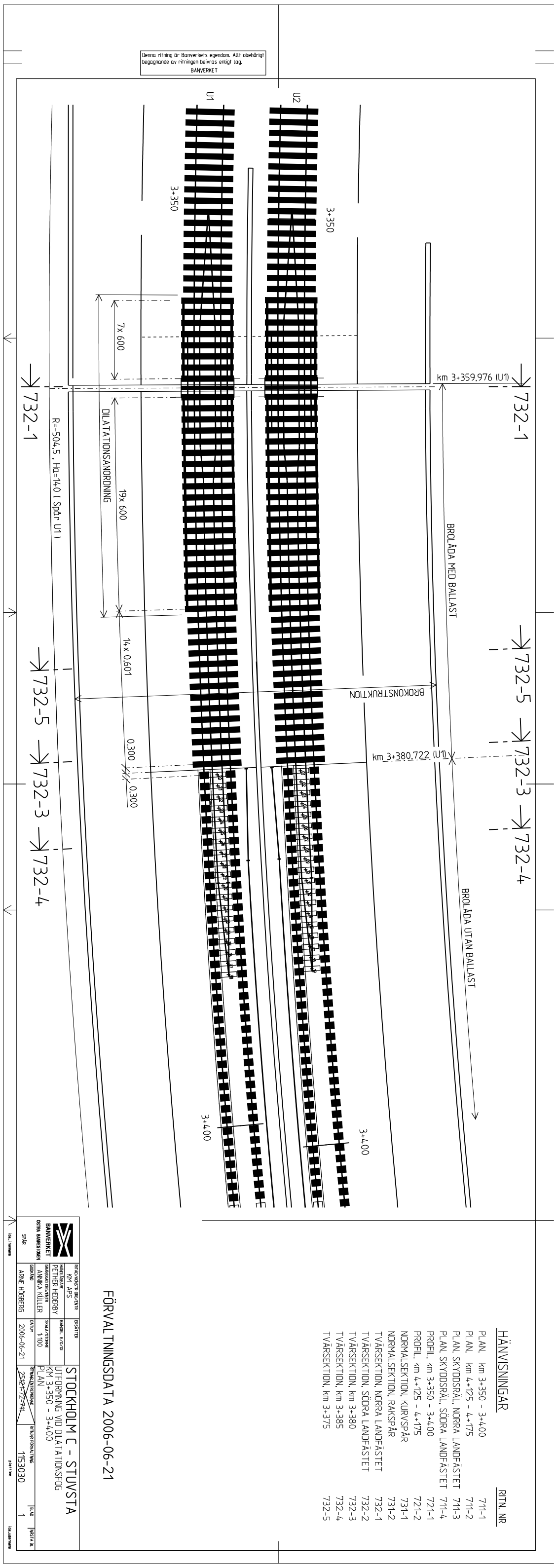
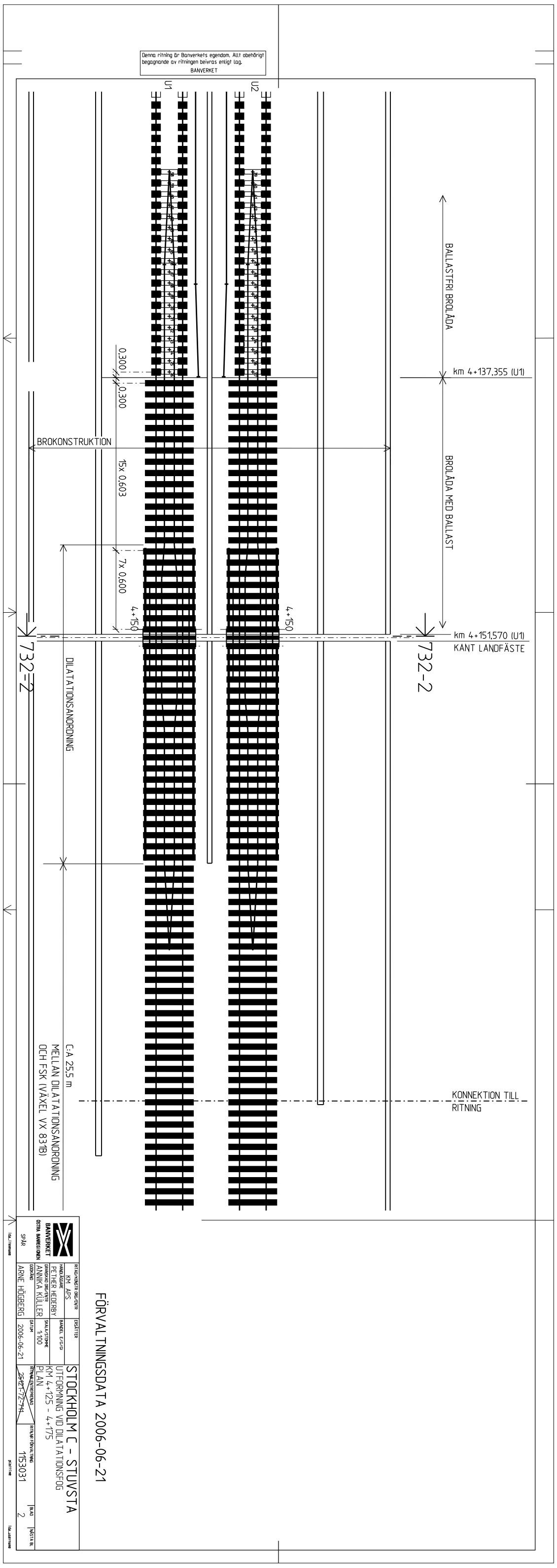
9 Appendix

9.1 Appendix 1



9.2 Appendix 2



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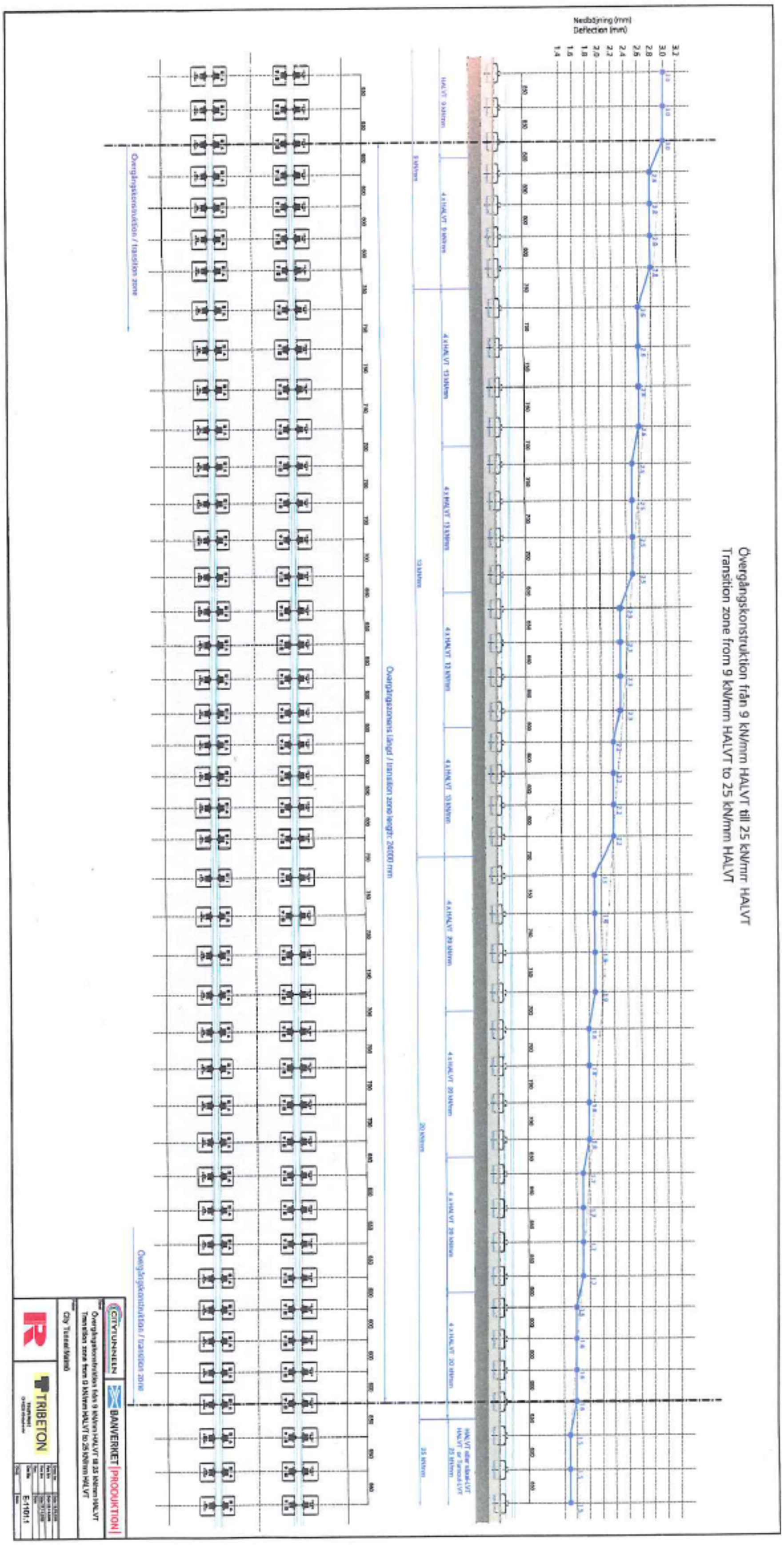

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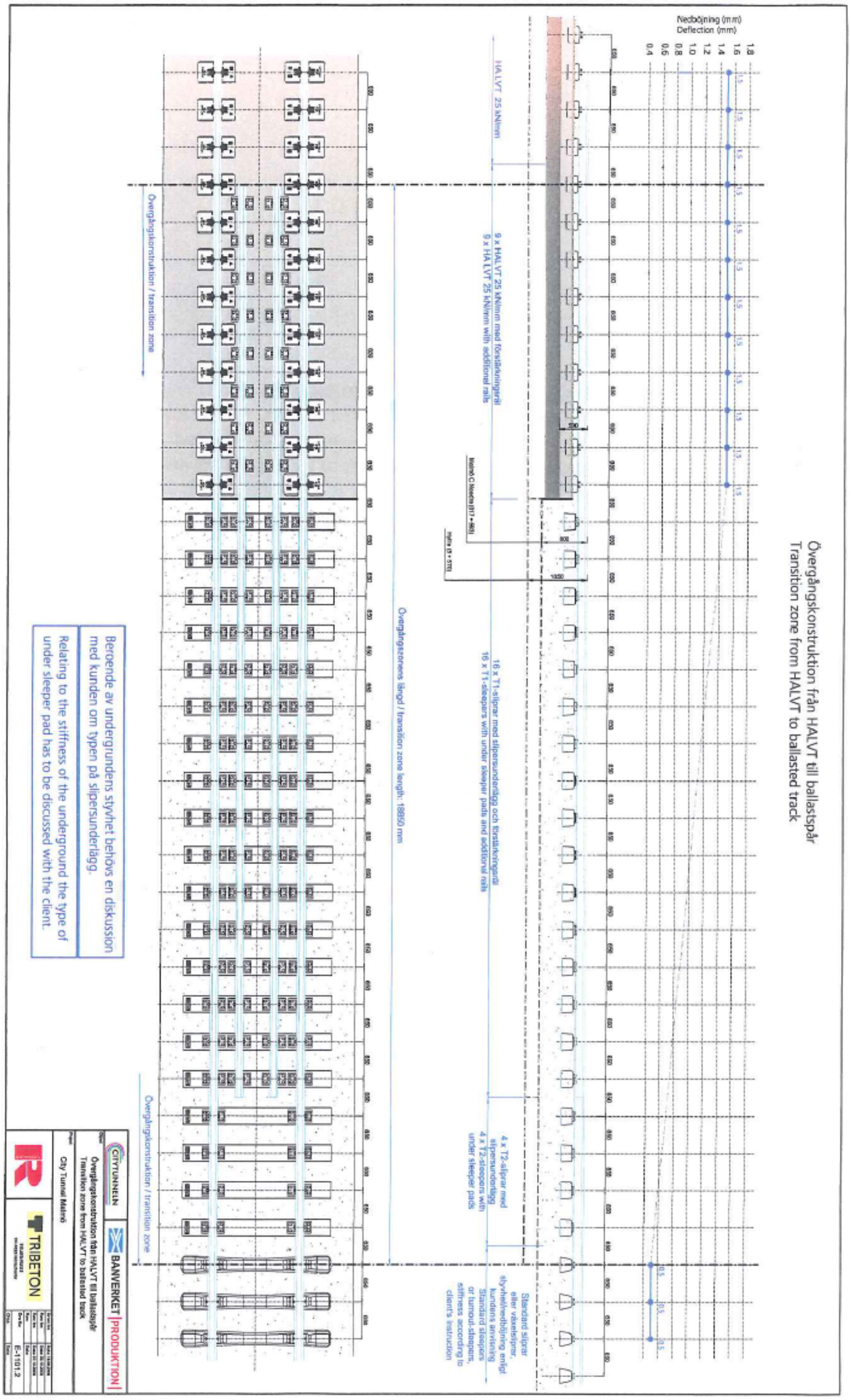
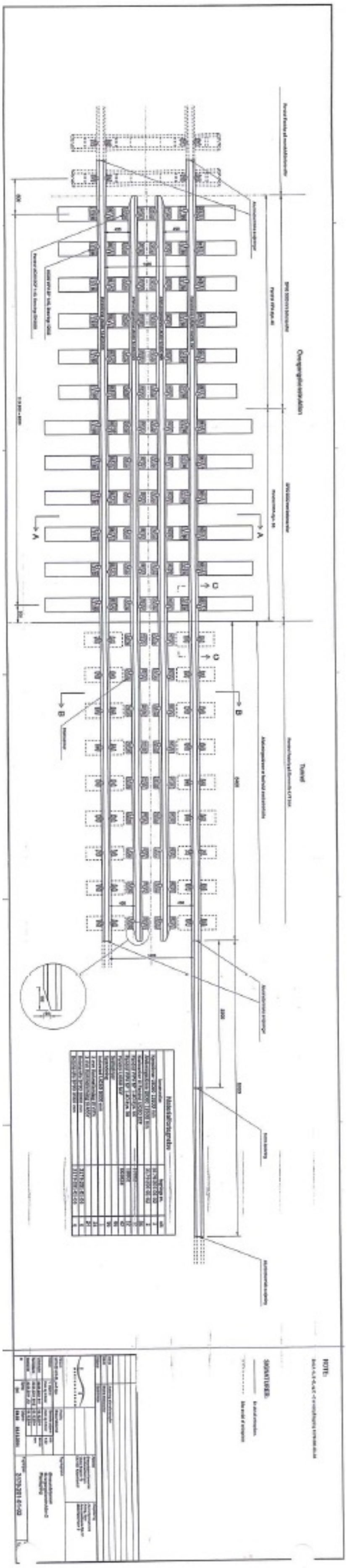


9.5 Appendix 5



9.6 Appendix 6