Green train

Concept proposal for a Scandinavian high-speed train

FINAL REPORT, PART B

Evert Andersson

KTH Railway Group, publication 12-02

Gröna Tåget

Trains for tomorrow's travellers

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Abstract

Gröna Tåget (English: Green Train) is a research and development programme, the aim of which is to define a concept and develop technology for future high-speed trains for the Nordic European market. The target is a train for **Scandinavian interoperability** (Denmark, Norway and Sweden), although the pan-European minimum standards must be applied.

Gröna Tåget is a concept for long-distance and fast regional rail services. It should be suitable for specific Nordic conditions with a harsh winter climate as well as mixed passenger and freight operations on non-perfect track.

Gröna Tåget delivers a collection of ideas, proposals and technical solutions for rail operators, infrastructure managers and industry. The programme aims to define a fast, attractive, environmentally friendly and economically efficient high-speed train concept based on passenger valuations and technical possibilities. Proposals do not take corporate policies into account as these may vary between companies and over time.

This is one of the final reports, specifying the functional requirements for the train concept from a technical, environmental and economic perspective, with an emphasis on the areas where research and development have been carried out within the Gröna Tåget programme. It is not a complete specification of a new train, but concentrates on issues that are particularly important for successful use in the Scandinavian market. It should be regarded as a complement to the pan-European standards. Research and development within the Gröna Tåget programme, including analysis and testing activities, are summarized. References are given to reports from the different projects in the programme but also to other relevant work.

Other summary reports deal with market, economy and operational aspects as well as a design for an attractive, efficient and innovative train from a traveller's point of view.

The main alternative proposed in this concept specification is a train for speeds up to 250 km/h, equipped with carbody tilt for short travel time on existing main-line track. The train is proposed to have high-power permanent magnet motors, low aerodynamic drag and modest adhesion utilization. It has low noise emissions and a track-friendly bogie design. The train should be equipped with active high-performance suspension to produce superior ride qualities on non-perfect track and minimize suspension motions. Due to the approximately 3.30 m interior width of the carbody, one more comfortable seat can be accommodated abreast, which will reduce cost and energy use per seat-km and also maximize the capacity of the train and of the railway system. One most important and critical issue is that the train must be able to run in a Nordic winter climate, where technologies have been tested, proposed and also compiled in a special report.

Most technologies developed can also be used for modified train concepts, such as non-tilting trains, trains for higher speeds than 250 km/h, trains with continental-width carbodies, and others. Further, many technologies developed in the programme are also useful for lower speeds. Newly developed technologies were type-tested in a special test train from 2006 to 2009. Endurance tests in commercial service were performed between 2009 and 2011.

Preface

Gröna Tåget (the Green Train) is a research and development programme, the aim of which is to define a concept and develop technology for future high-speed trains for the Nordic European countries, in particular for Scandinavia (Denmark. Norway, Sweden).

The programme was conducted between 2005 and 2011 as a collaboration between the Swedish rail infrastructure manager Trafikverket (formerly Banverket), the supply industry (Bombardier Transportation, Schunk and Liebherr), train operators SJ AB and Tågkompaniet, the train leasing company Transitio, as well as universities (KTH, Konstfack and Chalmers), other research institutes and consultants (VTI, Interfleet Technology, Transrail, Ferroplan, MTO). Vinnova (the Swedish Governmental Agency for Innovation Systems) has also supported the programme. The author wishes to acknowledge all these partners for their financial or in-kind support. He also feels a great degree of satisfaction at the great cooperativeness on the part of all partners being on both organizational and technical matters.

KTH (the Royal Institute of Technology, Stockholm) is responsible for coordination of the programme and the final reports, in addition to research in specific areas.

The programme has covered many important areas, for example economy, capacity and market aspects, conceptual design, traveller attractiveness, travel time, environmental issues, track friendliness and carbody tilt, winter operation needs, aerodynamics, electric propulsion, etc.

This report summarizes a great deal of research and development that has been performed in the Gröna Tåget programme. The various successful activities would not have been possible without the efforts of dedicated work package leaders, researchers, engineers, decision-makers and others. The author wishes in particular to acknowledge the following participants in the programme:

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Stockholm, January 2012

Evert Andersson
Programme co-coordinator

Content

Definitions and abbreviations

AC	Alternating current; i.e. the current flows in alternating directions, a new cycle or period occurring at a specified frequency.
ATC	Automatic Train Control; name for the Swedish ATP system.
ATP	Automatic Train Protection. Automatic system assuring that the train stops or reduces speed as required by the signalling safety system. ATP intervenes by braking the train if the train driver does not apply brakes in due time.
Banverket	Formerly 'Swedish National Rail Administration', now part of Trafikverket (Swedish Transport Administration).
Blended bake	Braking effort is provided by both the electric brake and the mechanical brake. Usually the electric brakes are used to its maximum performance, while the mechanical brake provides a supplement to achieve the desired braking effort.
Bombardier Transportation	Supplier of trains, train control systems and related services, with subsidiary in Sweden.
Cant (of track)	Height difference between the outer and inner rails in a curve. Normally the outer rail is at a higher level than the inner rail, in order to compensate for the lateral acceleration (or centrifugal force) due to the circular path of the train in the curve. Track cant is measured between the rail centre lines.
Cant deficiency	Additional track cant that is needed in order to neutralize the lateral acceleration (or lateral centrifugal forces). Cant deficiency is proportional to the lateral acceleration as measured in the track plane. A lateral acceleration of 1.0 m/s^2 is equivalent to a cant deficiency of 153 mm on standard gauge track.
Catenary	Electric wire(s) above the track, in order to supply current to an electric train.
Chalmers	Technical University in Gothenburg (Göteborg), Sweden.
Creepage	Sliding velocity between the rail surface and wheel rolling forward.
DC	Direct current; i.e. the current flows always in the same direction.

Eco-driving	Driving style that minimizes energy use and usually also brake pad wear.
EMU	Electrical multiple unit, i.e. a train unit consisting of self-propelled cars powered by an electric drive system.
EN	European standards.
ERTMS	European Rail Traffic Management System, being the new all-European system for safe train movements, signalling and radio communication.
Extended travel time	Reference travel time (see below) plus an additional margin for eco-driving, to be used if the train is not running late.
GHG	Greenhouse gas.
Ideal travel time	Same as 'reference travel time'; see below.
Interfleet Technology	Consultancy company with subsidiary in Sweden.
Konstfack	University College of Arts, Crafts and Design, Stockholm.
KTH	Royal institute of Technology, Stockholm.
LCC	Life Cycle Cost
Load factor	Same as 'seat occupancy rate', i.e. occupied seat-km (passenger-km) divided by the total number of performed seat-km of a train. Load factor is usually determined as an average of a period of time.
MBS	Multi-body system, usually mentioned in the context of mathematical modelling and simulation of mechanical systems.
Mechanical brake	Non-electrical braking means, such as disc brakes and tread brakes, both dependent on the wheel rail adhesion (friction).
Multiple unit train	Train unit usually operating in a fixed consist.
Nordic (countries)	In this report: Denmark, Finland, Norway and Sweden.
Pantograph	Current collector on the roof of a train.
Pkm	Passenger-km.
PM	Permanent Magnet (in this report: in a motor).
Primary suspension	Suspension (springs, linkage, dampers, etc.) between wheelsets and bogie.
PRM	People with reduced mobility

Reference travel time	Fastest possible travel time, assuming maximum acceleration and deceleration (within the performance limits of the train) as well as maximum line speed otherwise. Another word is 'ideal travel time'.
Regenerative braking	Braking with traction motors (see below) used as electric generators, with a system feeding electric current and energy back to the catenary and to other trains.
Scandinavia	Denmark, Norway and Sweden.
Secondary suspension	Suspension (springs, linkage, dampers, electro-hydraulic actuators, etc.) between bogie and carbody.
Service mass	Empty (tare) mass of the train, plus what is necessary to operate the train, usually driver and 2/3 of maximum mass of consumables (mainly water and food for catering).
SJ AB	Swedish passenger train operator.
Standard gauge (track)	Track gauge of 1,435 mm between the inside of the rails.
Sway	Combined lateral and roll motion of a train
Scheduled travel time	Reference travel time, plus margins for delayed departures, reduced driver and train performance as well as occasional disturbances due to the traffic situation along the line.
Tilt	The carbody leans toward the inside of the curve, in order to reduce the lateral acceleration (lateral force) experienced by the passengers due to the centrifugal effect.
TSI	Technical Specification for Interoperability (in Europe).
Traction	Propulsion, i.e. driving the train forward.
Traction motor	Motor for propulsion (traction) of a rail vehicle.
Trafikverket (TRV)	Swedish Transport Administration.
Transrail	Swedish consultancy company.
Tågoperatörerna	The Association of Swedish train operating companies.
UIC	International Union of Railways
Unsprung mass	Vehicle mass in direct contact with the track, with no suspension in between, i.e. wheels, axles and others.
Vinnova	The Swedish governmental agency for innovation systems.
X2	Swedish high-speed tilting train with a maximum operating speed of 200 km/h, in the marketing formerly named *X 2000*, recently changed to *SJ 2000*.

Part I

Introduction, infrastructure and climate

1. Introduction

1.1 What is Gröna Tåget?

Gröna Tåget is Swedish and means ’the Green Train’. It is a research, development and demonstration programme, the aim of which is to define a concept and develop technology for future high-speed trains, technically suitable for the Nordic European countries. These includes Sweden, Norway, Denmark, Finland and possibly also the Baltic states. The primary focus will be on Scandinavia, which includes Denmark, Norway and Sweden.

Gröna Tåget delivers a collection of ideas, proposals and proven technical solutions for operators, infrastructure managers and industry. Gröna Tåget is a proposed train concept, including a number of technical solutions, for improved and cost-effective fast long-distance and regional passenger services. The programme will not produce a prototype train, but purchasers of future trains will in cooperation with industry decide what proposals and technology will ultimately be used.

For attractiveness to travellers, a number of factors are highly important, all of them addressed in the Gröna Tåget programme. These include:

- Short travel time
- Low total operation cost for operators and for private travellers, enabling low fares
- High frequency (i.e. short interval between train departures)
- Good service and comfort for travellers
- High capacity and safety
- High reliability and availability, in particular in the harsh Nordic and Scandinavian winter climate and after collision with wild animals.

The most important ‘green’ effect is that the train has a high market share, because of electric trains’ superior performance regarding energy use and its related emissions. The above-mentioned points are therefore very important. In addition, it is also highly desirable that the train has other favourable characteristics, despite increased speed, such as

- Low energy use per passenger-km
- Low noise emissions
- Track friendliness (modest track deterioration and ability to run on non-perfect track)

Gröna Tåget makes it possible to improve productivity in the passenger rail sector and increase rail transport’s market share in an important segment. This will strengthen economic development as well as mobility and prosperity in society. If such a train is successful and increases its market share over other transport modes, it will also contribute to a more sustainable transport system.

To meet the challenges and attain the goals described above, the Gröna Tåget programme has covered a great many important issues, in particular the following:

- Economy and market aspects
- Capacity
- Conceptual design
- Attractiveness, functionality and comfort for travellers
- Energy use
- Noise emissions, both external and internal
- Track-friendly bogies and suspension
- Carbody tilt
- Requirements for winter operation
- Aerodynamics, in particular air drag and stability at cross winds
- Electric propulsion – new motor and pantograph technology
- Safety and driver's environment
- Standards for European and Scandinavian countries

The programme has conducted fundamental analysis and research on the different issues as well as development, design and testing of new technology. Most of these technologies have been type tested in a specially rebuilt test train – REGINA 250 – between 2006 and 2009. Also, for almost three years, from 2009 to 2011, a number of crucial technologies underwent functional and endurance testing in commercial service.

The test train has set a number of new Swedish speed records, of which the most recent was set in September 2008 at a speed of 303 km/h. This was achieved on standard track and overhead catenary on the Swedish Western Main Line, where top speeds in normal daily operations are in the range of 160–200 km/h.

Tests were performed in cooperation between Bombardier Transportation, Trafikverket, Schunk, the operators SJ AB and Tågkompaniet as well as the train leasing company Transitio. KTH and Interfleet Technology also participated in the type testing.

Figure 1-1 REGINA 250 test train – part of Gröna Tåget programme

1.2 Intended use of Gröna Tåget

As stated earlier, Gröna Tåget is a train for long-distance and fast regional services.

- ’**Long-distance**’ means that a majority of travellers spend more than 1.5 hours on the train for a single journey. Many also spend one or several nights away from home; considerable space for heavy **luggage** is therefore needed. **Catering** facilities for provision of hot meals of appropriate quality are also considered necessary.
- ’**Regional**’ means that most travellers make a round trip without an overnight stay. A typical journey has a duration of 20–90 min. The need for luggage storage and food service is comparatively low, although some drinks, refreshments and snacks should be available. Requirements concerning comfort, functionality and possibilities to work are about the same as for long-distance due to the needs of regional commuters.

In some cases, operators may want to combine long-distance and regional services in the same train, or use the same train for different types of services on different occasions. This requires a compromise between the number of seats and other facilities.

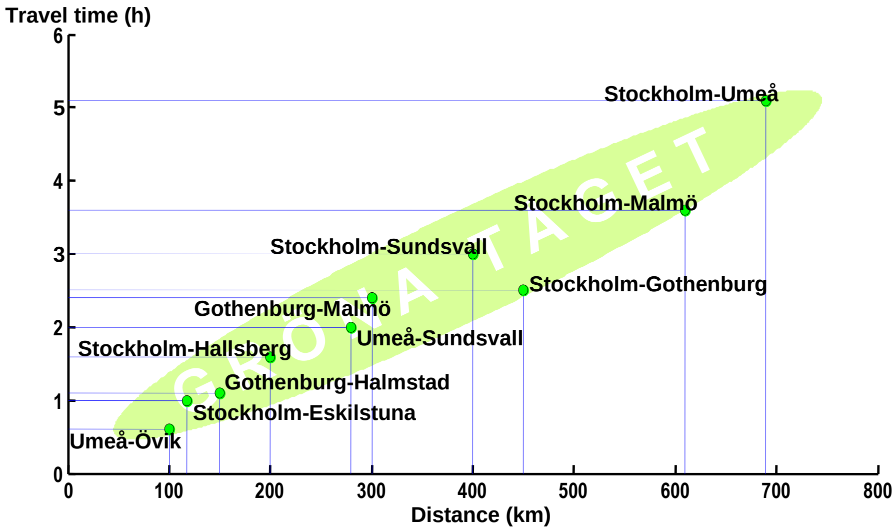

Figure 1-2 Travel time and distances – some Swedish examples

The main use of Gröna Tåget, at least until 2025, will be on existing lines with mixed passenger and freight operations. Many of these lines have a considerable number of speed-limiting curves. In order to achieve minimum travel time on these curvy lines, trains must be able to negotiate curves at extra high speed and consequently high lateral acceleration. Carbody tilt (inwards in curves, for passenger comfort) and specially designed track-friendly running gear (to avoid too high forces and wear on the track) are therefore needed. Other lines, built since 1990, have higher standard.

The target maximum speed is 250 km/h on conventional existing mixed-traffic lines. The Gröna Tåget concept and technology shall also allow operation on future new high-speed lines, mainly dedicated for fast passenger services. Special versions of the train should allow for speeds in the range of 280–320 km/h.

On conventional lines, Gröna Tåget will typically allow some 9–10% shorter travel time than present fastest train services (by *X2* in Sweden 2011). In addition to new trains the present rail infrastructure must also be upgraded to allow for higher speeds and increased capacity.

A detailed description of the intended use of Gröna Tåget is found in Fröidh [2].

1.3 European standards and specific Scandinavian requirements

The European railway standards according to TSI (Technical Specifications for Interoperability) [N1−N7] and European Norm (EN) must be followed as long as it is appropriate for the specific Scandinavian conditions. Besides legal requirements, this is desirable from several aspects: interoperability, proven components and systems, reliability, cost, etc.

However, TSI and EN are generally written as minimum requirements. In reality there are no trains that just meet TSI standards and nothing more. TSI is to a large extent written as a compromise between the large railway entities in Europe, in order not to disqualify any of the existing trains or railway networks in central or southern Europe. Specific demands with higher requirements must be identified and defined.

In the Nordic market, including Scandinavia, there are some obvious additional requirements as regards reliability and performance in **winter climate** as well as **braking deceleration,** the latter due to comparatively short pre-warning distances with existing national signalling systems on conventional lines.

By tradition, the Scandinavian requirements for **travellers with reduced mobility** are in some respects higher than current TSI specifications. Further, TSI contains no specifications regarding **operational cost** issues or **energy use** and is brief for **passenger comfort and functionality** – all of which are crucial to successful environmentally friendly train operation with high market share. Requirements concerning **track friendliness** are modest in the TSI.

Running time performance is not part of TSI, except that a (very moderate) starting acceleration is required. Further, nothing is said about damage and repair time after **collisions** with objects on track, in particular large animals.

All these limitations and deficiencies of the current TSI and EN are not necessarily a disadvantage and should not be criticized, but demonstrate the need for additional requirements to be identified and defined.

On Nordic electrified railways it is possible to allow **wider carbodies** (0.5–0.6 m) than on the continental European rail network. This is an opportunity to create a spacious interior, allowing either considerably higher comfort or more seats for a given train length, the latter by adding one more seat abreast. Additional seats reduce the number of cars for a given seating capacity, thus considerably reducing operational cost and energy use per seat-km. For the same number of cars, seating capacity can be enhanced by approximately 25%. Done in an appropriate way, such an arrangement should still be attractive for travellers' comfort and functionality. A low-cost and eco-friendly wide-body train concept achieving **Scandinavian interoperability** is therefore a main alternative in Gröna Tåget. However, most principles and most technologies developed within the Gröna Tåget programme are also useful with continental-width carbodies.

There are many issues where requirements additional to TSI are either necessary or desirable. On the other hand, the TSI and EN specifications can and should be used without exceptions or additions in a large number of cases. **This report will mainly focus on issues where additional or higher requirements are necessary or desirable.**

In this context the definition of different classes of trains and infrastructures, as given in TSI, should be mentioned:

- **Class 1** high-speed trains have a maximum speed of 250 km/h or more;
- **Class 2** high-speed trains have a maximum speed of between 190 and 249 km/h.

These trains can be

- articulated or equipped with two conventional bogies per car
- single-deckers or double-deckers
- carbody tilting or non-tilting.

Trains run on different categories of high-speed rail infrastructure:

- **Category I**: Specially built high-speed lines for speeds of 250 km/h or more;
- **Category II**: Upgraded high-speed lines for speed in the order of 200 km/h;
- **Category III**: Upgraded high-speed lines with special features due to topographical or other constraints, on which the speed must be adapted to each case.

Note that lines of Category II and III may have top speeds up to 249 km/h.

Note also that all high-speed trains must also be able to run on the connecting conventional rail network designed for lower speeds.

A summary of TSI and specific Scandinavian requirements, in particular for Sweden, is given in Leander [5].

In the Gröna Tåget programme and in this report, it is proposed that future trains have features according to the highest requirements in the range of 240-260 km/h. In most cases, requirements for Class 1 trains are higher, but on some issues Class 2 is the most demanding. In general, the difference between Class 1 and 2 is modest. In most cases the higher standard can be motivated whether the permissible speed is 240, 249, 250 or 260 km/h. For example, on-board detection of wheelset bearing health can be motivated for safety reasons, regardless of the speed limits mentioned above.

2. Infrastructure and environment

2.1 Rail infrastructure - overview

In general the existing rail networks of the Nordic countries are used for **mixed passenger and freight services.** On some lines, particularly in Sweden and Finland, 25 tonnes of axle load is allowed for freight trains, which in combination with frost upheaval may partially cause a relatively low track geometry quality. Most lines (counted in line-km) are single-track lines, although the intended operation of Gröna Tåget (in car-km) is expected to be run mainly – but not only – on double-track.

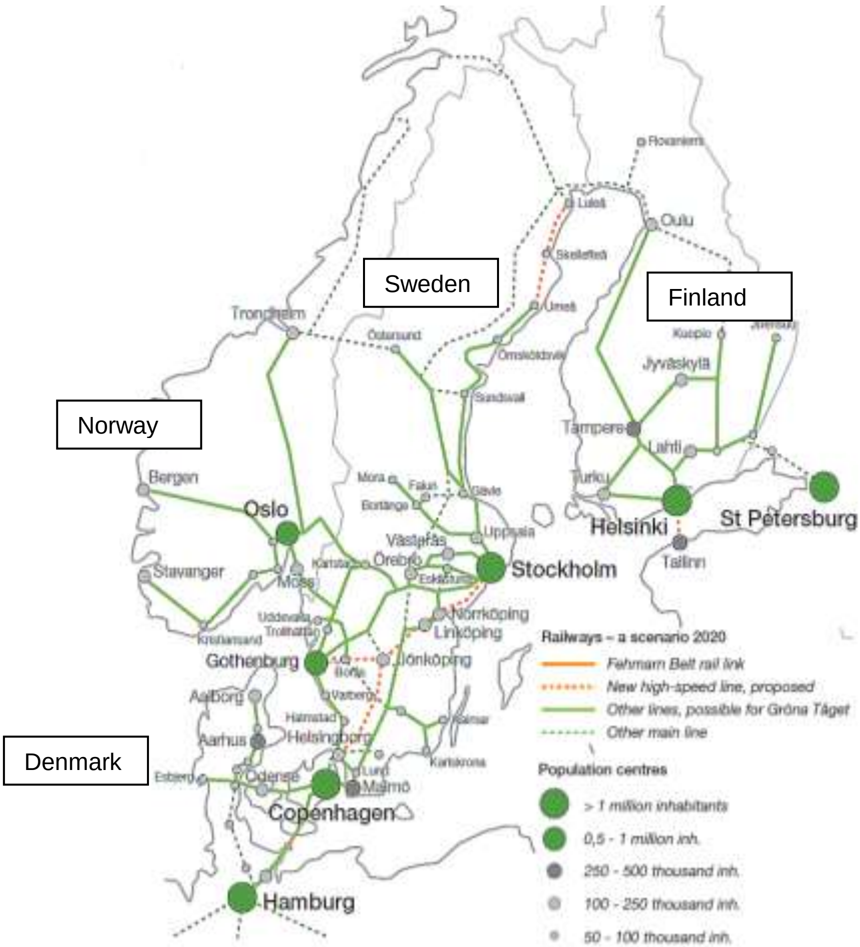

Figure 2-1 Main lines in Nordic countries, where Gröna Tåget would be suitable for operation. Possible connections to northern Germany and St Petersburg (Russia) and two proposed high-speed lines for speeds of at least 300 km/h are also shown. Ref: Fröidh [2].

Characteristics of the railway environment are described in Sections 2.2 and 2.3.

A target within the Gröna Tåget programme is to achieve **Scandinavian interoperability**, i.e. the same train can operate in Denmark, Norway and Sweden. Most other conditions, except the Finnish broad gauge, are similar in Finland and Scandinavia. However, a true interoperability is not possible with Finland.

The main technical characteristics of the Scandinavian railways are summarized in Sections 2.4–2.9. In particular the Swedish rail infrastructure is specified, with some notes on other Scandinavian networks. The latter is to be investigated and described more thoroughly as a separate task outside the Gröna Tåget programme.

2.2 Climate

In comparison with the European continent south of the Baltic Sea, the climate is characterized by long winters with cold and snow. In the southern half of Sweden, the average temperature is usually below zero (i.e. freezing temperatures) for 3-4 months. In northern Sweden, Norway and Finland, average temperatures (where railways exist) may be below zero for about 6 months. Since these conditions are normal and common in the Nordic region, **rail operations must continue regardless of the weather,** possibly with short interruptions for snow clearing and similar activities.

Although there may be winter days with temperatures above freezing in southern Sweden, it is common that freezing temperatures **persist continuously for several weeks** or even longer. This implies that snow can accumulate on a train for a long period of time, without melting naturally. Short train visits in above 0 °C conditions may worsen the situation, see below.

A number of specific severe situations occur frequently during the winter period:

- **Fine-grain snow** whirls around the train and penetrates into all available cavities and openings, in particular resulting from the air pressure from speed; See for example Figure 2-3.
- Train operations will be subject to **low temperatures**. The Swedish Transport Agency requires rolling stock approved for the whole of Sweden to be operable between **-40 and +35 °C**. For operation in only some parts of Sweden, the lowest required temperatures are shown in Figure 2-2.
- Sudden **temperature changes** of up to 30 °C are very common when trains enter tunnels and workshops. Occasionally, changes up to 60 °C occur.
- At **temperatures around zero**, heavy snowfall may within 2 hours of operation cause large amounts of snow to stick to the train;
- If **snow accumulation is partly melted** (occasionally in workshops or a few hours of operation in thaw, or temporary in long tunnels) snow turns to ice. A repeated number of such occasions may build up large amounts of snow and ice on the train. As a consequence, movements (for example in the brake system, in suspensions or moveable footsteps) may be blocked;
- Snow in combination with **strong winds** is common in parts of the Nordic countries (in particular Denmark, southern Sweden and mountain regions in Norway). This may cause trains to run into massive **snowdrift accumulations** on the ground, in particular where the line passes cuttings in soil or rock.

A more detailed review of climate conditions can be found in Kloow [13] and in Section 5 of this report.

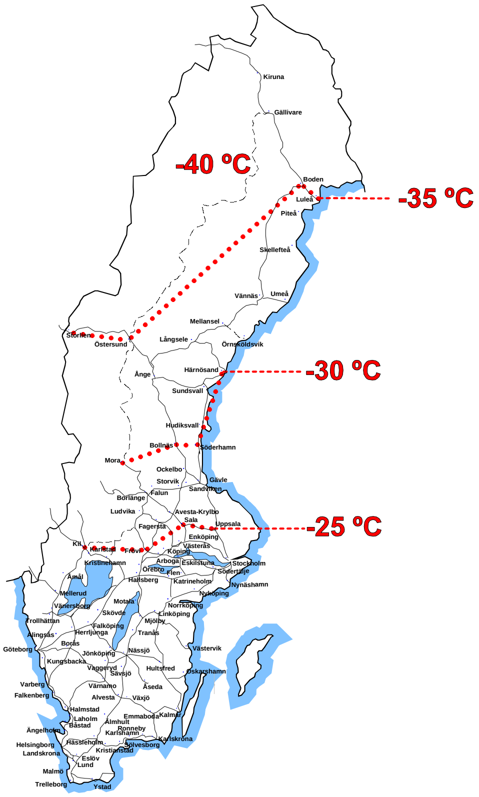

Figure 2-2 Lowest required operational temperatures in parts of Sweden.
Source: Swedish Transport Agency

Figure 2-3 Snow smoke whirling around a high-speed train passing a station at a speed of about 180 km/h. Source: Transrail [13].

2.3 Obstacles on track

Nordic railways are only partly fenced. Wild animals on the track are therefore part of the railway environment. These animals vary enormously in size, from rabbits and birds, through medium-sized deer and wild boars, up to 2.5 m tall elks.

It is proposed that challenging animals be classified into two groups, i.e.

- **Medium-sized animals**: with centre of gravity lower than coupler height (about 1.0 m), with a maximum mass of 200 kg. Examples: deer, reindeer and wild boars.
- **Big animals:** with centre of gravity of up to 1.7 m above top of rail with a maximum mass of 700 kg. Example: elks and runaway cattle.

For permissible speeds above 200 km/h we propose that fences be erected along the railways to keep animals off the track.

See also Section 2.7 on level road-railway crossings.

2.4 Track

Track construction

For high-speed operation above 200 km/h, the track is laid with 60 kg/m rails on concrete sleepers. In Sweden, an elastic pad approximately 12 mm thick is placed in-between. For speeds up to 200 km/h, 50 kg/m rails on thin stiff pads are also used; in Norway and Denmark, also 49 and 54 kg/m.

Ballast level and ballast pick-up

To prevent ballast pick-up when a train is passing and ice blocks from the train fall on the track, the upper level of ballast is usually laid 30-40 mm below the upper surface of the sleepers.

Nominal track gauge

Denmark, Norway and Sweden: 1,435 mm (standard gauge); Finland: 1,524 mm.

Rail inclination

The nominal rail inclination inwards towards the track centre is

Denmark, Finland: 1:40; Sweden: 1:30; Norway: 1:20

Horizontal curves, *R*

Existing lines have **horizontal curve radii** ranging from 250–300 m (especially in Norway) to 600 m (some sections or lines in Sweden) and further to 900–1,600 m (most old main lines in Sweden and Denmark). In particular, curves of 980–1,200 m radius currently restrict speeds on the two busiest main lines (Stockholm-Gothenburg and Stockholm-Malmö). New or upgraded lines, built from 1990 onwards, usually have curves of $\geq$ 2,000 m radius, although there are exceptions. Curves and curve combinations on switches and in yards are not part of this specification.

Cant, *D*

Maximum track cant D is 150–160 mm in all Scandinavian countries, which is within the limits specified in EN 13 803-1 [N12].

Permissible cant deficiency, *I*

The limit on cant deficiency is to a large extent related to passenger comfort. For **non-tilting trains**, carbody lateral acceleration of about 1.2 m/s² is considered acceptable. For vehicles with passive suspension, this means that a permissible cant deficiency of ***I* = 130–168 mm** could be allowed in the speed range of 80–250 km/h (where highest speed implies lowest *I*) according to EN 13 803-1. Slightly higher values could be accepted for vehicles with active suspension because of the reduction in carbody low-frequency yaw and lateral motions. In particular, trains with **active lateral suspension** eliminate the need for reduced permissible cant deficiency as a function of speed up to at least 250 km/h (see Section 8.5). Vehicles with active carbody roll control may have further increased permissible cant deficiency.

The target carbody lateral acceleration for **tilting trains** must be set lower than for non-tilting trains to make the combination of lateral acceleration, lateral jerk and roll velocity acceptable for the passengers. According to today's knowledge, a target of about 0.8 m/s² combines good passenger ride comfort and low risk of motion sickness. For a train with "full tilt", this corresponds to a cant deficiency ***I* of 275 mm**, which is also the recommended limit for speeds lower than 250 km/h in EN 13 803-1. A cant deficiency of 306 mm could be accepted as a maximum to be used (if necessary) to maintain speed in isolated curves.

Vertical curves, R_v

In Sweden, the minimum vertical radius *R* along the line is determined according to permissible speed V_x (km/h):

$R_v \geq 0.16\ V_x^2$ (m), corresponding to a vertical acceleration of 0.48 m/s².

Outside yards, vertical curve radii usually range from 2,000 m and up; on the main lines they are seldom less than 10,000 m.

Permissible vertical acceleration

In Sweden, the permissible acceleration due to vertical curves as described above is limited to 0.48 m/s². This is in line with the exceptional limits in EN 13 803-1, which accepts 0.59 m/s² for hollow curves. The recommended limit in the EN is 0.22 m/s².

Horizontal curves also contribute to the vertical acceleration perceived by passengers. In particular this refers to tilting trains, where the carbody floor may have an angle of up to about 12 degrees relative to the horizontal plane. This may produce an additional vertical acceleration (perpendicular to the carbody floor) of 0.43 m/s². Note that the contribution from horizontal curves and tilting always increases the vertical acceleration, i.e. felt as an increased downward force. Combining horizontal and vertical curves is therefore more critical on hollow curves than on a crest.

Track geometry quality

Measures and quantities for defining the geometrical positional quality of the track are divided into **vertical** and **lateral** directions as well **as track gauge**, **cross level** and **track twist**. Definitions of the different quantities are given in the European standard EN 13 848 [N13]. Vertical quality is often called "**longitudinal level**". Lateral quality is often called "**alignment**".

Future trains must be designed to cope with the minimum standard of EN 13 848. This standard is mandatory only for safety-related measures of track quality, with ultimate limits called Immediate Action Limits (IAL).

Most railways also define quality levels that are relevant for track deterioration, maintenance policies and life-cycle cost, as well as ride quality and comfort for travellers. Limit values for these quality levels are stricter than safety-relevant levels, but usually non-mandatory. In Sweden, several investigations have been made, both outside and inside the Gröna Tåget programme; for the latter see Karis [12].

Based on Swedish practices and studies, including research and tests within the Gröna Tåget programme, a preliminary standard according to Table 2-1 is proposed as safety- and comfort-related quality levels for speeds higher than 200 km/h. For comfort, the proposal can be seen as target levels to achieve good comfort in state-of-the-art high-speed trains. Note that Table 2-1 is not a complete specification.

Table 2-1 Track geometry quality limits proposed for high-speed lines.

- For safety: According to EN 13 848-5, Immediate Action Limits
- For comfort: Target levels proposed in the Gröna Tåget programme

Geometry quantity	*Speed range (km/h)*	*FOR SAFETY Wavelength (m)*		*FOR COMFORT [e] Wavelength (m)*		
		3-25 [a]	*25-70*	*3-25 [a]*	*25-70*	*70-150*
Vertical deviation, mean-to-peak max (mm)	231–300[e]	±16 [d]	±28	±4	±6	±10
" standard deviation (mm) [b, c]	201–300[e]	–	–	1.3	2	4
Lateral deviation, mean-to-peak max (mm)	231–300[e]	±10 [d]	±20	±3	±5	±10
" standard deviation (mm) [b, c]	201–300[e]	–	–	1.3	2	4
Cross level deviation, mean-to-peak (mm)	201–300	–		±4 for all wavelengths		
Twist at 3 m base, mean to peak (mm/m)	201–300	±5		±4 for all wavelengths		
Track gauge – mean over 100 m, min (mm)	201–230	1,433		1,435		
" " "	231–300	1,434		1,435		

[a] The current Swedish standard considers wavelengths in the range of 1–25 m, also containing a high-frequency content, generating brief but possibly high impact forces between wheels and track

[b] 95th percentile of standard deviation, to be determined over distances corresponding to the evaluation in EN 14 363 [N10]. This is also according to EN 12 299 [N11], Annexes D and E.

[c] 50th percentile levels of standard deviation are proposed to be 40% lower than the 95th percentile.

[d] Deviations are 22–35% lower in acceptance tests, according to EN 14 363, level QN3.

[e] For speeds up to 250 km/h some 20 % higher limits could be accepted for comfort.

Cold and frost upheaval: Norway, Sweden and Finland usually have 3–6 months of average temperatures below zero, which cause frost and – during winter and spring – frost upheaval in some locations. This means that the geometry quality of the track may sometimes locally be worse than proposed as the target level for comfort above. However, safety levels according to EN 13 848 must always be respected.

2.5 Electric power supply

This is not a complete specification of the electric supply system. Some of the most important main characteristics are mentioned below. Further details are specified in EN 50 163, EN 50 367, EN 50 388, NES TS 01 and NES TS 02. The NES documents are compilations of the relevant characteristics and requirements for the Nordic rail networks except Denmark.

Characteristics of the power supply may in many respects not be compliant with the TSI or EN specifications. In particular this is true for Norway and Sweden, which have power supply systems with fundamental characteristics from early electrification. It is considered to be prohibitive for cost reasons to make a change. Denmark and Finland have more modern systems.

Voltage and frequency

The nominal voltage (r.m.s.) and frequency are

- 15 kV – 16 2/3 Hz in Norway and Sweden;
- 25 kV – 50 Hz in Denmark and Finland.

Maximum and minimum voltages, as well as frequencies, are specified in EN 50 163. In Sweden and Norway, the maximum voltage allowed is 17.5 kV r.m.s. according to NES TS 02 [N18]. This is due to existing vehicles being limited to this voltage.

Current

For general unrestricted use, the maximum current drawn from the catenary is limited according to EN 50 388 [20] and NES TS 02 [18]:

- Sweden and Norway 900 A.

For Sweden, the above-mentioned maximum current of 900 A is not an absolute limit. Swedish lines with modern supply systems have a capacity of at least 1,200 A. In addition, trains are usually supplied from two directions, although not everywhere all the time. In a long train consist (say 3 units of Gröna Tåget, each utilizing 4,800 kW tractive power, plus losses and auxiliary power), the maximum current will be about 1,200 A at 14.5 kV. If the voltage drops below 15 kV, the current could be limited by the train. See also Section 9.4.

Voltage distortion and other specific requirements

A number of detailed specific requirements for electric rail vehicles operating in Norway and Sweden are stated in NES TS 01 [N17]. They are sometimes in accordance with EN or TSI, but there are also many national specific cases. These requirements deal among other things with

- allowed inrush current of vehicle transformers
- allowed power factor and reactive power
- requirements for telecommunication, signalling and track circuits
- neutral sections of the catenary
- voltage distortion and current harmonics
- low-frequency power oscillations
- exterior antennas.

In particular, considerable distortion in the supply voltage may occur. Details and examples of this issue are specified and shown in NES TS 02, Clause 4.3.3.

Catenary

The overhead electric catenary in Sweden usually has tension forces of 7–11 kN (lowest in the messenger wire, i.e. the upper supporting wire) for speeds up to 200 km/h. However, tension forces on new and upgraded lines are usually 15 kN in both the contact and the messenger wires.

The types of catenary design in Sweden are denoted by

- the absence or presence of a 'Y' (example ST and SYT respectively), where 'Y' denotes a stitched catenary (see Figure 2-4 lower) and absence of 'Y' denotes a simple sagged catenary
- Two numbers (for example 7.0/9.8) denote the tension force in the messenger and contact wires, respectively.

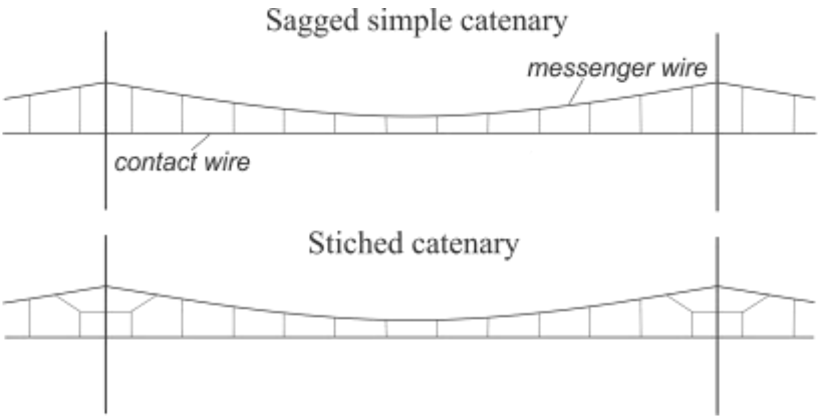

Figure 2-4 Catenary principal designs

Table 2-2 Types of catenary in Sweden

Notation of catenary type	Max speed (km/h)	Tension force (kN) Messenger	Tension force (kN) Contact	Area (mm^2) and material of contact wire
ST 7.0 / 9.8	180	7.0	9.8	100 Cu
SYT 7.0 / 9.8	200	7.0	9.8	100 Cu
ST 9.8 / 11.8	200	9.8	11.8	107 Cu
ST 15 / 15	250[a]	15	15	120 Cu+Ag
SYT 15 / 15	250	15	15	120 Cu+Ag

[a] At speeds of 220–250 km/h suitability is yet not confirmed for multiple operation with three pantographs.

2.6 Signalling and train control

This section on railway signalling has focus on the conditions in Sweden. The situation in the other Nordic countries is shortly described after the text on Sweden.

Automatic signalling blocks and **Centralized Traffic Control** (CTC) is introduced on all main lines. In contrast to many other European countries the signalling on double tracks is fully **bi-directional,** permitting maximum speed and capacity for both tracks in both directions. Double tracking thus is arranged as "two single lines located close together". The cross-overs between UP and DOWN tracks are frequent, often in the order of 10 km apart. This system design has had a substantial impact on train operation and reduction of maintenance costs:

- The time table planner and the train dispatcher have full authority on how to use the tracks. Both tracks can be used for trains in the same direction; for example for faster trains overtaking slower trains or used in parallel when the need for capacity is unsymmetrical. Capacity is also less affected at traffic disturbances.
- During off-peak hours, e.g. 09–15, or during evening or night time, efficient track maintenance is possible as one of the tracks be made free for maintenance, with track workers and heavy yellow machines.

Automatic train protection (ATP)

In Sweden a national-wide **ATP system** (called ATC) is used, Signalling information is transmitted at discrete locations via so-called **balises,** using a high frequency magnetic coupling. ATC transmits

(1) Fixed signalling information such as the basic line speed, "never exceed speed", gradients and target distances;

(2) Variable information such as basic permitted speed in the closest signal, basic permitted speed in the next signal, target distances as well as status of level crossings, moveable bridges, etc.

The track-dependent information is processed by the ATC equipment in the train, also using information of the train itself, such as current speed, permitted maximum speed, permitted (%) of over-speeding, actual brake pipe pressure, braking performance and train length.

The ATP (ATC) calculates a **speed envelope** taking the most restrictive conditions into account at every time. If the driver does not brake the train in due time the ATC equipment will automatically brake the train to a safe speed. The driver will be warned 13, 8 and 3 seconds in advance of the ATC brake intervention.

In Sweden this system is currently used for speeds up to **200 km/h**, although some installations for speeds up to 250 km/h exist. From a technical point of view the ATC could be used after adjustment and certification for higher speed, as ATC is originally specified for speeds up to 300 km/h. Of legal and policy reasons, based on the decision of European interoperability, it is however anticipated that the all-European ERTMS system will be used for speeds above 200 km/h; see below.

It is possible to increase the train speed above the basic line speed by a special **over-speeding function** in the ATC. Trains with superior vehicle-track interaction are allowed to run faster. Currently the basic speed in Swedish curves is based on a cant deficiency of 100 mm (Category A trains), while a second step (Category B trains) is allowed to run at 150 mm of cant deficiency. A third speed is used for tilting trains (Category S trains), currently allowed to run at 245 mm of cant deficiency in Sweden. This function is flexible, so a new class with another allowed cant deficiency can easily be added after approval.

For speeds above 200 km/h the all-European **ERTMS/ETCS - Level 2** is anticipated. Level 2 means that ordinary track circuits are used for train detection and positioning, but optical signals are replaced by radio transmission directly to the drivers desk display. However, Level 1 (with optical signals) will be used in complex station areas. All Nordic countries have decisions to introduce ERTMS. The implementation has started on the newly built Botnia line in Northern Sweden.

In order to handle the long transition time from the national ATC to ERTMS the train units will be equipped with a Specific Transmission Module (STM) for the existing ATC making the ERTMS equipment capable of reading and interpreting the existing signalling messages.

Minimum braking deceleration

Due to the wish of high capacity, signalling distances are generally short in Sweden. The ATC system has functions for *speed-step* signalling as well as *distance-to-go* signalling. The capability of the ATC system is combined with a requirement of a **higher rate of braking deceleration** compared to the European TSI. To generally run on the Swedish network a **minimum deceleration of 1.07 m/s²** is therefore required for a permissible speed of 200 km/h [N22, 5]; see further Section 12.

If the train has less braking capability, the ATC system as well as the ERTMS system will reduce the permitted speed in order to safeguard that a signal in danger will not be compromised and to maintain the necessary warning time for the driver.

Norway, Denmark and Finland

Norway uses the same ATP system as Sweden. There is operational and technical interoperability between the two countries, although some aspects in the signalling systems are somewhat different. Norway has also started implementing ERTMS.

The signalling system in **Denmark** has a very different layout when it comes to signal aspects. However the functionality in the signalling system is about the same as for the rest of the Nordic countries. The ATP system is also different but contains many of the functions found in the other Nordic ATP systems. Cross-border operation over the Øresund Bridge has made it possible to develop a change-over function implemented in additional hardware and software. At full speed of 180 km/h the ATP switches from Swedish to Danish and vice versa. The highest percentage of Nordic double tracking is found in Denmark. Denmark has also taken advanced steps for implementing ERTMS as a part of a nationwide signalling renewal programme.

The signalling system in **Finland** is also different compared to the Swedish signalling system. The ATP is however very much based on the later version of the Swedish/Norwegian ATP with some additional functions necessary for Finland. As the track gauge is different compared to the other Nordic countries, a true interoperability is not possible, although basically the same type of train could be used.

2.7 Level crossings

Level road-railway crossings are most common in the Nordic countries. The level crossings represent a most hazardous interface to the public. Nordic countries have more or less common challenges on how to reduce the number of level crossings as the cost for replacement like road traffic diversions, bridges, etc. is high.

In Sweden many level crossings are integrated in the ATP system. Sweden is also unique by permitting 180–200 km/h train traffic on lines with level crossings. A part of this strategy is that the 200 km/h high-speed train class X2 has higher collision strength than is common for rolling stock.

The integration of level crossings in the ATP (ATC) is done by giving the train a basic stop message that the level crossing is open to road traffic, i.e. the train must stop before the crossing. This message can be cancelled if certain safe conditions apply; see below.

For train speeds above 160 km/h there is an electromagnetic circuit in the crossing, checking whether a road vehicle is standing over the track. This system is logically connected to the ATP system, so that trains are stopped in case that an obstructive road vehicle is present in the crossing, i.e. the basic stop message is not cancelled in this case. The same applies if the barriers are not indicated to function properly. However, a road vehicle infringing the track by breaking the barriers may collide with a train if the train is close to the crossing.

On these lines where line speeds are high or if there is a wide span of train speeds it is often necessary to activate the level crossings in a suitable, not too long, time before the train arrives at the crossing. Otherwise some road travellers are expected to violate the stop signs and barriers. Activation of the barriers (and ATP cancellation of stop messages) is dependent on the actual train speed

For speeds above 200 km/h it is expected that no level crossings exist.

2.8 Platforms

Platform length at stations where high-speed trains are expected to make regular stops is generally in the range of 225–400 m, at least for some tracks at each station. At these stations shorter platforms may also exist, although long high-speed trains are expected to use the longer platforms.

(1) In Norway, some stations have platform lengths of 210 m. With a few metres' extension of these platforms, two 4-car trainsets (full-length carbodies; see Section 3.3) with a total length of 216 m can be used.

(2) In Sweden, some stations on the Laxå−Charlottenberg line (Sweden–Norway from the east) have 225 m platforms, also mentioned in the High-speed TSI as an exception for Sweden. Otherwise, a minimum of 250 m is used at all relevant Swedish stations. 250 m is also standard on some lines in Norway.

(3) 320–355 m is the minimum platform length at most mainline stations in Denmark, Finland, Norway and Sweden. With a few metres' extension of the 320 m platforms (Denmark, Finland) they could be compatible for three 4-car trainsets (full-length carbodies, see Section 3.3), or two 6-car trainsets with a total length of 322–324 m. In any case, doors used by passengers are expected to stay within the 320 m limit.

Platform height (nominal) in the Scandinavian countries is usually 0.55–0.76 m. Lower platforms (0.25–0.36 m) exist but it is anticipated that future high-speed trains will not approach these.

Proposal

It is proposed that platforms of length 210 and 320 m be extended a few metres as described in (1) and (3) above.

For platforms with waiting travellers, where trains are expected to pass at speeds higher than 200 km/h we propose that special arrangements be made on the platforms, for example barriers as well as acoustic and/or flashing visual alarms. For further detailed information**;** see Fröidh [2].

2.9 Vehicle and structure gauge

The existing rail networks in the Nordic countries have unique gauges for the surrounding structures and for the permissible exterior cross-section of rail vehicles. In general, a vehicle must meet the gauges in the countries where it is used and a vehicle for cross-border operation must therefore meet more than one gauge. The European railway standard according to TSI (Technical Specifications for Interoperability) has proposed gauge G1 to ensure pan-European interoperability. All Nordic countries, however, have larger gauges than G1 and a vehicle for the Nordic countries, utilizing the benefits of the larger gauges, will therefore exceed G1.

Normative gauges for Finland, Norway and Sweden are part of the European standard, described in EN 15 273 [N14, N15]. Gauges for these countries are always compatible with requirements for G1. Note that the gauge of vehicles is part of the infrastructure issues, as there is a close relation between infrastructure and vehicles.

Figure 2-5 (left) shows the Swedish reference gauge SEa and gauge G1 for continental Europe according to EN 15 273-2. However, a correct comparison between gauges must also consider the associated calculation rules and structure gauge widening in curves, which may have considerable influence on vehicle exterior size. In practice, a vehicle with the same carbody length and bogie centre distance as conventional passenger coaches may have a carbody width of about 2.89 m designed for G1 and about 3.50 m designed for SEa.

An interesting question arises if double-decks and/or wide carbodies are to be used in the Nordic countries; the result of a study is reported in Table 2-3. Double-decker vehicles are theoretically possible even in the G1 gauge, although with a very limited height of the interior ceilings. The French TGV-Duplex uses the somewhat larger gauge FR3.3, but limits the ceiling height to 1.90–1.95 m. In gauges G2, SEa and DE1-DE3 double deckers can generally be used with a ceiling height of 2.00–2.05 m.

The Gröna Tåget concept includes carbody tilt, which is not compatible with a double-decker. Wide-body single-deck vehicles offering comfortable 3+2 seating in second class are only possible in Sweden according to the general gauging rules. However, general acceptance may not be necessary as the vehicles in question will run on electrified main lines, where additional infrastructure space is often provided.

Investigations in Norway made by Jernbaneverket show that wide bodies can be allowed on all electrified main lines if some minor infrastructural improvements are made. Double-deckers with 2.00 m ceiling height can be allowed on selected routes. Investigations in Denmark within the Gröna Tåget programme, made in cooperation with BaneDanmark and supported by Danish Trafikstyrelsen, focus on the distance between adjacent tracks. The investigations so far show positive results for the use of wide bodies. Further investigations and formal acceptance remain to be made.

Table 2-3 Maximum carbody width and height for a vehicle with carbody length as for conventional coaches.

		General acceptance		*Acceptance on selected routes*	
Country	*Gauge*	*Vehicle height*	*Vehicle width*	*Vehicle height*	*Vehicle width*
Europe	G1	4.28 m	2.85 m	-	-
Sweden	SE1	4.75 m	3.45–3.54[a] m	-	-
Norway	NO1	4.42 m	3.35–3.44 [a] m	4.60 m	3.45–3.54 [a] m
Denmark	DKFjern	4.60 m	3.26 m	4.60 m	3.45–3.54 [a, b] m
Germany	DE1	4.60 m	2.85 m	-	-

[a] Possible width is preliminary, based on conventional passive suspension (lower limit) and active suspension (higher limit).

[b] Investigation is on-going in Denmark (Dec 2011).

There are different means to improve the carbody width. The first option is to reduce the bogie distance, as in an articulated train configuration. As an example, a reduction from 19 m to 15 m allows 0.136 m more carbody width. The second option is to reduce the displacement in vehicle suspensions. A modified lateral suspension including a Hold-Off-Device (HOD, see Section 8.7.3) will allow about 0.09 m increased carbody width. The latter case is shown as the higher figure in Table 2-3.

Proposal

A non-tilting double-decker vehicle can run in Sweden, Denmark, Germany and into the capital of Norway. A tilting wide-body vehicle can run in Sweden, on electrified Norwegian mainlines and probably most electrified main lines in Denmark. Such vehicles with active HOD can preliminarily have a carbody size as in Figure 2-5. Known obstacles in Denmark have been considered and use on mainlines in Norway would only require a limited number of infrastructural modifications.

The proposed width at 1.7−1.8 m above top of rail is 3.54 m and the maximum height is 3.8 m. This cross-section is designed for operation in the non-tilting mode in Denmark. A further alternative may be to allow the train to run in tilting mode also in Denmark. This will however reduce the width in the upper parts of the carbody.

Investigations in Denmark are to be completed. Formal approval must be done but this is outside the scope of the Gröna Tåget programme.

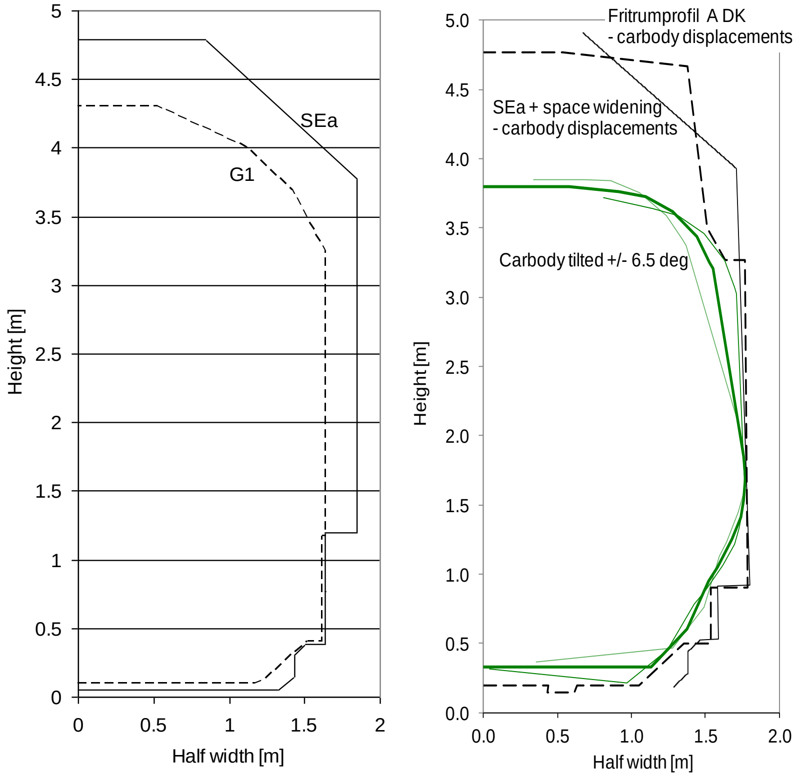

Figure 2-5 **(left) Reference gauge SEa (Sweden) and gauge G1 (Continental Europe).**

(right) Possible exterior cross section of a wide-body train for Sweden, electrified main lines in Norway and probably Denmark.

Lateral and vertical vehicle displacements and tolerances have been deducted from the reference gauges.

Part II

Functional requirements and conducted research

3. Train size and formation

3.1 Economic considerations

One of the main goals of Gröna Tåget is to **reduce operational cost** per seat-km or passenger-km (pkm), primarily to make it possible to reduce ticket prices and thus increase market share. Reduced cost also goes hand-in-hand with improved productivity and is likely to improve profitability for rail operators using the Gröna Tåget concept. In the future, large parts of the railway market in Europe are expected to be deregulated in the sense that different operators will compete for travellers on the same lines. In any case rail operators will compete with airlines and private cars. This situation implies that **profitability will be highest for the operator that offers an attractive journey at the lowest cost.**

There are a number of means to reduce cost, while still maintaining a high level of comfort, functionality and attractiveness to passengers. Very important means are:

- **Reduced travel time.** This will – on average – reduce cost for operators, due to improved utilization of both the rolling stock and the train crew (more kilometres can be produced for essentially the same utilized resources).

  Cost elasticity is usually around 0.4 in the average speed range of 130–170 km/h; for example, 20% shorter travel time reduces total cost by 8%.

  It should further be noted that reduced travel time will also increase traveller's willingness to pay, or to take the train instead of other transportation, or take a trip by train instead of not travelling at all. This will strengthen the income side of the account.

- **Higher load factor**; i.e. more paid passenger-km (occupied seats) relative to the offered number of seat-km.

  Cost elasticity for the actual high-speed train services is in the order of –0.8. For example; if the load factor is increased from 50% to 60% (20% increased passenger occupancy), the total cost per passenger-km is typically reduced by about 16%.

- **Improved space utilization.** A simple key parameter for trains, where travellers are expected to have a seat, is the number of seats per metre of train.

  For high speed trains with distributed power (so-called EMUs), cost elasticity is usually in the order of –0.6; for example 20% greater space utilization reduces total cost (on average) by about 12%.

There are also other means of reducing per-unit cost. For example, if the procurement cost per (comparable) train is reduced by 20%, the total cost is reduced by approximately 6%.

If train maintenance costs are reduced by 20% (from 20 to 16% of the total), total cost is reduced by about 4%.

Figure 3-1 shows the approximate cost reductions if different factors are changed by 20%. This is for the change of single factors, within the range of average speed etc as is typical for the mentioned high-speed operations. It should also be noted that the combination of different factors will not necessarily just add cost reductions. Such combinations could make cost reductions both stronger and weaker. Nevertheless, Figure 3-1 clearly indicates what factors are most important to change and improve.

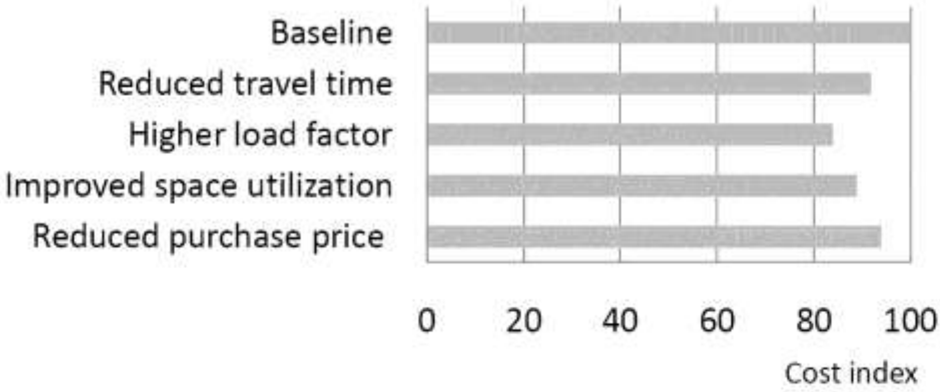

Figure 3-1 Approximate cost reduction if different factors are changed by 20%, as single measures without changing the others.

The economic considerations are more deeply elaborated in ref [2, 3].

Applying the main alternative of the Gröna Tåget concept (see Section 3.2–3.4), the total cost per seat-km can be reduced by about 20%, in relation to current services with the Swedish high-speed train X2. With somewhat higher average load factor – due to a flexible train concept according to Section 3.3 – and an increased number of seats per average train, the cost per passenger-km may be reduced in the order of 25%.

3.2 The use of wide-body trains

It is shown in the previous section that space utilization is a key parameter to reduce total cost in passenger train operations. If more seats are accommodated in the same length of train, the cost per produced seat-km can be reduced.

European long-distance high-speed trains have on average about 2.2 seats per metre train (up to 2.6 in double-deckers). Many of these trains have less than 2 seats per metre. This should be compared with Japanese high-speed trains (Shinkansen), which usually accommodate 3.3 seats per metre in single-deckers. This is despite very generous leg room in Shinkansen trains. There are several reasons for Japanese superiority in this respect: (1) a rational seat arrangement in rows (as in airplanes and buses), (2) a catering service by trolley bars (i.e. there is no dedicated restaurant car), (3) multiple units with distributed propulsion instead of having separate locomotives, and finally (4) **wide carbodies**, allowing one more seat to be placed abreast. This means that 1st class seats are arranged 2+2 (with a small table between two seats) instead of 1+2, and 2+3 instead of 2+2 in 2nd class. This arrangement increases the number of seats per car or metre of train by about 25% in a mixed 1st and 2nd class version.

A similar increased number of seats (20–35%) could be achieved by **double-decker trains**. Trains with distributed power (i.e. located in passenger cars) tend to perform at the lower end (20%) because propulsion equipment must be located in potential space for passengers. Further, only one deck can be accommodated above the bogies anyhow, and double-deckers need space for stairs etc. In trailer cars with no propulsion equipment, more seats can be accommodated, but this will require a separate power unit.

The double-decker option is successfully used in some European high-speed trains, specifically the French TGV Duplex hauled by a locomotive at each end and double-decker trailers in-between. However, double-deckers are not suitable for trains with carbody tilt for at least two reasons: (1) the high carbodies must be very limited in width in their upper parts, otherwise the tilt motion would cause excessive displacement outside the allowed space; (2) the high centre of gravity is not suitable for curving at very high lateral acceleration, due to risk of overturning at strong cross-winds.

For Gröna Tåget **a wide body train is chosen as the main alternative,** although **options with normal continental width are also possible within the concept.** If an **interior width of at least 3.3 m** can be provided in a wide-body train, this option will increase the number of comfortable seats per metre of train by about 25% compared with continental-width carbodies. The target is to create a train concept for **Scandinavian interoperability**, being able to run on electrified lines in Sweden, Norway and at least parts of Denmark.

The suitability and success of one more seat abreast is conditioned by two factors:

(1) that the percentage increase in cost for more seats is considerably lower than the percentage increase in the number of seats;

(2) that the increased number of seats will not considerably reduce the average traveller's willingness to pay or to go by train.

In Figure 3-2 the two options are presented, i.e. the main alternative with a wide-body train (left) and a double-decker with continental width (right).

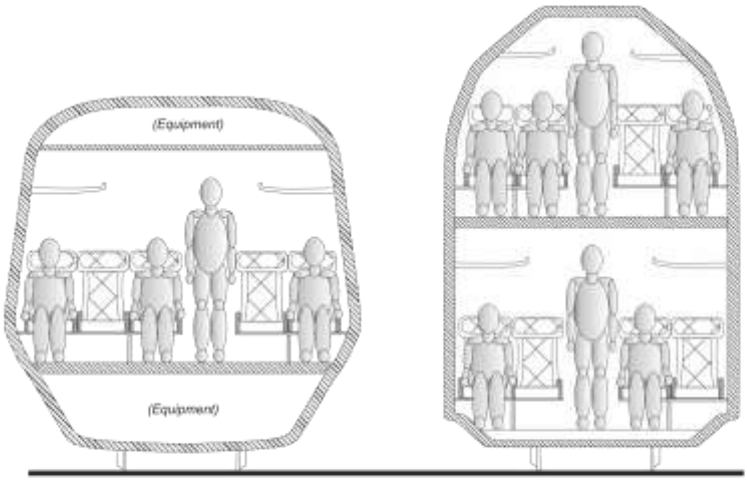

Figure 3-2 Wide-body (left) and double-decker with continental width (right)
Both alternatives offer some 20-30% more seats (per metre of train) compared to a single-decker with continental width.

After a cost analysis within the Gröna Tåget programme it is estimated that the operating cost (including capital cost, maintenance, crew, energy, track charges, administration, sales and stations) of running a wide-body train with 25% more seats is 5–8% higher than for a conventional single-decker train of ordinary width. The resulting **total cost** per seat-km is estimated to be **about 15% higher** for a single-decker train of conventional width than for a wide-body train. This means that the per-seat-km cost will be 13% lower for a wide-body train as defined above. This is elaborated in more detail in Fröidh [2].

The second issue mentioned above is whether travellers' willingness to pay will be reduced by having one more seat abreast. Several investigations referred to in Kottenhoff [3] have shown that the average willingness to pay is very moderately reduced by 1–2% for the single measure of having one more seat abreast on one side in 2nd class. This is a small change in relation to many other factors that will change willingness to pay by 5–10%. The slight disadvantage can easily be neutralized by other positive features, such as slightly **increased leg room** and/or **individual foldable arm rests**. The second improvement is important for travellers' comfort and perception of privacy, and is therefore proposed for the Gröna Tåget concept.

There are several reasons why wide-body trains with 2+3 seats are quite well accepted by most travellers:

(1) Some travellers prefer spontaneously to sit abreast in a group of three, for example three young people or a small family of two adults and a child;

(2) Most of the time there is an empty seat in the middle of a group of three which will improve the feeling of space and privacy;

(3) The "visual impression of space" in the interior seems to be valued positively, although the value is difficult to quantify.

A more detailed description and discussion on this issue is presented in Kottenhoff [3]. It is also further described and exemplified in Section 6.3 of this report.

The main conclusion is that an interior with one additional seat abreast will be accepted by most travellers. The average traveller does not care very much as long as this arrangement is executed in a proper way. It is more an issue of cost and environmental performance as well as of transport capacity.

3.3 Flexible capacity

High-speed train units are usually quite long, containing some 7–8 cars with a total of 400–500 seats, forming a standard European high-speed train. A shorter train unit has several benefits:

- **Capacity can be changed according to actual demand,** by coupling or decoupling of shorter train units. At peak hours with high demand a fixed train consist may have too little capacity, while its capacity may be too high during low-demand periods. This is not optimum from an economic point of view and it is not even optimum in order to meet travellers' demands.

  There is a risk that the step of adding another 400–500 seats is too big even during high-demand periods, thereby missing additional travellers. There is also a risk that train departures during low-demand periods will be cancelled due to a too big train for the actual need, also missing a number of travellers. Finally, **two multiple 7- or 8-car trains will be too long for many existing platforms.**
- Two shorter train units within the same train path **enable the two parts of the train to have different destinations or origins.** This would **save line capacity** on the most highly utilized track sections and allow travellers to have **direct train service** to different destinations without the drawback and disappointment of changing trains along the way. The advantage for the passenger of avoiding a change can result in about 20% more travellers on that route [2] and thus increased income and market share.

The disadvantage is that the total cost per seat-km is estimated to be 3–4% higher with 4-car units instead of 6-car consists. This is due to the extra cost for the driver's cabin and also the loss of seats for the space occupied by each cabin. This is included in cost estimations per seat. With a flexible train concept, however, the load factor can be raised and some travellers will avoid changing trains, which is estimated to compensate for the cost several times over.

The proposed main alternative for Gröna Tåget is a train unit comprising 4 full-length cars, with a total length over couplers of about 108 m. These units can be combined into trains with 8 cars and even 12 cars. Gröna Tåget can also be arranged as trainsets with 5–6 cars, although the benefits of flexible train units will be lost.

Combinations of 4-car units suit the existing platform lengths on Scandinavian main lines quite well, cf. Section 2.8. Almost all existing stations on these lines have platforms of approximately 225, 250, 320 or 350 m minimum length; the 320 m platforms should possibly be extended a few metres in the case of 12-car trains. Two multiple 6-car units are suitable for the 320 and 350 m platforms, but not for 250 m platforms. The latter is quite usual on stations in Sweden and Norway.

A 4-car wide-body train (see Section 3.2) will allow some 280–340 seats, depending on the level of comfort and service provided – dedicated regional versions will probably need less space for catering and luggage and possibly also fewer toilets. A 12-car train, made up of 3 train units as described above, accommodates some 840–1,020 seats, the latter in a dedicated regional version. The total train length will be about 324 m.

For a more detailed description and motivation of alternatives, see Fröidh [2].

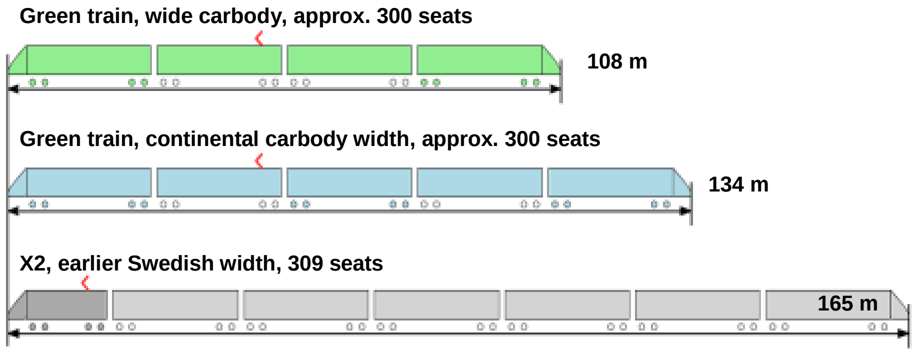

Figure 3-3 Main alternative of Gröna Tåget (4-car full-length wide bodies) in comparison with 5 cars (with continental width) and with the current Swedish high-speed train X2. All trains are single-deckers.

3.4 Convenient entrances

Gröna Tåget must be designed to minimize dwell time at stations and improve punctuality, in particular during holiday periods with many families travelling. Doors, vestibules, luggage racks and aisles must be designed for short boarding and alighting times with many travellers, large amounts of luggage and also people with reduced mobility. The latter include disabled people and also travellers with baby prams. See further [2] and Section 6.1. For these purposes, the following issues are crucial:

- An appropriate number of doors should be available along the train and no entrance should serve considerably more traveller flow than others;
- The free opening at doors should have sufficient width for convenient passage of travellers with two pieces of luggage, which requires 0.8–0.9 m;
- A maximum of two steps between platform and interior floor is preferable, but for platforms of 0.5–0.7 m height it may be necessary to have three steps of moderate height, covering a total height difference of about 0.5–0.6 m;
- Areas inside the doors should be arranged for a continuous flow of travellers, without being stopped by luggage handling or similar.

Travellers with reduced mobility

- On each side of a trainset one entrance shall be accessible with a wheelchair. This entrance should preferably be level in relation to a platform height of 0.55–0.76 m with a maximum of 0.05 m gap and height difference. From a traveller's perspective, it would be best to have a variable height of the vestibule floor, but a lift platform on the train may also be acceptable.

3.5 Configuration of carbodies and running gear

Gröna Tåget has several options regarding the arrangement of running gear and carbody length. These options are shown in Figure 3-4 below.

- **Two bogies under each carbody**. Bogie centre distance is 17.5–19 m. Distance between intermediate couplers is usually 25–27 m. This concept is called **full-length cars**, designated (L) in the following.
- Two **carbody ends are supported by the same bogie**, except at the ends of the train unit. This concept is usually called '**articulated train**'. Distance between bogie centres is usually 16–19 m. This concept is designated (A) in the following.

  Fewer bogies are required. In addition, the geometric overthrow in curves is reduced, if the shorter distance between bogie centres is chosen. This increases the allowed carbody width, in particular in Denmark and on the European continent.
- **Semi-trailers**, i.e. some cars have two bogies at the ends of which adjacent car-bodies are also supported. Distance between bogie centres is usually 12–15 m. This concept is designated (S).

  The geometric overthrow in curves is further reduced and carbody width can be further increased.

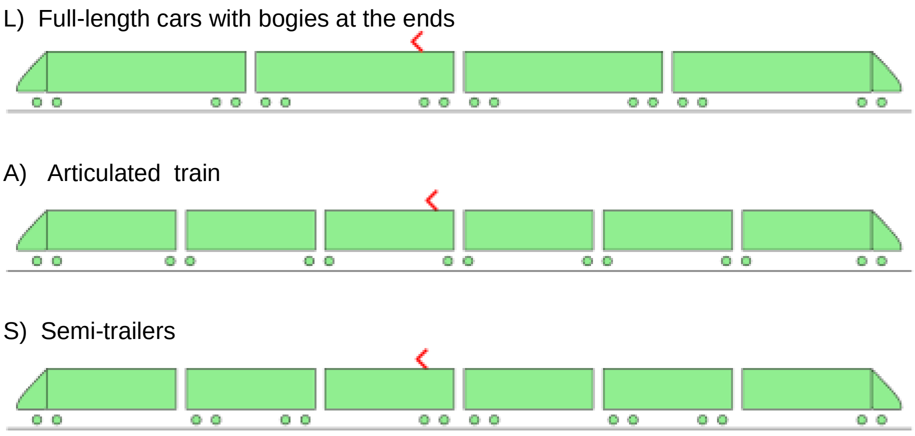

Figure 3-4 Possible train configurations for motor coaches, i.e. train units with distributed power

All the above configurations can principally be used within the Gröna Tåget concept, although the first concept (L) is usually shown in the different chapters and figures.

In all configurations it is proposed that the **pantograph** – or pair of redundant pantographs – is located above bogie No 4 in the train. By this means the minimum distance between pantographs in multiple trainset operation will be at least 100 m.

4. Travel time performance

Travel time performance must be seen in the perspective of the value of travel time, for the travellers and for the train operator. Travel time performance should also be seen in relation to energy use and wear on brakes and other subsystems. The cost of installing power for acceleration and braking must also be considered.

4.1 Many factors influence travel time

In addition to cost, travel time is the most important factor in attracting travellers to go by train. Travellers are usually willing to pay extra for saving travel time. Generally shortened travel times will also allow trains and train crew to produce more kilometres per year; i.e. productivity will improve.

It is **door-to-door travel time** that is most important to travellers. Over long or intermediate distances the time spent on the train constitutes a large proportion of the total door-to-door time. **Average travel time** on the train – or the inverse **average travel speed** – is therefore crucial to traveller's patronage. The average travel speed is in turn dependent on a number of factors, as listed below. For a given number of stops it is essential to have:

- high top speed (if applied to a large part of the run)
- high speed otherwise (for example incurves)
- high rate of acceleration and deceleration
- quick alighting and boarding at stations – to minimize dwell time

At least the two first 'speed factors' depend on both the train and the rail infra-structure. A number of technical factors may more or less limit the speed along the line and various speed restrictions are common. The third and fourth factors (acceleration/deceleration and dwell time) are mainly dependent on the train. The influence of the last two factors also depends on the **number of stops.**

Travel time performance can be calculated taking all the above factors into consideration, thereby achieving an **ideal reference travel time** that represents the **fastest possible run** with the actual train on the actual line, without any time margins. However, in all train operations **time margins** are needed to cope with unplanned stops or speed restrictions at signals, track work along the line, etc. Further, departures may be delayed and permitted speeds are not always applied – for many reasons.

The time margins needed depend on the quality of planning, the reliability of trains and infrastructure and of the time precision and discipline that train crews and dispatching staff are able to deliver. On the Swedish main lines the minimum time margin is some 5–7%, but in most cases higher margins are needed in order to keep the timetable with reasonably high probability. On long-distance routes on Swedish double-track main lines, a time margin of at least 8–10% is used instead. Further margins are applied if the line is single-track or if many train operations along the line are tightly scheduled. These situations cause a high interdependence between train paths.

4.2 Eco-driving

How much of the time margin that is necessary to use is a stochastic variable. Sometimes the whole time margin – or more – is used. On many occasions, however, there is a real time margin left that can be used for driving the train in a manner that minimizes energy use and/or brake pad wear – so-called **eco-driving**.

Research and development of eco-driving techniques and driving advice systems is not part of the Gröna Tåget programme. Such systems already exist and are continuously developed on a commercial basis, for example CATO [7] and EBI Drive [8]. Nevertheless eco-driving is proposed to be used in future high-speed trains operations.

Tests of these systems have shown that an average of about 10–15% of net energy can be saved relative to "manual" driving (in some cases up to 25%, depending on type of train operation). Driving advice from these systems is shown to produce the same or higher probability of arriving on time as without using eco-driving advice.

One of the means of eco-driving is to use **electric regenerative brakes** instead of mechanical brakes. Regenerative brakes will feed back electric energy to the power supply system while running the traction motors as generators. Regenerated energy can be used by other trains or (in some cases) fed back to the public electric grid. Thus the **net energy** (energy intake minus regenerated energy) is reduced, compared with a case where no regeneration takes place.

Other eco-driving techniques use **coasting** (no traction or brake force, just rolling, in particular before braking or a downhill gradient), or **avoid accelerating** when just a short section ahead is allowed for higher speed, due to restricted line speed or a restrictive signal. Finally, it is sometimes possible to accelerate with a traction force in the force-speed region where **energy efficiency** is high, i.e. the relative losses are low.

Another kind of saving when using electric regenerative brakes is that **wear to the mechanical brakes** is reduced, thus saving maintenance cost.

By using eco-driving some time is usually lost, i.e. the travel time will be extended above the ideal (shortest) reference travel time. There is thus usually a **trade-off between saved energy and effective travel time.** However, if the train is scheduled with a time margin – and is running on or before the actual timetable – at least part of this margin can be used for eco-driving. Experienced train drivers normally apply 'manual' eco-driving to some extent when time-keeping allows, thereby saving energy and brake wear.

In recent years computerized eco-driving support to drivers has also been developed. Usually, some **driving advice** is presented, proposing the driver how to use power, brakes and speed allowance in order to **save energy and still be on time**. As stated earlier, some mechanical brake wear and related maintenance cost are also saved.

Studies conducted for Gröna Tåget

The use of regenerative braking and its benefits have been studied in the Gröna Tåget programme, see Sjöholm [6], Lukaszewicz et al [11]. Energy saving is an obvious goal, but also saving of brake wear. According to the developed wear model [6] the brake wear is close to proportional to the mechanical braking energy. This is at least true for the moderate temperatures that occur during normal operational braking. Three principal types of braking were studied:

(1) **Blended brake** (mechanical + electric): a constant deceleration of 0.6 m/s^2

(2) **Dynamic brake**: only electric regenerative at higher speeds and blended brake (0.6 m/s^2) at lower speeds

(3) **Electric regenerative brake** only, with a maximum deceleration of 0.6 m/s^2; at higher speeds the deceleration is limited by the available power of the electric brake.

In addition, a number of simplified **eco-driving** cases were also studied.

It is shown that reductions in net energy use in the range of 12–25% (after regeneration) can be achieved in relation to the blended brake case with ideal shortest travel time. The highest savings were found for a proposed very-high-speed line Stockholm–Gothenburg with some steep gradients. A considerable amount of mechanical braking energy can also be saved, resulting in reduced brake wear. For details, see Sjöholm [6].

It should be noted that some savings would also arise from ‘manual’ eco-driving by experienced drivers, independently of a systematic approach by computerized driving advice.

Proposal

Gröna Tåget should be equipped with an Eco-driving advice system, saving energy and brake wear when time-keeping allows.

4.3 References for travel time and energy use

In this section references for ideal travel time, energy use and mechanical braking energy are presented for five train operations on Swedish lines. These cases were chosen to represent different types of rail services where Gröna Tåget could be used, both long-distance with few stops and fast regional service with relatively frequent stops, see Table 4-1 below. They are assumed to be **representative for future high-speed operations** in Sweden and partly also in other Scandinavian countries. Both conventional lines (built or upgraded to 250 km/h maximum) and a proposed dedicated line for very high speed (320 km/h) are investigated. However, until 2025 mainly operations on conventional lines are expected.

Studies conducted for Gröna Tåget

An extensive study of travel time has been presented by Sipilä [9], incorporating many different services on Swedish lines, with varying numbers of stops, levels of allowed speed, track cant and cant deficiency incurves as well as propulsion power, acceleration and deceleration. A study with fewer cases, but including also estimations of energy use and mechanical brake wear, is presented by Sjöholm [6]. Persson [23] has studied the influence of carbody tilt, tractive power and top speed.

Table 4-1 presents five cases on three selected Swedish mainlines. Case 1 corresponds to the existing upgraded line Stockholm-Gothenburg (Göteborg). Case 2 is for a proposed future very-high-speed line between the same cities. Case 3 is a fast regional train service running on an existing and slightly upgraded main line.

Table 4-1 Reference cases for estimation of Gröna Tåget travel time and energy use.

	Top speed (km/h)	*Number of stops*	*Dwell time at stations (min)*	*Max power at wheel (MW)*	*Running resist [a] (kN)*	*Number of pass*
. Stockholm–Gothenburg (455 km)	250	0	0	7.2	36	280 [d]
“	250	8	13	7.2	36	280 [d]
. As above via Eastern Link/Götaland Line (467 km)	320	0 [b]	0	9.0	47	280 [d]
”	320	9 [b]	15	9.0	47	280 [d]
. Gothenburg–Malmö–Copenhagen (342km)	250	14 [c]	24	7.2	36	240 [e]

[a] Running resistance is here given at top speed at horizontal track in open air, incl. mechanical friction, impulse and air resistance. Note that running resistance is speed-dependent. No consideration is taken to tunnels on the very-high-speed line in the reference case. A 10% tunnel share is expected to increase the average running resistance by approximately 5 %.

[b] Via Skavsta airport, according to [6] [c] Via the ‘Hallandsås’ tunnel and ‘Citytunneln’ in Malmö [6].

[d] Average load factor: 60% at 465 seats, or 65% at 430 seats.

[e] Fast regional train with 530 seats; average load factor 45%.

All trains are assumed to have 6 cars (which is assumed to be the operational average) with a mass of 360 tonnes. This could be achieved by operating 50% 4-car trains and 50% 8-car trains. They are assumed to be wide-body train units according to Section 3.2–3.3. The load factors and number of occupied seats are shown as notes below Table 4-1. For details, see Sjöholm [6] and Sipilä [9].

All presented cases on conventional lines have a maximum track cant of 160 mm in curves and 275 mm maximum cant deficiency, i.e. carbody tilt is necessary. On the proposed future high-speed line (Eastern Link/Götaland (high-speed) Line between Stockholm and Gothenburg), the maximum track cant is also 160 mm on high-speed sections, with a maximum cant deficiency of 80 mm (although speed is always limited to 320 km/h). Gradients along the lines are taken into consideration.

Note that the dwell time at stations can be influenced by the layout of the entrance areas as well as the number and height of steps between platform and the interior vestibule floor. This has been mentioned in Section 3.4 and is one of the main issues in Fröidh [2]. From Sipilä [9] (only considering travel time) the following can be concluded:

- A top speed higher than 250 km/h has very little effect on travel time for the existing line Stockholm–Gothenburg and others (less than 1 minute).
- On the existing Stockholm–Gothenburg line it is shown that high track cant (160 mm) and high cant deficiency (275 mm) achievable by tilting, has a very significant influence on travel time (32–34 min) in comparison with a case with recent cant and cant deficiency for conventional trains (150 + 150 mm respectively). This is for a top speed of 250 km/h.
- It is also concluded that a non-tilting modern high-performance train with a top speed of 250 km/h running at normal cant and cant deficiency (150 mm) on the line Stockholm–Gothenburg, will have 3–8 minutes longer travel time than the present X2 with carbody tilt and a top speed of 200 km/h.
- Low tractive power (10 kW/t instead of 20 kW/t, short time) has a significant negative influence on travel time (up to 6 min for 8 stops Stockholm–Gothenburg) at a top speed of 250 km/h.
- Increased rate of acceleration and deceleration above the level of 0.6 m/s^2, has modest influence on travel time (maximum about 1 min each) for up to 8 stops. For regional trains, with frequent stops, higher acceleration may be considered. For Case 3 (14 intermediate stops), improved acceleration up to 0.8 m/s^2 results in 2 minutes shorter travel time.

It should be noted that the above-mentioned attempt to summarize may not be generally applicable in detail; results depend on the line characteristics, the number of stops and other factors. For a complete overview, see Sipilä [9]. It should also be noted that, in this single study, no attention is paid to eco-driving and energy regeneration, which will increase the influence of some factors, in particular the power in the propulsion and electric braking system.

Reference travel time (including dwell time at stations), net energy use (after regeneration) and mechanical braking energy are calculated by mean simulations for cases according to Table 4-1. These reference data are related to the fastest possible travel time and maximum energy use, see Sjöholm [6]. The following conditions are applied **for the reference cases**:

- In all cases, starting acceleration is 0.6 m/s² until the available power limits the acceleration, while braking is accomplished by blended brakes with a constant deceleration of 0.6 m/s² from full speed to stop. Between acceleration and braking, the maximum allowed speed on each section is applied. This means that there are no attempts at 'eco-driving'.
- The regenerative electric brake is normally used at its full capacity, although within the limits of acceleration and deceleration (0.6 m/s²). Maximum electric braking force is 3% higher than during acceleration at the same speed. Further, it is generally assumed that 10% of the intended electric braking (measured as energy) is performed by the mechanical brakes since it is not always possible to feed all the energy back to the overhead catenary, due to occasional emergency braking, limited receptivity of the supply system, etc.
- Data on energy use includes an addition of 14% in excess of energy measured at the pantograph-catenary interface. This is to also include energy losses in the railway's electric supply system (catenary and frequency converters), applicable to Swedish conditions; Andersson et al [10].
- At every stopping station the exact time is considered, but the final end-to-end time is rounded off to the closest minute.

Reference data for travel time, energy use and mechanical braking energy are all given for an ideal case, i.e. the **fastest possible run** with the actual train along the actual lines without time margins. These data are shown for the five cases in Table 4–2.

Table 4-2 Reference travel time (fastest possible, including dwell time), energy use and mechanical braking energy.
The two latter are presented per passenger-km (pkm).
Eco-driving is not considered. Source [6].

	Top speed (km/h)	*Number of stops*	*Travel time (h:m)*	*Energy use (Wh/pkm)*	*Mech braking energy (Wh/pkm)*
1 a. Stockholm–Gothenburg (455 km)	250	0	2:19	49	4.0
b. "	250	8	2:45	53	5.1
2 a. As above via Eastern Link / Götaland Line (467 km)	320	0	1:47	69	5.2
b. "	320	9	2:21	73	7.3
3. Gothenburg–Malmö–Copenhagen (342 km)	250	14	2:36	68	8.4

Comments: The lowest energy use (per passenger-km, pkm) is found for the conventional upgraded line Stockholm-Gothenburg with a maximum speed of 250 km/h. Very high speed will increase energy use to some extent in the reference cases, but eco-driving can improve these figures; see Section 7.1. Otherwise the highest energy use (per pkm) is for the fast regional train, mainly due to the lower load factor for this type of train.

The data on energy use in Table 4-2 do not include the influence of increased running resistance in tunnels. With a tunnel share of 10–12% on a high-speed line, the air drag is expected to increase by about 7%, while the total running resistance increases by about 5% on average. The energy use increases by 3–4%. This is however only applicable for newly built lines for very high speed; to some extent also to Case 3 Gothenburg–Copenhagen. See further Lukaszewicz et al [11].

Note 1: The above estimated data should only be considered as reference data, for the case of fastest possible run. Energy use is often reduced in the order of 5–10% by experienced drivers, running smoothly and sometimes using a higher share of the regenerative brake in normal operations. Additional energy reductions are expected with different means of eco-driving. This is in particular true for mechanical braking energy, see Section 4.4 and Section 7.1.

Note 2: Dwell time at stations is included according to Table 4-1.

Note 3: The braking performance of the train will be higher than the assumed deceleration of 0.6 m/s^2; see Section 12. Higher deceleration can be used if it is desired in order to compensate for train delay, but it will reduce energy regeneration and increase wear of the mechanical brakes.

Example: The following percentage of train services (in pkm) is tentatively assumed: (1a) 15%; (1b) 45%; (2a) 5%; (2b) 15%; (3) 20%.

The weighted reference energy use per pkm is then 60 kWh/pkm, including losses in the railway's electric supply system (Sweden), but excluding the (modest) effect of tunnels. 10–15% of tunnels along very-high-speed lines will increase the average energy use by about 1%. Running time and mechanical braking energy will practically not be affected.

If only train services on conventional lines (Cases 1 and 3) are considered an average of 54 kWh/pkm is achieved.

Proposal

The reference data shown in Table 4-2 can be used for baseline specifications of travel time and energy, with appropriate weighting of the different cases according to the intended use of the train.

4.4 Value of travel time, energy and braking

As pointed out earlier, travel time must be valued in relation to travellers' average willingness to pay for reduced travel time. The value of travel time should also be determined in relation to its effect on operating cost, including changes in capital cost for trains as well as costs for crew (per seat-km), but also possibly increased energy and maintenance costs.

Studies conducted for Gröna Tåget

Value of travel time - for traveller and operator

According to Swedish official socio-economic valuations, as used in [2], the value of saved travel time for private long-distance rail travellers is 102 SEK/h and 275 SEK/h for long-distance business travellers. The average value thus depends on the share of business travellers.

- For 20% business: Average value 137 SEK per saved hour
- For 30% business: Average value 154 SEK per saved hour
- For 40% business: Average value 171 SEK per saved hour

For Gröna Tåget, 30% business travellers is tentatively assumed as an average for all types of services. However, in the value estimations it is possible to use any realistic share that can be justified.

These values are assumed to be the minimum **willingness to pay (WTP)** for reduced travel time. It should be noted that the values stated above are averages. Individual travellers – or different groups of travellers – may have individual and specific valuations.

The train operator can benefit from reduced travel time in several ways:

- The operator has the possibility to **increase ticket price**s according to the willingness to pay (WTP). At 30% business travellers, this is worth 154 SEK per saved hour, or 2.57 SEK per minute. Alternatively, the **number of travellers will increase** if ticket prices are raised less than WTP – this is sometimes called consumer surplus. In the latter case, operator revenues will also increase, although costs may also increase if more production resources are needed.
- If travel time is reduced, the operator would be able to run more annual kilometres with the same train and the same train crew. In such cases, **productivity will improve** and the cost per seat-km or passenger-km will be reduced. The capital cost of the train (amortization and interest) and crew costs are essentially the same, regard less of the kilometre performance. In Gröna Tåget, it is assumed that half of the cost reduction will increase the operator's profit margins and half is the benefit to passengers of a reduced ticket price, see further [2]. A lower ticket price will increase the number of travellers.

The last point calls for a cost estimate based on the number of kilometres to be run per year, as a function of the average travel time or average operating speed. However, cost could also increase when speeds are increased, see below.

Example: Total operating cost according to Fröidh [2] is 110 SEK per train-km for a 4-car trainset. For an average 6-car train the approximate cost will be 160 SEK per train-km. It is estimated that 45-50% of the cost is time-dependent; the rest is fixed cost or dependent on the running distance. The time-dependent cost will then be in the order of 75 SEK per train-km (6 cars). Time-dependent cost is capital cost for the train, train crew and some maintenance and energy. With 280 travellers (average) on each train, the time-dependent cost will be 0.27 SEK/pkm. At an average operating speed of 150 km/h the time-dependent cost is 40 SEK/h per traveller, or 0.67 SEK per minute. It is assumed that this is approximately also the value of saved travel time, due to improved productivity.

Hence, the total value is estimated as

- Value of travellers' WTP: 2.57 SEK per minute
- Value of improved productivity: 0.67 SEK per minute.

For the operator the value of higher WTP can be questioned to some extent, if the resulting change in ticket prices is lower than WTP. However, the value of increased patronage should also be taken into account.

One of the main goals of Gröna Tåget is to increase trains' market share. From this point of view, increased patronage due to saved travel time is always a benefit.

The cost of reduced travel time

If reduced travel time requires a higher top speed or higher propulsion power, there may be additional costs for the train, both capital cost and possibly also additional costs for maintenance and energy. However, if travel time is saved through smarter ways of driving or through improved train dispatching, there is no additional cost.

If we consider the first case – i.e. that the **procurement cost of trains** will increase – the additional amortization and interest must be considered. In such a case we must determine an appropriate technical-economic life-time of the train, as well as an interest rate. The basic assumption for Gröna Tåget is 20 years amortization and 6.5% interest rate [2] (including a mix of own capital assets and loans). This corresponds to about 9% annuity, i.e. this is the annual capital cost as a share of the initial investment (procurement cost).

In many cases, however, the operator and/or the owner of a new train have a more short-term perspective of the pay-off time for an additional investment, partly because of assumed technical risks and partly because benefits would possibly not materialize to their full extent. Rather, 10 or even 5 years of amortization will in some cases be considered.

Depending on the desired amortization time the annuities will be as shown below, still assuming a 6.5% average interest rate.

- 5 years of amortization => Annuity 24.1%
- 10 years of amortization => Annuity 13.9%
- 20 years of amortization => Annuity 9.1%

If reduced travel time requires higher top speed **energy** and **maintenance** costs may also increase unless these additional costs are not compensated by appropriate means. More power and braking energy may also increase maintenance costs, all other factors being equal.

Do small changes in travel time have a real value?

It is sometimes questioned whether small changes in (theoretically calculated) travel time are worth anything at all. It is sometimes argued that trains will anyhow have time margins and risk being delayed more minutes than a few minutes of calculated travel time reduction. Further, a few minutes of travel time reduction will probably not lead to any extended use of the train or its crew, i.e. more kilometres per year.

These arguments may in most cases be relevant if we are looking at an individual train schedule from A to B. However, sometimes – when a certain limit is passed – there will be a step that makes it possible to run an additional train path with the same train during the day. Similar step effects may also relate to travellers' valuation of travel time.

A new train concept - like Gröna Tåget - will be used for a long time, in many different services on different lines, with different types of travellers, and probably also by different operators with different and changing business strategies. In many cases, slightly reduced travel time has only a small value, but in others there will be a 'step' making the value very high. We conclude that even **small changes in travel time shall – on average and on the long term – be valued as much (per minute or hour) as larger changes.** This conclusion is also in line with Trafikverket [63].

Maintenance cost - in particular brake wear

If an increased share of braking is performed by the electric brake (i.e. through the traction motors) the wear to the mechanical brake equipment will be reduced; see Sjöholm [6]. The marginal cost of brake wear is mainly related to **wear to brake pads**. Wear to brake discs and other brake equipment is usually not a marginal cost as long as these components are changed at the same times as wheels are worn out and changed. This will usually happen after some 1–1.5 million train-km. Only if brake discs could safely double the wheel change interval, reduced brake would disc wear contribute to lower costs.

Brake pad wear is **almost proportional to the mechanical braking energy** [6]. This is at least the case when braking at moderate pad temperatures in normal operation, also using the electric regenerative brake system. According to [6], the marginal brake wear cost is in the order of 0.13 SEK per kWh (or around 0.04 SEK per MJ) of mechanical braking energy. This is based on two case studies with fast regional train services in Sweden, where braking energy was compared with brake pad wear and the related cost of changing the pads.

Cost of energy use

Generally, the use of electric regenerative braking will save (net) electric energy (often called electric power). Regenerated energy is usually fed back to the catenary and used by other trains. This option exists at least in electric supply systems with alternating current (AC), as is the case in the Nordic and Scandinavian countries, as well as Germany and some others.

If **more tractive power** is installed in the train it will also make it possible to brake the train with regenerative electric brakes as the normal operational brake, which may **save energy**; see [6] for more a detailed analysis.

For Gröna Tåget, the basic assumption is that electric power supplied from the catenary to the pantograph has a price of 0.72 SEK/kWh. This corresponds to 0.63 SEK/ kWh for electric power supplied from the public grid. The difference is due to energy loss in the railway's supply system (converters and catenary) and is applicable to Swedish conditions for a few years from 2010 onwards. In the future, however, price of electric power is likely to increase in the Nordic countries, partly as result of the integration of the electric power markets with continental Europe. The latter has recently had 50–100% higher prices (including taxes) than Sweden, where a tax reduction is since many years in effect for electric power used by heavy industry, which includes the railways. This tax reduction might be withdrawn in the future.

Besides the savings in monetary terms, there is a considerable **image and ethical value** in a train with low energy use and (indirect) greenhouse gas emissions. Railways have to maintain their superiority over most other transport modes in this respect; this is one of the main arguments why electric railways should be further developed and used in the future.

4.5 Implementation and procedures

Use of time margins

As stated in previous sections, fast passenger train operations on double-track in Sweden typically allow approximately8–10% time margins in the timetable relative to the fastest possible time, although there are variations due to local conditions and traffic density. This is done in order to provide a sufficiently high probability that trains will arrive on time.

The real margin and the time-keeping for train operations vary considerably over the week and over the year, depending on occasional conditions, for many reasons. **As an average it is estimated that one third of the total margin, i.e. around 3% of the ideal shortest travel time, can be utilized for eco-driving, still keeping the timetable.** Sometimes time margins are larger, sometimes they are smaller. On occasions the train will not arrive on time, regardless of actual driving style.

The remaining two thirds of the total margin, i.e. 5–7% of the reference (shortest) travel time, should be used as a margin for other disturbances, such as temporary speed restrictions, extra stops ahead of signals, delayed departures, etc.

Proposal

The following procedure is proposed in order to determine an optimum combination of travel time, energy use and brake wear:

1. Ideal travel time T_i is determined for the actual train, comparable to **reference travel time** in Table 4-2. **Extended travel time** T_a is determined as T_i plus an addition of 3%. These travel times are determined as weighted values according to the actual intended service for the train, see Section 4.3.

2. **Reference energy use** E_i per passenger-km (pkm) is determined with data as in Table 4-2, weighted according to the train's actual intended service.

3. **Reference mechanical braking energy** E_m per passenger-km is determined with data in Table 4-2, weighted according to the actual intended service for the train.

4. Travel time, energy use and mechanical braking energy for the train is **optimized** for **eco-driving,** taking into account different values and costs, i.e. value of time, cost of energy use and mechanical braking energy, as well as the capital cost of the train and other expected variations. 3% of ideal travel time T_i is tentatively proposed to be used in this optimization, i.e. the travel time (without occasional disturbances) will be extended to T_a.

   - For every (%) or minute of **saved travel time** relative to reference T_i or extended T_a a **bonus** per occupied seat and year is credited, depending on the estimated cost and economic values. For every (%) of additional travel time above T_i a **malus** of the same order is debited.

   - For every (kWh) of **saved energy** relative to reference E_i, a tentative bonus of 0.63 SEK/kWh is credited (electric energy measured at intake from electric public grid). Additional energy use is debited at the same value per kWh. A higher value of electric energy may be considered, as energy prices are expected to increase in the future and energy usage also has an additional image and ethical value.

   - For every (kWh) of **saved mechanical braking energy** relative to E_m, a bonus of 0.13SEK/kWh (or 0.036 SEK/MJ) is credited. Additional mechanical braking energy is debited at the same value per kWh.

Alternatively, instead of trying to determine an optimum travel time on a rational and economic basis, fixed desired travel times (for different operations) may be set by the operator for market or image reasons. Such a procedure will still make it possible to consider eco-driving which saves energy and brake maintenance.

In summary, a process is proposed that pays due consideration to the relations between travel time, train performance, maintenance and energy use. Eco-driving techniques should be part of the optimization.

5. Winter climate performance

5.1 The challenge of high-speed winter operations

As stated earlier, the Nordic climate is characterized by **long winters with cold and snow**. These conditions are described in Section 2.2. Because this is normal and common, **rail operations must continue** with only short interruptions. Operations must be reliable and comfortable most of the time and safe all the time.

The mentioned winter conditions require due consideration and a number of measures to be taken to secure a reliable rail service during winter months. These measures relate to both **train design and maintenance**, as well as to **infrastructure design and maintenance** and **operational practices**. Some of the necessary features of trains and infrastructure should be considered early in the planning and design process. This also means that equipment and systems made for southern and continental Europe are not generally suitable for Nordic conditions. It would be complicated and expensive to just add on some of the necessary features. In this sense there are no "standard" or "interoperable" trains in Europe, unless they are designed and maintained for extreme weather conditions.

Hundreds or thousands of different features (small ones and more extensive) must be applied to trains and infrastructure. Some of these features must be planned and built-in from the first outset of a new product or system.

Studies conducted for Gröna Tåget

Three main activities on winter issues within the Gröna Tåget programme are conducted in order to collect, summarize and strengthen know-how for high-speed operation in Nordic winter climate. These are

1. **Collection and summary of present knowledge and experience** from winter train operations in general and high-speed in particular. Experience of winter operations above 220 km/h is however quite limited. This is a study made by Transrail Sweden AB under a special contract with the Gröna Tåget programme. The study covers rolling stock, infrastructure and (to a certain extent) also operational issues. It is summarized in Kloow [13].
2. Winter tests with a specially equipped test train, basically the REGINA 250 that is briefly described at the end of Section 1.1. Tests are summarized in Scholtz [15]. Different designs of snow intrusion protection were tested, in particular in the suspensions, as well as the effect of bogie skirts. Experiments also attempted to induce **ballast pick-up** - sometimes called 'ballast projection' - by dropping 2-litre ice blocks from a height of 1–1.5 m above rails, at trains speeds of 160–250 km/h. Thanks to the low ballast level (30-40 mm below the upper surface of sleepers, see Section 2.4) no ballast pick-up was observed in about 100 repeated experiments. All ice blocks were pulverized by hitting 6–8 sleepers, according to observations with a high-speed video camera. No ballast stones were hitting the underframe equipment as far as observed.

3. **Long-term functional and endurance tests** in commercial service, also including winter operation during the harsh winter seasons of 2009/10 and 2010/11. A number of new types of equipment and technologies have been tested, such as new track-friendly bogies, active lateral suspension, permanent magnet motors, pantograph and different new adaptations for winter climate. The tests were entirely planned, executed and financed by Bombardier Transportation, but are nevertheless part of the Gröna Tåget total programme for securing future reliable and safe winter operations.

Experience and knowledge from the three above-mentioned studies and experiments form the basis for proposals in the following Sections 5.2 and 5.3. Some of the winter challenges are almost independent of operational speed, while others are speed-dependent. It is also obvious that some issues have a strong interdependency between trains and infrastructure.

Figure 5-1 Bogie and carbody covered with snow and ice (Source [13])

Conclusions and proposals

In conclusion, high-speed winter operation is a challenge for all parties involved. It is one of the very important issues to consider and prepare for. However, although much information is available in general, there is relatively little experience and knowledge of winter operation at speeds higher than 200-220 km/h. **Further research and development, in particular high-speed testing under winter conditions, are needed. A comprehensive program is proposed.**

Critical issues include friction characteristics of brake pads in snow smoke conditions and low temperatures, as well as other details in order to guarantee a proper brake function. They also include wheel-rail adhesion at high speed under winter conditions, protection of sensitive equipment from being hit by blocks of ice and possibly also ballast stones. Current collection with pantographs during high-speed winter operation is another challenge that needs further study.

It is also proposed that **standardization** and **operation management** be further developed.

5.2 Train

In this section a number of important issues for high-speed trains are presented and discussed. For a more complete and detailed description; see Kloow [13].

5.2.1 Snow accumulation and intrusion into bogies and underframe

- Generally, snow and ice is preferably accumulated at air flow **stagnation points.** Sometimes the process may be delayed by mounting appropriate **spoilers**, but these must be designed for operation at all speeds in both directions.
- The number of stagnation points shall be minimized; for example a fully c**overed underframe** containing most equipment is better than several individual boxes.
- Covered underframes should be **pressurized** to some extent, thus preventing snow from intruding. This will require a tight shell and tight seals.
- Surfaces moving towards each other should be designed to avoid or delay snow accumulation. Large flat surfaces must be avoided, **surfaces with edges** or rounded shape are better.
- Surfaces may also be covered with **low-friction covers**, preferably as **deformable plastics** made of poly-carbonate or similar material. This will contribute to break down accumulated snow.
- **Bellows** of rubber or other **covers** to stop snow intrusion can be used at sensitive locations. They must be durable under motion at low temperature.

5.2.2 Bogies - particular considerations

- Low adhesion in a winter climate may cause increased problems with **wheel flats** during braking and/or excessive **wheel tread wear** during both driving and electric braking. **Low adhesion utilization** is preferable, for example through modest deceleration when braking and a high portion of powered axles in the train. **Heating of sanding devices** is also usually necessary.
- **Wheel slip** and **wheel slide protection** must be durable and have fast response.
- **Winter durable detectors** for **wheel flats** and **hot boxes** (wheel flats may damage bearings) should be applied. Note that **water or other liquids** may intrude into bearings during de-icing procedures.
- **Axles** must be protected from **ballast hits**, by rubber or plastic covers. To avoid ballast stones becoming stuck in a “pocket” above the axle (between axle and traction motor), a “roof” above the axles should be mounted where necessary.
- **Height levelling valves** and mechanisms for the **air suspension** must be robust and located in a position shielded from ice damage and ballast hits.
- **Hydraulic dampers** in exposed position must be shielded for ice and ballast hits.
- **Rubber springs** and **seals** in dampers must be qualified for low temperature.
- **Steel** and other metallic materials must be selected to cope with low temperatures while maintaining **sufficient fatigue and impact strength.**

- **Suspensions** shall be designed for **minimum snow accumulation and compaction** according to 5.2.1. Note that limitation of suspension motions may cause **excessive dynamic loading**s on track, axles, bearings, bogie frames, etc. Also the **ride comfort** may be deteriorated.

5.2.3 Braking system

The braking function must be guaranteed regardless of climate, as braking is a most important part of safety. First, two general issues are mentioned below.

- **Compressed air must be dry** to avoid freezing of its water content into ice plugs in tanks, valves, pipes etc. Air intake must be **filtered from snow**; compressed air must be **dried** (dehumidified) prior to use in the brake system.
- **Material for all hoses and seals** must be qualified for low temperatures.

Snow smoke may cause aquaplaning and reduced friction between brake pads and brake disc, so that braking distances become longer. Further, magnetic rail brakes may be covered with snow, thus reducing the friction and braking force on the rails close to zero. The latter requires speed restriction. However, many measures have been shown to be effective, alone or rather in combination:

- **Brake pads** with effective **water drainage**, by suitably designed channels or other means. Also, the brake pad linings must be qualified for low temperatures.
- **Automatic application of brakes** at suitable intervals, cleaning braking surfaces from water. This will to some extent increase brake pad wear and energy use.
- Installation of **disc covers** (see the example in Figure 5-2). The risk of aquaplaning is reported to be much reduced, although not entirely. However, inspection and replacement of brake pads will be more complicated and tedious.
- Disc brakes may need **splash covers** to prevent melted water freezing in the brake mechanisms, thus reducing brake function or cause other problems.
- **Magnetic rail brakes** must be functional, by **heating** the brake shoes or by frequent **de-icing.** They must be **protected from water splash.**
- **High power** in the electric drive system, in combination with low or **moderate adhesion utilization**, facilitates the use of electric brakes, which are independent of mechanical brakes. However, full braking effort must always be available.

Figure 5-2 Disc covers reduce the risk of aquaplaning in snow smoke. (Source [13])

5.2.4 Carbody tilt

- Measures to **prevent blocking of tilt motions**, both between bogie and carbody as well as internally in the tilt mechanism, in principle according to 5.2.1 above.
- **Detection of motion limitations** as excessive tilting force is needed. Tilt angle limitation should be considered, as well as warning message to the train driver.
- **Splash covers** should be considered when melted water (from brakes etc) risks freezing and blocking tilt motions.
- The **total tilt system** - control, electrics, hydraulics with sealing, etc - must be qualified for very low temperatures. Start-up pre-heating may be necessary.
- **Sensors, connectors, cables, hoses** and **piping** in bogies and underframe must be protected against ice and ballast hits. Note that ice can be accumulated on moving surfaces which may cause sensors, cables etc to be crushed.

5.2.5 Carbody with interior and exterior equipment

- **Doors** must be **insulated** to avoid unpleasant temperature inside. They must be **tight** and prevent snow from intruding. **Rubber seals** must be qualified for low temperature.
- Snow, ice and sand must **not block motions** of **doors and movable footsteps**. Sometimes heating has to be used, in particular at moveable steps, but melted water must not float away to another place where it risks freezing and blocking other motions.
- Risk of **slippery footsteps** shall be reduced. A possible solution, besides heating, is to make them perforated like a door scraper.
- Travellers' inside climate - **heating, air condition, warm and cold surfaces,** etc – shall meet the requirements in EN 13129-1 [N14]. One of the challenges is to meet requirements on maximum and minimum temperatures for surfaces surrounding the comfort envelope, despite the low outside temperature and high temperature gradients.
- Between the exterior doors and the travellers' compartment an **additional door** shall be inserted to **avoid cold reaching travellers**. Both doors should be open just long enough for passage.
- For outside water and WC **tanks,** including pipes, valves and connections, both **insulation** and **heating** are usually necessary to prevent them from freezing. Alternatively WC tanks may be designed to tolerate the maximum content which is fully frozen. Tanks without heating, or when heating can not be guaranteed, must be **automatically emptied** at temperatures lower than about +4 °C. Pipes and valves must also be emptied.
- **Front windows, lights** and rear **mirrors** must be **heated** to avoid snow or condensed humidity. Note that the cooling effect from speed is very large. Glass in windows etc must withstand heating at standstill. The **wiper motor** must withstand wipers being frozen to the window.

5.2.6 Couplers and gangways

- **Automatic couplers** normally have both pneumatic and low-voltage electrical connections. These must be **heated** both in use and when idle. When not used, the coupler must be **protected with a tight cover** that can easily be removed.
- The **coupler pocket** must be **free from snow and ice** to allow necessary movement. This can be achieved with a **flexible bellow** between the coupler head and the carbody.
- **Gangway material** must be qualified for low temperatures, i.e. have the necessary strength, durability and flexibility.
- For travellers' comfort **gangways** need to be **heated, illuminated** and **insulated,** as well as **sealed** against snow intrusion. Rubber seals must be qualified for low temperatures.

5.2.7 Snow plough and front

- Generally speaking, the snow plough and front should act to remove obstacles - including medium-sized and large animals - from the track under all weather conditions. This means, for example, that the plough should **reach as low as possible,** with respect to the gauging rules and expected vehicle motions (suspension, wheel wear, carbody tilt etc).
- Snow and obstacles shall be **removed mainly laterally** to one or both sides. Animals are more frequent on the track during the winter with deep snow conditions. After a collision with a large animal it is important that damaged parts can be simply and quickly replaced at low cost.
- Snow ploughs for locomotives and heavy motor coaches in Sweden and Norway are well proven and functional; see the example in Figure 5-3. A similar **plough** should be **integrated into the motor coach design**, with functional and safety requirements having priority. This plough could possibly be removed in summer.
- The plough and front must be designed to **avoid lifting forces on the train**, thus providing for safety against derailment.

Figure 5-3 Example of functional snow plough for Nordic conditions.
(Source: Lokomotivmans Tidende, Norway)

5.2.8 Electric traction and control

Moisture on electric insulation in combination with water or humid air is a main cause of trouble and malfunction, with a risk of short-circuits and flash-over. Moisture, water and humid air must be kept out from electric equipment. This issue also includes condensed water that adheres to cold surfaces in humid air. A train arriving from deep cold in a warm workshop with high humidity is one of the challenges.

A number of design principles should be respected:

- Air ventilation for forced internal cooling should be taken from the outside on **locations where snow and moisture are expected to be at a minimum.** As a rule air intakes should be located at a **high level**. A good location might be in the fairly well-protected space **between carbody ends.** It is not advisable to take ventilation air for cooling of electric equipment from the underframe or bogies.
- Ventilation air must usually be **filtered** in order to remove snow smoke and moisture. Ventilation **air flow** should preferably be **minimized** through automatic control in cold climate.
- **Electronic equipment** must be further protected, preferably located **inside** the carbody. Some equipment must be **pre-heated** after parking in low temperature without heating.
- Cabling and connections outside must be **water sealed**. They must also be **protected from ice and ballast strikes**, as well as possible damage caused by incautious snow and ice removal.
- It is important to keep all **electric equipment clean**. This is an issue of maintenance and sealing.
- The safest way is to **avoid forced cooling**, and thus rely on **external cooling** of closed electric equipment. One example is permanent magnet motors, where rotor losses are very small and do not need internal cooling of the rotor. Stator cooling can usually be made by external cooling, including channels in the stator.

5.2.9 Pantograph and current collection

Current collection at high speeds, with **rime and possibly ice on catenary and pantograph** is a challenge. To maintain proper and reliable winter operation, at least the following points should be considered:

- A trainset shall be equipped with **two pantographs**, to have redundancy for damage. Every pantograph must have an **emergency-drop** function, which is activated if the carbon strip suffers severe damage.
- **Rime** on the contact wire (at catenary) may cause severe arcing that produces heat. Carbon strip **temperatures of 200–250 °C** have been measured. Ensure that the carbon strip and its fastenings can withstand these temperatures. Some designs have been found to be sensitive.
- **Rime** also causes **wear** on the carbon strip; in severe cases – up to 10 times the normal wear. Inspection intervals should be shortened.

- Design the traction control system to allow **short interruptions of power** without going down.
- Ensure that the **pantograph's flexibility** and **damping** are sufficient also at low temperatures. Rubber, hydraulic oils and other materials must be qualified for low temperatures.
- The **lifting force** must be large enough to lift the pantograph with some ice up to the catenary, and also to maintain a proper up-lift fore during operation. One possibility would be to develop a pantograph with **active control.**
- **Air for the lifting pneumatic device** must be filtered and dry.
- Trains with carbody tilt require **anti-tilt of the pantograph** relative to the carbody. Winter testing and approval for high speeds are needed. Ensure that **movements are not blocked** by snow or ice and that the necessary **insulation distance** for high voltage is maintained. Frequent **de-icing** may be needed as for other parts of the pantograph.
- Use preventive **de-icing** as far as possible, for example at each destination station. It is proposed that such techniques be developed. Also check for and rectify **excessive wear** or **damage** to the carbon strip.

5.2.10 Maintenance

In a harsh winter climate with snow and ice accumulation, ordinary maintenance takes longer. In addition, there is a greater need for corrective maintenance and trains may be delayed, which leads to less time being available for normal preventive maintenance. Capacity in the workshops – both workshop tracks and human resources – is critical for maintaining at least the larger part of ordinary operations. Extra human resources are likely to be needed. Generally speaking, **preventive maintenance** should be rescheduled and carried out in advance as far as possible **before the winter period.**

- **De-icing** is a major measure to maintain high-quality, reliable operations. De-icing must be done before most other maintenance can be done. It is necessary for proper performance in operation. De-icing also contributes to a low risk of ice blocks falling from the train, thus minimizing ballast pick-up and blocking of switch tongue movements on the track.
  De-icing always takes time; with conventional methods it takes several hours, sometimes 24 hours or more. The **de-icing capacity** must be sufficient for de-icing the **whole fleet of trains** completely at least once a week, probably more often for high-speed trains in severe winter conditions. In addition, **pantographs** may need special de-icing at the end destination, and probably also parts of the **brake system**.
- De-icing with **cold water** from fire-hoses or similar takes time and risks damaging parts of the train due to water intrusion. The train must be completely drained and dried before it can enter operation at temperatures below freezing.

- De-icing with **hot water** takes less time, but the problems with water drainage etc are essentially the same as with cold water. The total time before the train can enter operation may be longer than the time for the de-icing operation.
- De-icing with **hot air** also takes time (5-8 hours), but the train may enter normal operation almost immediately afterwards. However, the air must be dry; otherwise humid air will probably cause condensation in sensitive electric equipment. Air dryers also use a lot of energy.
- De-icing with **polypropylene glycol** has been used on aircraft for about 20 years but is new in railway applications. The liquid can be sprayed at low pressure on the train at high temperatures (up to 90 °C). De-icing of a bogie is reported to take about a minute, but is of course dependent on the amount and type of accumulated snow and ice. Nonetheless, it is concluded that de-icing can be done quickly and efficiently. It is also reported that snow will not adhere to surfaces treated with polypropylene glycol. There is thus a long-term effect that will delay snow accumulation. The liquid is re-circulated; it is water-soluble and classified as environmentally comparatively friendly.

  In 2010/11 there are four de-icing installations in Norway using this method. The Russian railways use it for their Velaro high-speed trains. Tests in Sweden have reported it to be less efficient for reasons not known, but the method may be further developed.

  If this de-icing method is as efficient as has been stated, some of the measures to cope with snow and ice accumulation may be redundant or at least of reduced importance.
- **Electric equipment** should be subject to regular checks for **cleanliness** of inside isolated parts, without contamination from moisture and similar. They should be cleaned if necessary. The necessary interval depends on the actual conditions.

Figure 5-4 A train de-iced with polypropylene glycol at the highest altitude station of Bergensbanen, Norway. Note the lack of snow and ice on the train. Source: [13]

5.3 Infrastructure

This is a concept proposal for a train. Measures in the infrastructure to attain reliable winter operations will therefore not be covered in detail. The brief coverage should not be interpreted as saying that infrastructure measures are less important than measures on the train; they are in reality equally important. A more complete description can be found in Kloow [13].

- **Snow clearing on the line** is a most important issue. Clearing should be done both over the track and between the rails. Sufficient resources should be available to clear all important tracks before the morning peak hours, except in very extreme weather. Both machinery and human resources must be used.
- **Snow drifts** in strong winds may be an aggravating situation. In particular this happens in **cuttings**, also of moderate height. Deep masses of snow may cause trains to stop and eventually even derail. Even more severe effects are **avalanches** that may occur at some locations with steep slopes. **Snow barriers** must be installed at appropriate locations as protection against snow drifts and avalanches.
- **Switches** are sensitive components. If snow or ice penetrates between the switch tongue and the stock rail, it may be impossible to move the tongue enough to get an indication that the tongue has been moved to a proper, safe position. Also, the mechanical mechanisms may be affected by freezing water, which risks blocking movements of the switch tongues. Small and medium amounts of snow can be removed by heating in switches, but at low temperatures this may not be possible. A severe challenge is **blocks of ice falling from trains** into the gap between the tongue and the stock rail. They have to be removed, usually manually.
- Space for **snow storage** may be necessary, in particular close to large yards.
- **Ballast** on tracks shall not reach higher than 30-40 mm below the upper surface of the sleepers. This measure prevents ballast pick-up when blocks of ice fall from trains.
- Considerable **human resources** are needed. Some of the necessary staff must be temporarily employed and are thus not familiar with the railway environment and its inherent safety risks. Adequate advance **training** is necessary.

Figure 5-5 Snow clearing on the line in Sweden.

6. Passenger comfort and functionality

This chapter presents an overview of the different amenities that are proposed for Gröna Tåget. The first four Sections 6.1-6.3 are elaborated in more detail in Fröidh [2] and Kottenhoff et al [3], while vibration, motion sickness and noise (Sections 6.5–6.7) are described in more detail in the present document. Section 6.4 on pressure tightness only refers to the Technical Specification for Interoperability (TSI) [N1].

6.1 Mobility and design for all travellers

The train concept of Gröna Tåget should suit all categories of travellers. These include travellers with reduced mobility as well as travellers with baby prams and heavy luggage. Special requirements apply to "persons with reduced mobility" (PRM) according to TSI PRM [N3], but the TSI also includes requirements for people with reduced hearing and/or vision. This is also the case in a Swedish policy document from Banverket (now Trafikverket) [64]. In some aspects the later document goes further than the TSI.

However, it is also very important that the majority of travellers find the train attractive and worth its ticket price, so cost-drivers should be avoided as much as possible. The most prominent cost-driver is space; every square-meter of space is principally worth the possible revenues from 1–1.5 seats, which is some 200–400,000 SEK per year (20–40,000 EUR). Nevertheless, what is necessary for people with reduced mobility or other impaired travellers is usually also convenient for the majority of travellers.

The Swedish policy document [64] includes some matters that are more demanding than the TSI. Leander [5] summarizes the mandatory and desired features, both in TSI and other references. Important features are listed below:

- At least one **level entrance** is desirable at each side of the train. The height difference between the platform and the floor/footstep should not be more than 0.05 m. A horizontal gap of maximum 0.05 m is also required to allow the small wheels on a wheelchair to pass over without difficulties. Ramps may be used for other platform heights than 550–580 mm. This can be arranged in different ways. One example developed as a possible concept within the Gröna Tåget programme is shown in Figure 6-1.
- If a level entrance is not provided it is recommended that **lifts to take wheelchairs into or out from the train are located within the train itself,** i.e. not requiring permanent or temporary lifts on the platforms that is allowed according to the TSI. Preferably travellers in wheelchairs should be able to manage and manoeuvre the lift by themselves. Due to the high weight of some motorized wheelchairs used in Scandinavia (so-called "Permobiles" and similar) the lifting capacity must be 300 kg, instead of the 200 kg as specified in the TSI. One such lift should be operable from each side of the train unit.

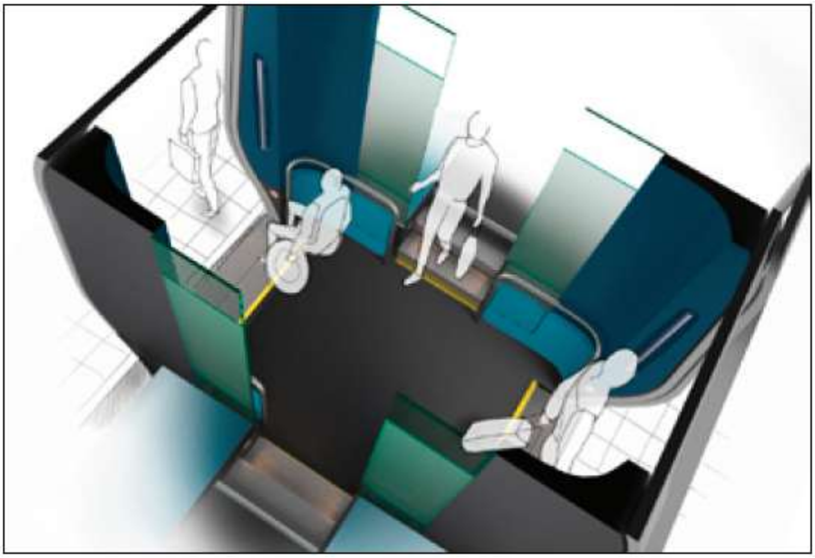

Figure 6-1 **Concept of entrance, self-adjusting to the actual platform height. The vestibule floor moves between the platform height (0.55–076 m) and the upper floor level (about 1.20 m). Travellers with reduced mobility, including those with baby prams, can easily board or alight the train. When the vestibule floor is at the upper level, travellers and service crew can easily move through the train. At the lower level, the 3-step stairs can be used.** Source: Konstfack [4].

For general use, i.e. for the majority of travellers, at all entrances, the following features are proposed:

- **External and internal doors** must have at least 0.80 m free width where passengers with reduced mobility (PRM) have to board the train according to TSI PRM. However, to be able to board the train conveniently and fast with two pieces of luggage a **free width of about 0.90 m is preferable**. The latter is proposed for all or most doors where heavy luggage has to be moved.
- The **maximum gap between platform and step** in the train should be
  - Maximum 0.125 m on straight track;
  - Maximum 0.200 m in curves.

  A **moveable step**, closing most of the gap, is desirable.
- It is crucial that **a continuous passenger flow through the entrances into the compartments** (and reverse) can be brought about. This is for traveller's convenience, but also – most important – for quick alighting and boarding. A jam inside the entrance causes a severe **risk of delaying the train**, which is detrimental for both punctuality and transport capacity along the railway. These issues, with examples of interior layouts, are thoroughly discussed in Fröidh [2] Section 6.2.

6.2 Functional and space-efficient seating

The TSI or the EN do not specify detailed functionality and comfort for the majority of travellers, i.e. non-PRM travellers. In this section we initially summarize requirements for PRM, then present proposals for general application.

According to TSI HS PRM, at least 10 % of the seats, preferably those close to the external doors, shall be **priority seats** for PRM. The special features to be respected for these seats are mainly:

- The clear headroom above each seat shall be at least 1.68 m above floor level;
- Where uni-directional priority seats are provided the distance between the front surface of the seat back and the vertical plane through the rearmost part of the seat in front, shall be minimum 0.68 m; see Figure 6-2;
- Where face-to-face priority seats are provided, the distance between the front edges of the seat cushions shall be minimum 0.60 m. Where a table between the facing seats are provided, the distance between the front edges of the seat cushions and the edge of the table shall be at least 0.23 m. Foldable edges of the table could be used to meet this requirement, although not mandatory.

The two latter requirements should not be far from the general proposals for Gröna Tåget. They comply with a seat pitch of 0.90–0.95 m in uni-directional seating, and a back-to-back distance of 2.05–2.20 m in face-to-face seating, depending on the inclination of the seat backs and the table dimensions. The priority seats will require some 5–10% more space than the general proposals for Gröna Tåget. See Fröidh [2] and below for comparison.

The requirement of minimum 1.68 m free headroom may raise overhead luggage shelves at priority seats some 0.10 m above the generally proposed level for Gröna Tåget (1.65−1.70 m for the upper surface of the shelves). The lower height for the majority of travellers is proposed for convenient luggage handling.

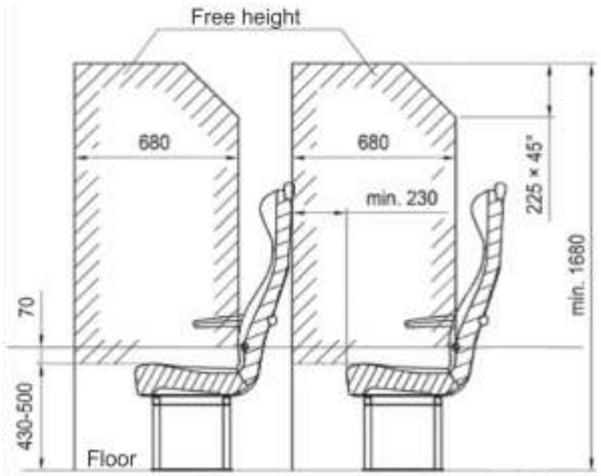

Figure 6-2 Minimum dimensions of uni-directional priority seats for persons with reduced mobility. Measures in (mm). Source: TSI PRM [N3].

Attractiveness for all travellers is a basic target for Gröna Tåget. This means appropriate space at the seat. As mentioned above in Sections 3.1 and 6.1, rational space utilization is crucial for low cost. Different means can be used in order to make seats comfortable while also saving space; see Kottenhoff et al [3]. The most important are:

- 2+3 seating is the main alternative for 2nd class (or economy class) in Gröna Tåget; see Section 3.2. In 1st class comfortable 2+2 seating is possible, with a small table between two seats. Some seats in the train may be flexible, so that seats could be converted from 1st class to 2nd class in a simple manner; see Figure 6-3. This is to optimum use of seats and space when the demand changes between business and private travelling;
- The seatback inclining mechanism should be made to avoid a reduction of the legroom for the traveller behind. The **seat backs' centre of rotation** should not be lower than at knee-height, i.e. at least 0.55–0.60 m above the floor;
- **Seat backs should be rounded at the bottom**, so that travellers can extend their legs under the seat in front; see figure 6-4. Furthermore, the minimum **distance between the floor and the bottom edge of the seat** should be at least 0.30 m, preferably 0.33 m. Gröna Tåget research results [3] showed that this distance was just as important for comfort and feeling of space as 0.09 m extra seat pitch. This implies that about 10% space can be saved;
- **Seat back thickness** should be reduced from typically 0.12 m to 0.06 m. By suitable means such a reduction should not reduce comfort. One of the important issues is to provide **lumbar support**. The seats should have **head rests** at both sides. **Neck rests** must be adjustable. These amenities are shown in Figure 6-5;
- **Individual foldable armrests** should be provided. In particular this is important in the 3-seat group, but is also preferable on the 2-seat side. Also some space should be provided close to the wall and window; see figure 6-6;
- **Tables should be large** enough to be suitable for a lap-top computer, a drink and other smaller items. This requires a width of at least 0.40 m, preferably 0.45 m at uni-directional seating. The table should **fold down** towards the user; this is to save space at knee-height. At uni-directional seating the table should be able to pull out, to provide **space for a lap top** with proper angle to the user; Figure 6-7.

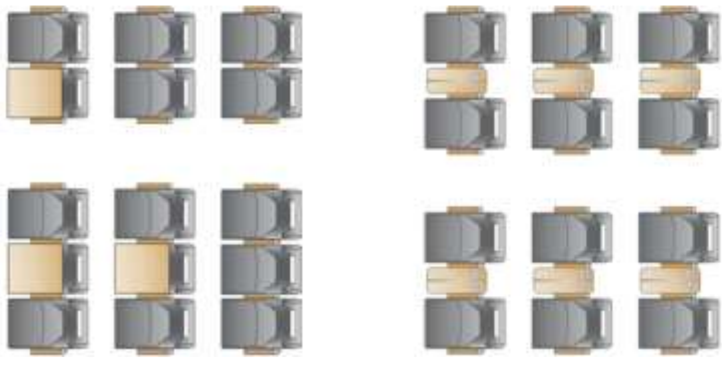

Figure 6-3 Flexible seat arrangement (left), where seats can be converted for different demands. 1st class seating (right) with a table between seats. Source: Kottenhoff [3].

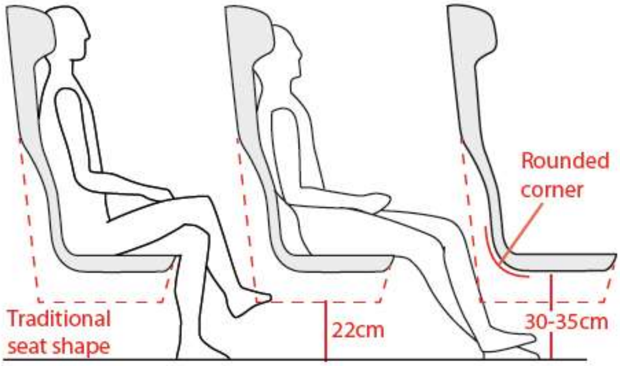

Figure 6-4 Rounding and raising the bottom of the seat also gives tall people ample space for stretching out or to cross their legs. Source: Kottenhoff [3].

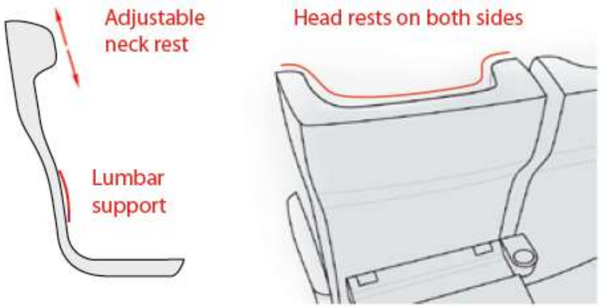

Figure 6-5 Lumbar and head support should be provided. The neck rest must be adjustable to suit various travellers. Source: Kottenhoff [3].

Figure 6-6 Individual armrests and space between seat and wall a important for comfort Source: Kottenhoff [3].

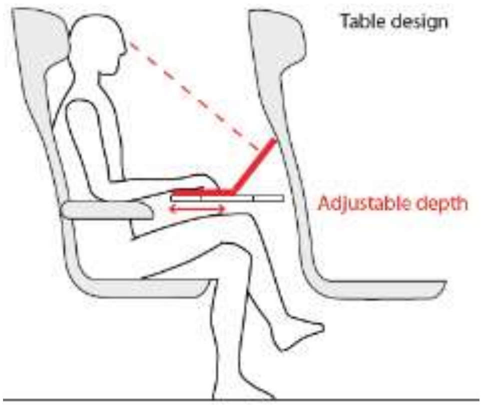

Figure 6-7 Table deep enough for appropriate watching of a lap-top screen.

The **seat pitch** – i.e. the distance between the same part of two unidirectional seats, or the distance between the outer seat back surfaces in face-to-face seating – is not a primary goal; the feeling of space and the functional requirements are the most important. Considering these matters, the resulting seat pitches for Gröna Tåget are discussed in Kottenhoff [3] and proposed in Fröidh [2]. The latter proposes two levels: **'comfort'** and **'capacity'**. The 'comfort' level has generous space, in particular at the 3-seat side in 2nd (economy) class. The capacity level has more restricted space, but is still better than on most intercontinental flights in economy class.

It should be noted that the features and measures proposed on the two previous pages, will substantially contribute to functionality, comfort and feeling of space, in comparison with most traditional seating on current trains.

Table 6-1 Proposed seat pitch for different classes. Source: Fröidh [2].

	1st class	*2nd (economy) class*	
		Comfort	*Capacity*
Uni-directional, 2 seats abreast	1.00 m	0.90 m	0.86 m
Uni-directional, 3 seats abreast	n/a	0.975 m	0.91 m
Face-to-face with table, 2 seats [a]	2.10 m	2.00 m	1.90 m

[a] Possibly the seat pitch should be increased by about 0.1 m in face-to-face seating, in order to improve space for feet and knees. However, the need for improvement depends on the seat design and their seat-back inclination. Face-to-face with 3 seats abreast is currently not proposed but could be considered if arranged in an appropriate way.

Other means of improving comfort and functionality are, for example

- Foldaway **foot-rests**, being at least 0.35–0.40 m over floor when folded away, to allow travellers to stretch their legs;
- Individual **reading lamps** over each seat;
- **Foldable table edges** at face-to-face seating, to ease access to window seats.

6.3 Other on-board facilities

More amenities for persons with reduced mobility (PRM) and other impaired travellers are specified in the TSI PRM [3]. For example

- **Toilets** for PRM, regarding size and facilities;
- Space for **wheelchairs:** Minimum 2 wheelchairs per 205 m train length must be provided, arranged close to the entrances for PRM;
- **Other facilities** such as handrails, alarms at doors, alarms that can activated by the PRM traveller, doors, push buttons, visibility of signs, lighting, etc.

Details are given in TSI PRM [3] and partly in Leander [5].

All travellers should benefit from a number of amenities for handling and storage of clothes and luggage, food service, HVAC (heating, ventilation and air condition), etc. A number of facilities are proposed; see below.

Clothes

Travellers want to have their **clothes close to their seat**. This is both for availability during the journey and due to the risk of theft if hung in a wardrobe far away. Thus wardrobes at the entrances should not be provided; they consume space and they will hardly be used. Wardrobes in the seating areas could possibly be useful, at least in 1st class.

Instead small **hooks** should be provided **on the wall** close to the seat, preferably moveable so that they can be adjusted to the desired position; see Figure 6-8. Bear in mind that some **space should be provided between the seat and the wall**, as in Figure 6-6. Otherwise there is a risk that clothes will drape themselves over the seat-backs. **Hooks** should also be placed **on the seat-backs**, as close as possible to the edge. This is a very efficient, simple and non-expensive way to store small and medium-sized clothes.

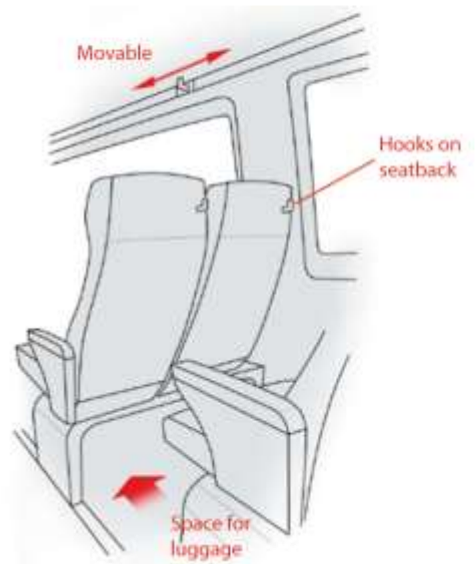

Figure 6-8 Moveable hooks should be provided on the wall, besides a hook on each seat-back. Some small luggage items could be stored under the seat, provided that the height is sufficient (i.e. 0.30-0.35 m). Source: [3].

Luggage

Luggage is a challenge on trains, because it is usually not checked-in as on airlines. Investigations in Sweden; see Kahn et al [65] and Fröidh [3], have shown that private travellers during holidays or during weekends bring about 1.5 pieces of luggage each, as an average. About 5 pieces per 10 travellers are estimated to have a size "larger than cabin luggage". This includes about one baby pram per 25 travellers, where the pram can be folded or be standing upright.

Smaller items are simple to handle and store at the seat. With a free height of 0.30−0.35 m under the seats there is room for some small and medium-sized luggage; see Figure 6-8. Otherwise medium-sized items can preferably be stored on the **shelf above the seat**. Some larger, but not too heavy, items may also be stored above the seat or between the back of a seat and a wall, for reasons of immediate availability.

Storing heavy items above the seat is however questionable: Firstly, lifting large and heavy items up to a level of 1.7 á 1.8 m is not convenient for many travellers. Secondly, heavy luggage on the shelf may impose a risk of traveller injury, if the train collides or derails, or if the carbody tilt system is suddenly switched off at curving. Collisions or derailments are very unlikely to happen, but the carbody tilt could sometimes be switched off. Not even the latter case has been a substantial problem on the Swedish tilting train X2, but if it is judged that an improvement has to be made, the shelves above the seats could be closed with hatches as on airplanes.

In addition, **separate shelves** should be provided **for large items and baby prams**, preferably near the entrances, but in some cases also within the seating areas. The proposal is that about 1.2 – 1.5 metres of shelves be provided for each 10 seats. Fröidh [3] has made proposals and possible car layouts.

Food service

Which degree and quality of food service that should be provided is a question for the operator and cannot be generally proposed. It is however anticipated that hot food should be provided on long-distance journeys. This can either be made in a "bistro" car, or by food service at the seat. It is crucial for overall cost that the space occupied for these services is as small as possible, because non-seating space is one of the cost drivers (or e.g. low-revenue space); see Section 3.1 and 6.1. For long-distance services with a 4-car train about a third of a car may be used for a bistro, in addition to a galley for hot food preparation in 1st class. Trains for dedicated fast regional services may likely have less space used for food service. See Fröidh [3] for more details.

Heating, ventilation and air condition

On this matter EN 13 129-1 [N23] has relevant specifications that can mainly be used. This EN does not only covers air cooling and dehumidification, but also ventilation, heating and temperatures at different parts of the seating areas. Some specific issues are worth mentioning:

- Different external temperature zones are defined, of which Zone III must be used. This zone is defined for external temperatures between -40°C and +28°C. Zone II with external temperatures down to -20°C is not sufficient.
- A "comfort envelope", ranging 0.1−1.7 m above floor level, is defined in seating areas. Within this space the normal interior air temperature shall be +22°C, with some possibility to changes. At high external temperatures the interior temperature shall be raised above the normal temperature.
- Humidity of the interior air shall be maximum 65%, but at interior temperatures higher than +23°C the humidity shall be reduced.
- Air velocity at the outlets shall not be higher than 0.1 m/s at an exhaust temperature of 18°C, and maximum 0.2 m/s at 21 °C. Large outlets are thus required.

- Temperature on surrounding surfaces shall be within comfortable limits. For example: (1) window surfaces must not have temperatures more than 12°C below the interior air temperature; (2) window frames must not have temperatures more than 9°C below the interior air; (3) walls must not deviate more than ±7°C from the air temperature;
- Although not mentioned in the EN, a moveable **sunshade** should be provided at all windows.

The last mentioned requirement is a challenge at the very low external temperatures of 20−40 degrees below zero. For example, a considerable amount of warm air must be extracted from outlets just below the windows, to prevent cold downdraughts. This risks overheating the wall below the window, i.e. so that temperature tolerances cannot be achieved.

Electric supply and internet connection

A modern train must provide sockets for electric supply of traveller's equipment (230 V) as well as a high-capacity internet connection.

Interior layout

No specific interior layout is shown or proposed in this report.

Fröidh [2] proposes a number of wide-body interior layouts for 'comfort' and 'capacity' cases. Also trains with "continental width" are shown. These layouts also include catering facilities, toilets, vestibules and entrances, etc.

As mentioned earlier, **fast boarding and alighting** is crucial for punctuality and capacity along the railway lines. Therefore, entrances and doors must be designed for fast passenger flow. It is also most important that the flow continues inside the car, so that luggage handling and similar does not cause the flow to stagnate. Also these issues are thoroughly discussed in [2], where also tangible proposals are made.

6.4 Pressure tightness

Pressure tightness − or rather a longer time for outside pressure changes to intrude into the interior – is a necessary requirement for traveller's comfort on high-speed trains running in tunnels, say at speeds above 200 á 220 km/h.

Train must be sealed so that passengers do not experience a too fast change in the interior pressure. TSI HS RST [N1] has requirements on allowed pressure variations in sealed trains. These are:

- 1000 Pa within a period of 1 s
- 1600 Pa within a period of 4 s
- 2000 Pa within a period of 10 s.

Conditions regarding tunnel area and speeds are given in the TSI HS RST and TSI HS INS [N2]. They are also briefly mentioned in Section 7.1 of this report.

It should be noted that a wide-body train has larger cross-section area - and thus a higher pressure change in a given tunnel - than a single-deck train with a narrow continental-type carbody. However, a double-decker may have larger cross-section than a wide-body single decker and will thus be an even more demanding case in the same tunnel at the same speed.

6.5 Ride comfort and lateral acceleration

The sensation produced on passengers (travellers) during the application of oscillations (vibrations) and/or inertia forces from the train, is usually called **ride comfort.** Lower vibrations and/or inertia forces produce a higher comfort level, while higher vibrations etc. produce **discomfort**. Ride comfort (or discomfort) is evaluated and quantified by objective methods based on the processing of measured (or simulated) accelerations. Every method delivers a figure for evaluated comfort, or part of the comfort sensation. Such methods are specified in EN 12 299 [N11].

In most of the standardized methods accelerations in three perpendicular directions are measured or simulated. These directions are longitudinal (*X*), lateral (*Y*) and vertical (*Z*), where longitudinal is in the forward direction, lateral is parallel to the floor and vertical is defined perpendicular to the floor.

Given the measured or simulated accelerations as well as the evaluation methods, a criterion must be applied which interprets the results, i.e. whether the ride comfort is good enough and how good it is.

We will for Gröna Tåget limit our evaluations of ride comfort to the so-called 'Mean Comfort' M_{MV} by the 'Standard method' and the evaluated frequency-weighted r.m.s. accelerations in the individual lateral and vertical directions. The latter accelerations are part of the N_{MV}.

Mean Comfort NMV

Accelerations are measured in three directions (*X, Y, Z*), then processed through frequency weighting filters (different for vertical and horizontal directions, defined by ISO) and determined as r.m.s. (root-mean-square) quantities.

60 sections (about 5 s each) along the line are defined as a test zone being measured and evaluated. The 95$^{\mathrm{th}}$ percentile is determined from the sixty 5 s sections, i.e. the r.m.s acceleration level that is not exceeded 95% of the measured sections. R.m.s accelerations are given in (m/s^2).

Mean Comfort for seated passengers is determined by the formula

$$\boldsymbol{N}_{\mathbf{MV}} = \mathbf{6} \cdot \sqrt{\left(\boldsymbol{a}_{\mathbf{X95}}^{\boldsymbol{w_d}}\right)^{\mathbf{2}} + \left(\boldsymbol{a}_{\mathbf{Y95}}^{\boldsymbol{w_d}}\right)^{\mathbf{2}} + \left(\boldsymbol{a}_{\mathbf{Z95}}^{\boldsymbol{w_b}}\right)^{\mathbf{2}}}$$

where $\boldsymbol{a}_{\mathbf{X95}}^{\boldsymbol{w_d}}$, $\boldsymbol{a}_{\mathbf{Y95}}^{\boldsymbol{w_d}}$ and $\boldsymbol{a}_{\mathbf{Z95}}^{\boldsymbol{w_b}}$ are measured r.m.s. accelerations in X, Y and Z directions, frequency-weighted with filters $\boldsymbol{w_d}$ and $\boldsymbol{w_b}$ respectively.

ISO frequency weighting filters are not presented here; see EN 12 299 Annex C, or Andersson et al [39] Chapter 11. Longitudinal and lateral directions (filter w_d) have maximum human sensitivity at 0.5–2 Hz, while the vertical direction (filter w_b) has maximum sensitivity at 4–12 Hz.

Ride comfort is usually determined over several test zones along the track. Mean Comfort assessed with the standard method should be determined (a) on the floor at the centre of the carbody and (b) on the floor at both ends of the passenger compartment, or (alternatively) above the bogie centres.

According to EN 12 299 the following interpretation may be used:

- $N_{MV} < 1.5$ Very comfortable
- $1.5 \leq N_{MV} < 2.5$ Comfortable
- $2.5 \leq N_{MV} < 3.5$ Medium
- $N_{MV} \geq 3.5$ Uncomfortable or Very uncomfortable

For Gröna Tåget we propose that N_{MV} should be maximum 2.0, preferably below 1.5. This level of ride comfort should be achieved at all operating speeds on "Comfort track" according to the proposal in Section 2.4, Table 2-1. Note that the 5 s sections for N_{MV} evaluations may be replaced by test sections according to EN 14 363, with some variation in length and duration. This is proposed as an alternative in EN 12 299 and is also indicated as a note below Table 2-1.

Lateral and vertical r.m.s. accelerations

R.m.s. frequency-weighted accelerations in the individual lateral and vertical directions can also be used as indicators of ride comfort in the different directions. These accelerations will be determined at the N_{MV} evaluations above. In EN 12 299 these accelerations are used for determination of so-called 'Continuous Comfort', denoted C_{CY} and C_{CZ} respectively.

According to EN 12 299 the following preliminary scale may be used for C_C in the Y and Z directions

- $C_C < 0.20$ m/s² Very comfortable
- $0.20 \leq C_C < 0.30$ m/s² Comfortable
- $0.30 \leq C_C < 0.40$ m/s² Medium
- $C_C \geq 0.40$ m/s² Less comfortable

For Gröna Tåget we propose that C_{CY} *and* C_{CZ} should be maximum 0.20.

It is understood that the 95th percentile of accelerations shall be used. This level of ride comfort should be achieved at all operating speeds on "Comfort track" according to proposal in Section 2.4, Table 2-1.

Lateral mean acceleration in circular curves

When negotiating a curve passengers experience a lateral acceleration or a 'centrifugal force', if the horizontal acceleration, determined by the speed and curve radius, is not balanced by track cant and/or carbody tilt. A complete evaluation according to EN 12 299 shall consider both the mean lateral acceleration in the circular curve as well as the peak-to-peak acceleration in the same curve, according to the P_{DE} criterion. As a simplified measure only the lateral mean acceleration experienced in the carbody is proposed to be used, assuming that some dynamic peak-to-peak accelerations also occur according to experience. Standing passengers is the most critical case, in particular when those passengers are walking along the train. Also, if the lateral acceleration is too high different items may start sliding on the tables or on the floor.

It is judged that a **mean lateral acceleration in the carbody of about 1.2 m/s² is acceptable** for Gröna Tåget in non-tilting operation. This limit is based on experience, but is also compatible with the P_{DE} criterion in EN 12 299, giving only a few percent "disturbed" passengers with plausible dynamic peak-to-peak accelerations.

For tilting operation a reduced level is proposed, see Section 8.6.

6.6 Motion sickness

Motion sickness can be experienced on trains and other modes of transportation, where motion sickness at sea is the most well-known. The **sensory conflict** is the most common explanation of motion sickness. The different sensitive capabilities of the human motion information sources give a sensory conflict. This conflict can be exemplified by a passenger sitting on a moving ship or train, looking inside and feeling the movements but unable to see them.

Tilting trains have a tendency to provoke higher incidence of motion sickness in sensitive travellers than non-tilting trains. Investigations have shown that 5–8% of average Swedish passengers feel some symptoms of motion sickness. The target is to bring this incidence down, or at least not to increase it even if train speeds are increased.

The difference between non-tilting and tilting rolling stock has attracted particular interest in Japan and Europe. This was the starting point for the EU-funded research project Fast and Comfortable Trains (FACT) [58]. FACT involved on-track tests where the evaluation showed good correlation between variation of the vertical carbody acceleration and motion sickness. However, vertical acceleration was not claimed to be the primary cause of motion sickness, but rather a consequence of tilting.

Regarding motions, the largest difference between tilting and non-tilting trains is the roll motions. The additional vertical acceleration felt by the passenger is also higher when the carbody tilts in curves.

Laboratory tests have proven that the visual reference and head movements relative the body are important for the onset of motion sickness. The internal reference is more provocative than no visual reference at all. Head movements increase the onset of motion sickness when combined with other motions. Rotational head movements were as early as 1964 pointed out as being the prime cause of motion sickness on trains when combined with translational acceleration in curves. Combinations of motions are the likely causes of motion sickness on trains even today as no single motion can explain the onset of motion sickness on (tilting) trains.

All the above agrees with Swedish research in the 1990s, see for example Förstberg [40]. On-track tests involving human test subjects on the tilting train showed some 30–40% reduced incidence of motion sickness when the tilt angle and the tilt velocity were reduced. This result agrees in general with the research conducted for Gröna Tåget, which is presented in Section 8.8.

From what is stated above it is concluded that **tilt angle and tilt velocity should be limited as far as possible**, for example by not tilting more than necessary in order to meet other comfort requirements concerning lateral acceleration and jerk. The research and development conducted within the Gröna Tåget programme is presented in Section 8.8.

6.7 Interior noise

Noise can be defined as annoying sound. This section deals with interior noise, while Section 11.3 deals with external.

Noise in train interiors is transmitted from the **wheel-rail contact** either as **air-borne** noise or **structure-borne** noise, i.e. via the structural or suspension elements (made of steel, rubber, etc) of the bogie and carbody. Structure-borne noise dominates in the low-frequency region (say up to 100–200 Hz), while noise with higher frequencies is mainly air-borne. Noise from the wheel-rail interface is sometimes called 'rolling noise'. This noise usually (but not always) has a time-continuous broadband character without significant variations.

In addition to 'rolling noise' there are usually also other sources of annoying sound. At very high speeds (say above 250 km/h) **aerodynamically induced noise** may also be important. Such noise maybe generated from protruding and sharp objects (pantograph, other electrical roof equipment, bogie parts and others). Also this noise usually has a character that is continuous in time.

Other sources of annoyance may be of a more or less discontinuous nature, some of them emanating from the train and some from travellers' activities. Common sources are:

- Fans and hydraulic pumps
- Traction equipment, in particular motors, gears and electric converters
- Brakes (disc or tread)
- Wheel squeal, in particular in curves
- Bumps and rattling from bogies and suspension
- Rattling and screeching of interior panels, interior doors, lighting armature and similar
- Toilets
- Conversations between travellers or on mobile phones
- Baby crying

In addition to the discontinuous nature of these noises, some of them may be 'sharp' with considerable high-frequency content. They can also contain pure tones above the general average sound level, which is also annoying.

The traditional way of specifying interior noise is by the **A-weighted sound pressure level,** usually denoted L_A which is frequency-weighted from the original physical sound pressure level L_P. These levels are usually measured in *dB(A)* or *dB* above a reference level of $2 \cdot 10^{-5}$ Pa. This may be a relevant measure for a sound which is (almost) constant overtime and also has a broadband frequency spectrum with no significant peaks. Another descriptor is **loudness**, usually denoted N and measured in *sones*, which is similar to frequency weighting A, although slightly more sensitive to higher frequencies.

However, interior noise in trains very often has more complex characteristics. Even if the average A-weighted sound pressure level is quite low, say 60 dB(A), the discontinuous or tonal sound(s) may be very annoying. These aspects are usually described under the term **sound quality**.

There is no widely accepted standard for interior sound quality on trains. For a comfortable, attractive journey sound quality, however, is most important. A number of descriptors for sound quality (or rather the inverse) have been proposed and are listed here:

- Sharpness S (expressing the content of high frequencies in a sound mix);
- Fluctuation Strength F and Roughness R (expressing fluctuation of noise);
- Tonality T (narrowband frequency components, higher than the neighbouring components);
- Impulsiveness (in particular a descriptor for 'bumps' and 'beating').

For details and definitions, see Möller et al [35] or Zwicker et al [37], with further references.

Proposals for a total noise index exist, for example the **Sensory Pleasantness** P according to Zwicker and Fastl [37], but have not been developed for the specific character of interior train noise. Relative pleasantness P/P_0 is given as

$$P/P_0 = e^{-0.7\cdot\frac{R}{R_0}-1.08\cdot\frac{S}{S_0}-(0.023\frac{N}{N_0})^2}\cdot(1.24-e^{-2.43\cdot\frac{T}{T_0}})$$

where index *0* indicates reference levels; N = loudness (sones)

Another example, which is relevant to interior train noise, is the Annoyance Index (*AI*) developed by Möller and Wahlström [35]. A total of ten train noises were recorded, both smooth time-continuous noise and more specific discontinuous noises (acceleration, braking, tunnels, open window, hydraulic pump). This was done for a Swedish loco-hauled InterCity train and for the tilting high-speed train X2 (formerly *X 2000*). The noises were normalized with respect to A-weighted sound pressure level and duration. In all, 29 listeners performed subjective tests in the laboratory where they expressed their annoyance or satisfaction on a scale from 0 to 100. The Annoyance Index (AI) developed is expressed as follows

$$AI = L_A + (47\cdot S + 163\cdot F - 80)$$

The proposed *AI* showed a coefficient of determination (R^2) of 63% in the listening tests. This should be compared to R^2 = 30% for an index that only includes the A-weighted sound pressure level L_A, i.e. the first term in the above equation.

For comparatively pleasant sounds (recorded within X2), *AI* was 24–33. For annoying sounds with the pressure level raised by 10 dB, the *AI* was determined at levels up to about 70 (recorded on the InterCity train). The train X2 in open field with L_A raised 5 dB(A) to about 65 dB(A), was rated *AI* = 35.

The annoyance from **pure tones**, also called **tonality**, is not included in the proposed *AI*. Pure tones should be limited to a level where only moderate annoyance is anticipated, preferably some 2–3 dB(A) above neighbouring frequency components.

Another experiment was made by Khan [36], who studied the masking effects of annoying interior train sounds. Additional masking sound originating from the air flow of a ventilation fan with an average L_A of 62 dB(A)was added to the original sound by means of load speakers. The experiment was conducted with a total of 42 subjects on a Swedish regional train, which had some rattling noise as well as mobile phone conversations.

The average **overall acoustical comfort was better in the masking condition**, where L_A = 65 dB(A) was achieved, than at the original 62 dB(A). It was still better at 67 dB(A). However, the result was not significant at a 95% level.

Although the above experimental results of masking may not be generally applicable for all trains, there is a strong indication that some masking of annoying sounds is desirable. A very low general sound level, say in the order of 58–60 dB(A), risks inducing annoyance from rattling, screeching, hydraulics, fans, toilets, mobile phone conversations, babies, etc.

Studies conducted for Gröna Tåget

Studies conducted within the Gröna Tåget programme are reported in detail by Carlsson and Frid [30].

Besides mastering discontinuous, sharp and tonal noise, i.e. the issue of sound quality, the understanding and prediction of structure-borne noise is a crucial issue. The vehicles' structure is very complicated in terms of different wave types as well as of transmission paths. The focus within Gröna Tåget has been on identifying and ranking the different transmission paths from the bogie into the carbody interior. Suspension parameters like bushing stiffness and components' internal dynamic properties may have a significant influence on interior noise. Furthermore, new technologies such as active radial steering bogies, bogie skirts or permanent magnet motors may have an effect on interior noise.

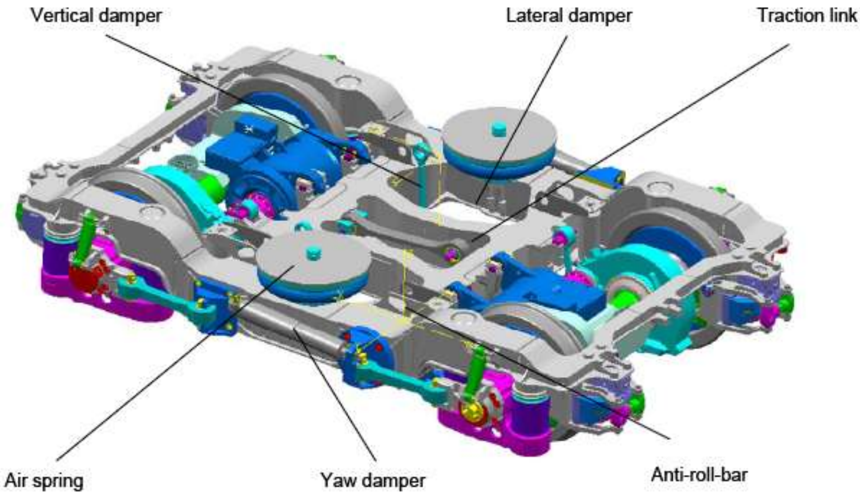

Figure 6-9 REGINA 250 test train bogie with bogie-carbody interface elements.

An extensive investigation of the structure-borne transmission paths from bogie to carbody interior was carried out. As an important part of this, the dynamic characteristics of eleven coupling (or transmission) elements were investigated. A combination of vibration measurements on both a stationary and a running REGINA 250 test train was used. The bogie of the test train is shown in Figure 6-9. The most prominent sound transmission components were found to be the **vertical damper** and the **yaw damper**.

To reduce structure-borne interior noise it would be fruitful to reduce the dynamic stiffness of these components. However, the intended benefit of stiff yaw dampers is to suppress unstable dynamic behaviour of the bogies, so a change of stiffness may not be possible in this case. Nonetheless, the increased knowledge of the different components is very useful for understanding and predicting noise. A thorough analysis of the transfer paths together with the development of a simplified simulation model is presented in Kraft [38].

There was negligible influence on interior noise from the active radial steering bogie and from the 'soft' wheelset guidance (see Section 8.4). Note that the new bogies were not designed for acoustic performance. Not even the bogie skirts (Section 11.3) increased the interior noise. The bogie skirts thus reduce exterior noise (see Section 11.3) without increasing interior noise.

Another new technology is permanent magnet (PM) motors (Section 9.2). In comparison with the traditional asynchronous induction motors, the noise at low speed (during acceleration or electric braking) is lower for the new PM motors, while the noise at high speed is almost negligible for both motor types. Even if the PM motor is self-ventilated with a cooling fan directly mounted to the shaft, this does not have any negative influence on noise.

Proposals

A future comfortable train should strive at a moderate but not too high interior sound pressure level L_A, preferably in the order of **65 dB(A) in passenger seating areas at any speed**, from zero speed up to maximum operating speed. Because sound measurements are usually made with quite smooth wheel and rail surfaces, it is expected that the sound level will, on average in real operations, be some 2 dB higher. On the other hand, the train will often run at a lower speed than top speed, which will suppress rolling and aerodynamic noise. A total sound level of 64–67 dB(A) is expected to mask a great deal of annoying noises from the train itself but also from disturbing human sources, i.e. other travellers. In an ideal situation, it is possible to comfortably have a conversation with the person one is sitting next to, but not be disturbed or overheard by other travellers further away. Another advantage with a moderate requirement regarding sound pressure level is that excessively complicated, heavy and costly noise mitigation measures are not needed.

A further possibility is to create a **synthetic background sound** with a pleasant character, either as masking noise or to add to the positive travel experience.

In the entrance vestibules, a few decibels higher noise level could be accepted. However, vestibules are suitable areas to make phone calls, so for reasons of speech transmission and intelligibility the noise level should be moderate.

Consideration should also be paid to avoiding **pure tones** in the sound characteristics.

Care must be taken to eliminate discontinuous, tonal or sharp noise from different sources. As a tentative descriptor for **sound quality** the Annoyance Index (*AI*) may be used. An *AI* of 35–40 maximum at any operational speed (including acceleration and braking) should be strived for. Note that *AI* also includes the above-mentioned descriptor L_A, i.e. the A-weighted sound pressure level.

If the operator or the train supplier has other, better sound quality descriptors than *AI*, verified by convincing human tests, they may be used. The important matter is to thoroughly consider the issue of sound quality, to have an adequate objective descriptor, and to eliminate annoying noise being produced by the train.

In order to master sound quality a number of means and measures are needed:

- A product and performance specification that includes all relevant noise issues;
- Careful design and selection of materials as well as mounting methods that maintain good function for a long time;
- Testing for conformity with the performance specification before delivery;
- Service and maintenance schemes that include regular inspection of and necessary correction to component mountings, suspension characteristics, wheel surface status, wear to components, etc.

7. Aerodynamic performance

7.1 Overview and TSI requirements

The final design of a train is an optimization that balances various requirements. These can originate from specific customer requests which in their turn are formulated to meet the requirements of the transport market in a specific region. Further, legal specifications from authorities must be adhered to. Designing the outer shape of a train has a major impact on the performance of the vehicle.

Aerodynamically induced forces are at least proportional to speed, in many cases however as the square of speed. For example, if speed is increased by 50%, the air drag force is increased by a factor of approximately 2.25, i.e. 125% higher.

Several issues have to be considered: air drag, impulse resistance, slipstream wind speeds, pressure pulses, pressure variation in tunnels and aerodynamic loads due to strong crosswinds.

Air drag, i.e. the resistance against motion induced from the relative wind due to speed (and sometimes also from the wind speed relative to the ground). Air drag is due both to pressure around the front, to a wake behind the rear end, as well as to friction resistance along the train, including the influence of inter-car gaps and protruding objects on the train. This resistance is essentially proportional to the square of speed. Air drag should be as low as possible. Lower drag reduces the energy use.

Impulse resistance, due to the mass of accelerated air (ventilation air and other masses of air caught and then released by the train). This resistance is essentially proportional to speed. In the speed range in question (160-320 km/h), impulse resistance is much lower than air drag, but is not negligible.

Aerodynamic loads, caused by the **slipstream** along the train, that affect track workers and passengers on a platform close to the train when passing at speed. At the speeds in question (160-320 km/h), these loads are essentially proportional to the train's speed, but speed may be of higher importance in the wake behind the train.

Maximum permitted induced air speed is specified in TSI HS RST [N1]:

- For track workers: max 20 m/s peak for speeds below 250 km/h (22 m/s for speeds ≥250 km/h), measured 3 m from track centre, determined as the average plus two standard deviations from at least 20 tests.
- **For passengers on platform: max 15.5 m/s peak at 200 km/h, 3 m from track centre, 1.2 m above platform level, determined as the average plus two standard deviations from at least 20 tests.**

  Note that no maximum air speed is specified for when train speed exceeds 200 km/h. If trains have to pass platforms at higher speeds (for example up to 249 km/h) with passengers standing on the platform, we propose that special arrangements be made at the platforms, for example extended safety distances, barriers, and acoustic and/or flashing visual alarms. Such practices, however, must be approved by the responsible national authorities.

Pressure loads in open air, i.e. pressure pulses generating stresses on surrounding structures and other trains in the speed range in question, pressure loads are essentially proportional to the square of speed, but may have a lower dependency. Maximum permitted pressure loads are specified in TSI HS RST [N1]:

- Peak-to-peak pressure change: ≤ 720 Pa at speeds below 250 km/h (795 Pa at 250 km/h), measured 2.5 m from track centre, determined as the average plus two standard deviations from at least 10 tests. This must be shown for seven different heights between 1.5−3.3 m above top of rail.

Pressure variations in tunnels, influencing pressure variations within the train (own train and other trains in the tunnel). In the speed range in question, pressure loads are approximately proportional to the square of speed, but may have a lower dependency.

Maximum permitted pressure variations in tunnels are specified in TSI HS RST [N1]:

≤ 3700 Pa at 200 km/h in a tunnel cross-section area of 53.6 m^2

(≤ 4100 Pa at 250 km/h for Class 1 trains in a tunnel cross-section of 63 m^2)

Some additional detailed requirements are also specified. The TSI requirements are independent of whether the train has carbody pressure tightness or not.

According to TSI [N2], the cross-sectional area of the tunnel shall be enlarged by the infrastructure manager, so as to comply with pressure variations indicated above, if permitted speeds are higher than the above-mentioned reference speeds.

Cross-winds striking the train may in exceptional cases cause the train to turn over, which is a severe safety case. The lateral and lifting forces must therefore be controlled and limited. The cross-wind issue is further elaborated in Section 7.3.

The final goal is to generate an outer shape design which has good performance with respect to both the slipstream generated behind the train and the pressure distribution around the front because on most modern trains the front can also operate as the rear. Improving the performance with respect to slipstream has significant impact on aerodynamic drag and energy use (about 15% of the energy can sometimes be saved by means of appropriate optimization)

TSI requirements concerning slipstream air speeds and head pressure pulse are more difficult to fulfil for wide-body trains and high (double-decker) trains. As shown above, the air speed and pressure pulses is to be measured 2.5 or 3 m from the track centre line, not at a specified distance from the train's outer surface. The TSI requirements are derived from experiences from trains with cross-sections as used in continental Europe, which do not represent Swedish or Nordic conditions.

7.2 Development of prediction methodology

All the phenomena introduced in Section 7.1 need to be taken into full consideration in the design stage of a new train. If the train fails to meet one or more criteria in the verification testing process, this will probably cause serious delays and/or high additional cost, as many aerodynamic phenomena are dependent on the train's basic design. The interdependence between all the above-mentioned phenomena should also be studied systematically by varying parameters.

Research conducted for Gröna Tåget

In the Gröna Tåget programme we have developed a system that helps to optimize the aerodynamic performance of rail vehicles using state-of-the-art computer-aided engineering (CAE) tools. Traditionally, a way of exploring the set of design modifications with regard to aerodynamic performance, has been to check them experimentally in a wind tunnel. The iterative development of further designs is based on theory and engineering skills. However, this approach is rather costly and time-consuming. Further, in many cases, due to the large number of possible designs, it is unlikely that the truly optimal design can be found without the assistance of automatic tools. Optimization procedures are facilitated by the use of today's fast computers.

An important objective of the Gröna Tåget programme was to increase knowledge of slipstream air flow of wide body trains at high speeds, to fully understand the implications for the front shape and to develop a prediction methodology. The front design will in parallel be optimized with respect to head pressure pulse, cross-wind performance and air drag, see further Section 9.3 and 9.4.

The starting point has been the REGINA 250 test train which has been subject to extensive aerodynamic testing, partly in order to collect reference data for validation of simulation models. An example of slipstream wind speed during passage of the Gröna Tåget REGINA 250 test train is shown in Figure 7-1. It is observed that bogie shirts are beneficial from a slipstream point of view.

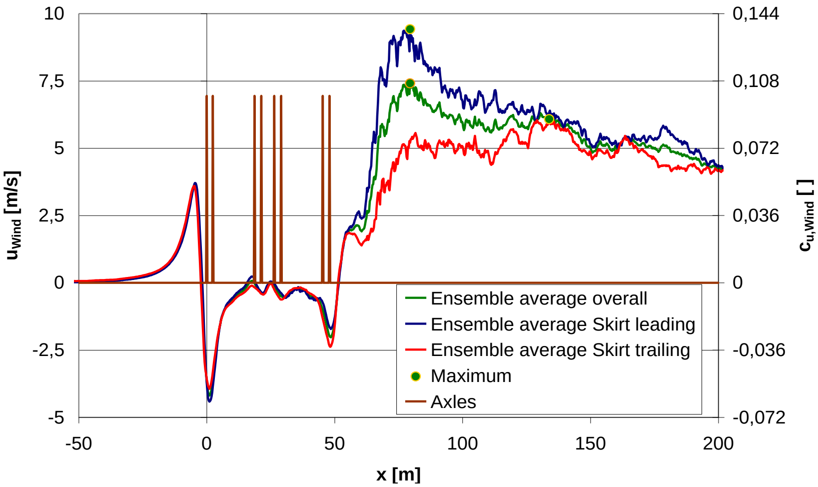

Figure 7-1 Measured slipstream wind speed at the track side during passage of the Gröna Tåget REGINA 250 test train. Source: Bombardier.

In order to improve the relation between the shape of the front of the train and the slipstream effect, the work performed at KTH has included 'Proper orthogonal decomposition (POD)' and 'Koopman mode decomposition' to extract the most dominant flow structures of a simulated flow in the wake of a high-speed train. The ability to use decomposition methods to successfully identify dominant flow structures for an engineering geometry is achieved by using a flow field simulated with 'Detached Eddy Simulation (DES)', a turbulence model enabling time-accurate solutions of the flows around engineering geometries. The work is reported in Muld et al [16, 28]. An example of simulated air flow along and behind a train is shown in Figure 7-2.

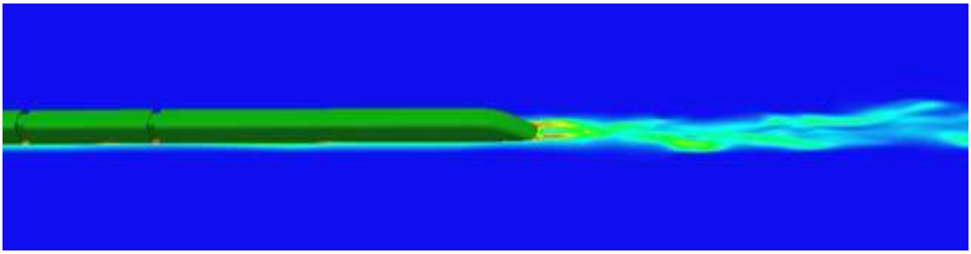

Figure 7-2 Visualization of the air flow along and behind the train, as computed with CFD methodology. Source: KTH.

A parallel activity is the development of computational models at CHALMERS, mainly concentrated around pressure pulse and cross-wind forces, the latter partly in tunnels or at tunnel exits. The development was done step-wise from simpler models to more complex ones. The most critical issue is to achieve realistic conditions for the cross-wind meeting the train just outside the tunnel. In the final and most advanced model, a moving computational grid (thus a moving train) was applied. This is reported in Krajnović et al [19]. The flow around two passing trains is shown in Figure 7-3.

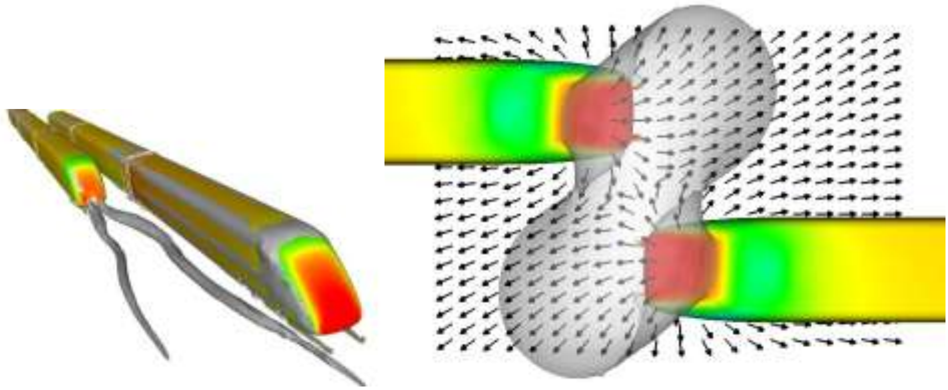

Figure 7-3 Visualization of the flow around two trains passing each other. The simulation included moving computational grids. Source: Chalmers [19]

7.3 Effects of strong crosswind

Loads from cross-winds may cause a risk of **overturning** the train about one of the rails. In particular in combination with high lateral acceleration (high cant deficiency) when curving with tilting carbodies, the risks must be thoroughly evaluated. This is a strong safety requirement. Although the risk of train turnover is not only dependent on aerodynamic forces (suspension and general vehicle dynamics are also important), aerodynamic forces are the most decisive factor. This issue is therefore discussed in this section.

The **leading vehicle in a train** usually experiences the highest load from crosswinds. This vehicle therefore **usually the most critical**, at least if it has roughly the same mass and axle load as other vehicles in the train. Higher mass and low centre of gravity stabilize the vehicles in strong crosswinds.

Present TSI specifications are only valid for Class 1 non-tilting high-speed trains with maximum speed of 250 km/h or more. For these trains, TSI defines a set of Characteristic Reference Wind Curves (CRWC), where minimum required train performance regarding wind speed is shown for different situations - straight track and curves at different speeds, for embankments and flat ground, different wind angles and lateral acceleration, etc. The maximum lateral acceleration specified in the TSI is 1.0 m/s^2, corresponding to 153 mm of cant deficiency The safety criterion according to TSI is that the peak wheel unloading must not be higher than 90% of the nominal wheel load on average on the inner wheels of the most critical running gear in the train. TSI specifies a cross-wind gust of 2−3 seconds' duration, overlaid on an otherwise constant wind speed of 60% of the gust wind. A detailed description is given in TSI HS RST (Section 4.2.6.3 and Appendix G) [N1] and partly in Leander [5].

For the currently on-going revision of the TSI, the EU FP7 project AeroTRAIN [ref: www.triotrain.eu] (ending in May 2012) aims to provide input for TSI requirements relating to conventional trains and Class 2 high-speed trains on a new reference setup according to EN 14067-6. There will also be a revision of the high- speed Class 1 criteria based on the same principles. The approach will be similar to the current TSI HS RST as mentioned above. However, tilting trains will not be covered.

The TSI criterion can be seen as a tentative requirement, based on the actual performance of presently existing high-speed trains in continental Europe, said to have a safe history of operation. It is an indirect criterion intended to have a margin against train turnover. It is thus not possible to make an estimation of the probability of train turnover at different locations along the line, depending on curving speed, meteorological wind probability, etc. Further, **TSI specifications are not applicable to tilting trains** running with high lateral acceleration (cant deficiency) in curves. This fact does not exclude versions of Gröna Tåget without tilting carbodies, made for speeds of 250 km/h and above, being required to meet the TSI requirements for non-tilting trains.

According to TSI, the infrastructure manager shall, if necessary, take measures to maintain the level of crosswind safety by locally reducing the speed, installing wind protection (barriers) or by other means. However, the **crosswind safety targets** and the **process of providing safety** from crosswinds are not defined in TSI, but are to be made **in accordance with national standards** [N2].

Historically, comprehensive studies of this subject have been made in Sweden, in particular for the high-speed tilting train X2 (in the 1980s) and more recently for the newly built high-speed Bothnia Line (Botniabanan).

Our conclusion from the above-mentioned is that safety assessment regarding train turnover for tilting trains in strong crosswinds cannot be made according to the (tentative) TSI specifications. Another process must be applied. It is proposed that experience from earlier national (Swedish) studies be used.

Studies conducted for Gröna Tåget

In the Gröna Tåget programme, no specific studies or developments regarding the risk assessment for train turnover at strong crosswinds have been made. Instead, numerical methods for simulation of aerodynamic loads have been developed, partly regarding cross-winds. Reliable estimations are critical because train turnover performance cannot be verified by testing.

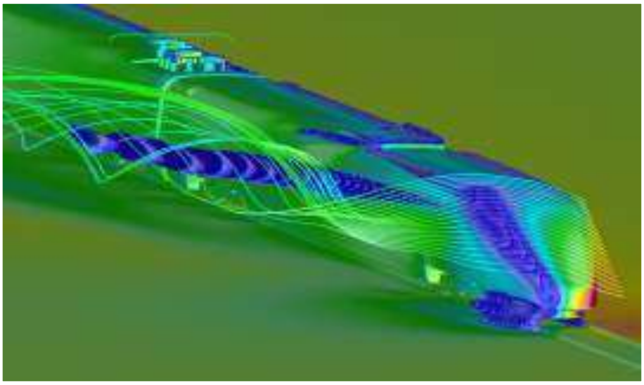

Figure 7-4 Visualization of the air flow under the influence of a strong crosswind, computed with CFD methodology. Source: Bombardier

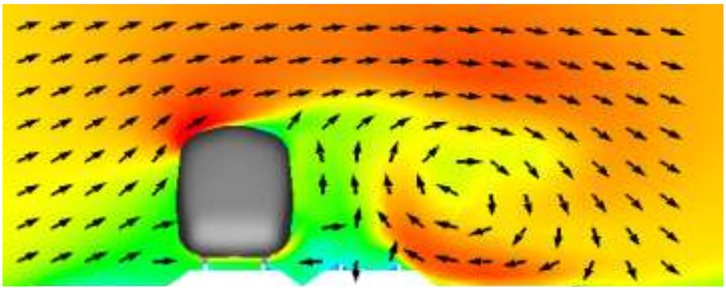

Figure 7-5 Visualization of the air flow in a cross-section under the influence of a strong crosswind, computed with CFD methodology. Source: Chalmers [21]

Proposals

As stated earlier, the process of providing safety from crosswinds is not defined in TSI, but is to be carried out **in accordance with national standards**. A Swedish national view and conscious treatment of crosswind safety are required.

The safety of trains in operation is quite complex. It depends on the train's capacity to withstand wind and the wind probability locally along and above the track. The local flow field above the track depends on the surrounding topography, roughness (atmospheric boundary layer) and particularities of the infrastructure (e.g. embankments and viaducts). An example of how to make this assessment is discussed below. Doing that for existing and new lines would involve significant work.

However, experience shows that current operation in Europe (almost no accidents) and in Sweden (no accidents to date) is largely safe. Hence, an alternative is to use this experience together with a relative assessment of new vehicles and existing vehicles with a safe safety record, which is the basis of the vehicle assessment in TSI. Then complement this with assessments of new lines to ensure that the crosswind risk is not increased or too high. One idea might be to introduce a wind speed above which train speeds are drastically reduced or train operation stopped.

For tilting trains, as there is no TSI requirement foreseen even in the next TSI revision, the required level of wind capacity needs to be determined. Two simple alternatives exist:

- Have the same minimum wind speed capacity as for other trains, but each at their maximum train speed and cant deficiency.
- Have the same requirement as existing tilting trains.

These simple alternatives might be too conservative. They are not even suitable for assessing preventive measures in the infrastructure. Alternatively – or in combination – a risk assessment method can be used to find the required level of wind capacity of the train by comparing with the minimum capacity of a non-tilting train (with a sufficiently long historic period of safe operation) on a chosen representative or critical line.

A method for safety assessment regarding crosswinds has earlier been developed and applied to the new high-speed Bothnia Line in northern Sweden, see Andersson et al [20]. This line has a length of 190 km and partly approaches the coastline, where strong winds are expected. There are 15 tunnels and 140 bridges. Further, the Bothnia Line is designed and built for tilting-train operation at speeds of up to 250 km/h.

Assessment of the risk of overturning consists of six steps, defined below:

1. Critical locations along the actual line with expected strong crosswinds or sudden changes in cross winds are identified. Critical locations are embankments, open landscape in vicinity of the sea, tunnel exits exposed to wind, curves with high cant deficiency, etc.
2. The probability of strong winds is determined from meteorological data (available from a meteorological institute) at the critical locations, including consideration to topological particularities, embankments, bridges, etc. The wind probability must be given for different wind angles.

3. Wind forces and moments in different directions (lateral, lift, roll, pitch and yaw) are estimated with CFD methods; as a complement wind tunnel tests can also be made (the latter is required according to the TSI for Class 1 trains).
4. Critical cross-wind speeds for the train in question are determined by using validated multi-body system (MBS) simulation software, as is also used in other vehicle dynamics simulations. Real turnover must be simulated in this case, because this information will be used later for risk analysis (i.e. an indirect criterion as percentage wheel unloading is not sufficient). Consideration must be taken to wind forces at different train speeds and cant deficiencies, as well as to the train's dynamic behaviour due to its suspension and masses. Such a critical crosswind speed characteristic for a high-speed train is shown in Figure 7-6.
5. A risk analysis is performed, using meteorological wind data according to (2) and critical wind speeds according to (4).
6. An acceptable risk is determined. For the Bothnia Line a risk of a train turn-over accident per 10^9 or 10^{10} train-km was considered acceptable, as this risk is approximately equivalent to the general risk in railway operations. This safety level can of course be discussed and questioned as being too high, as the risk of overturning is estimated for short and very critical locations only. The safety level should be approved by the responsible authorities in cooperation with operators and train suppliers.

For a full understanding and details; see [20].

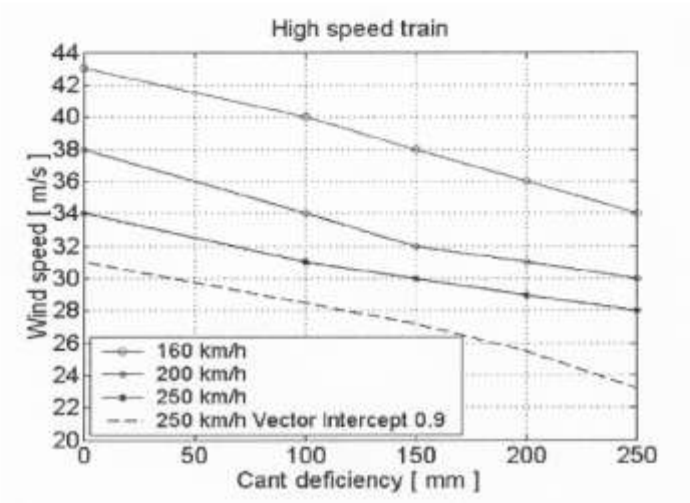

Figure 7-6 Example of critical wind speed characteristics for a high-speed train, as function of cant deficiency and speed. The three upper cases (160–250 km/h) are related to real (simulated) train overturning, while the lowest is related to 90% wheel unloading.
Note that wind speed is constant in this case. The 'vector intercept 0.9' corresponds to the same wheel unloading, i.e. 90%. Source [20]

Example: For the Bothnia Line, six critical locations were identified according to the initial investigation described in step (1). In the final risk analysis (5), two locations along the 190 km line were found to exceed the accepted risk level according to (6). Both of them were locations close to the sea. At these locations, either wind barriers or speed restrictions have to be applied. For the Bothnia Line, the consequences of crosswind were thus very moderate. Along other lines, for example along the Swedish West Coast, in Denmark or in mountain regions in Norway, the consequences may be more extensive.

Note: If Gröna Tåget is designed and operated as a Class 1 train (250 km/h or above) a separate investigation must be made according to TSI, applying the highest lateral acceleration that the train will experience without using carbody tilt, i.e. 1.0–1.2 m/s^2 (153–183 mm cant deficiency); c.f. Section 2.4. A corresponding safety assessment using meteorological data and infrastructure measures, according to national standards, must be made also in this case.

Also note that train performance and measures in the infrastructure must be coordinated. The example characteristic in Figure 7-6, however, could be regarded as a first preliminary level of the crosswind performance of a tilting train.

General advice

Generally speaking, a high-speed train, in particular trains with carbody tilt and enhanced speed in curves, must be carefully investigated and designed with regard to turnover in strong cross-winds. An appropriately designed front and cross-section is crucial, as well as low centre of gravity, small lateral suspension motions and not too low axle load, in particular for the most critical front vehicle of the train.

7.4 Aerodynamic optimization

Within the framework of the Gröna Tåget programme, a comprehensive and innovative optimization process has been developed which helps to develop and build new products by calculating the best way to reduce head pressure pulse and drag. The system is based on genetic algorithms that use

- Parameterized, three-dimensional models; see Figure 7-7.
- Detailed simulation of head-pressure pulse, cross-wind forces and drag
- Decisive optimization software

The objective is to give input to front design including shape constraints. This includes front design considerations such as crash structure, industrial design and ergonomic constraints such as the visibility of signals along the track as well as the space available for the passenger compartment. It also considers the necessary geometry for coupler interaction. It then offers a choice of the best possible solutions to optimize the vehicle's aerodynamic performance. For details, see Herbst et al [17], Kållberg [18], Krajnović et al [21].

The aerodynamic work package will be completed in 2012. No final report on this subject was therefore available in December 2011.

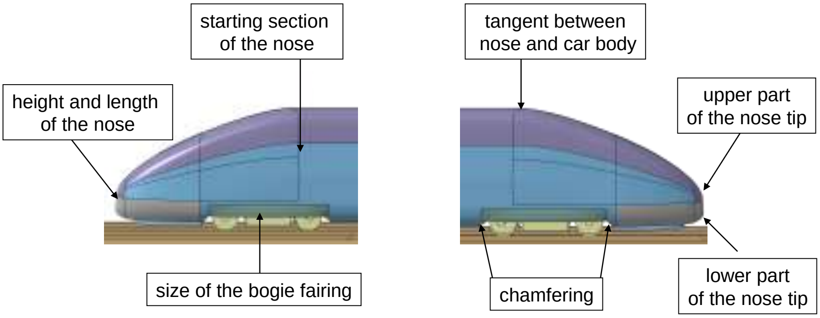

Figure 7-7 Examples of parameters and considerations for optimization of the front shape. Source: Bombardier.

7.5 Increased air drag in tunnels

The air drag increases in tunnels, due to changes in the boundary layer around the train. A narrow tunnel (with small cross-sectional area) will increase air drag more than a wide tunnel.

Tests have been performed with the REGINA 250 wide-body test train in tunnels on the newly built Bothnia Line at speeds up to 275 km/h. In tunnels with a cross section area of 47 m^2, the air drag increased 2.2 times that of the open-air conditions.

The factor of 2.2 is about 15% lower than an extrapolation of an earlier prediction referred to in [11] (page 13).

The somewhat lower factor found in the above-mentioned on-track tests with a real wide-body train will make the average energy use on a very-high-speed line slightly lower (about 1% less than previously predicted, with the same tunnel area and number of tunnels) or will make allowances for a slightly higher number of tunnels along the line. Due to the limited influence of this change, it would not make sense to revise the earlier estimations of energy use of the future Gröna Tåget.

7.6 Proposals concerning aerodynamic performance

Some proposals regarding aerodynamic performance of the Gröna Tåget concept are made below. They are considered to be means of achieving realistic targets for an environmentally friendly train with high safety, that is also compliant with the TSI specifications when applicable.

Air drag and impulse resistance

Based on experience from modern high-speed trains in general [11, 21], as well as from the optimization activities, quite high performance is expected.

With moderate effort, an average 6-car train intended for a maximum speed of 250 km/h may achieve in the open air

- Air drag and impulse resistance $\leq 60\,v + 6.1v^2$ (N), where v is train speed (m/s).

For this purpose, some exterior roof equipment, inter-car gaps and the upper parts of bogies are proposed to be partly shielded. The front should be appropriately designed, although without reducing passenger space by more than approximately 3 m, compared with an intermediate car without streamlined front and driver's cab. The underframe containing technical equipment should be closed.

With more ambitious targets, in particular for top speeds higher than 250 km/h, more extensive measures should be taken. These measures may include more streamlined and longer front and tail, although without impeding passenger space more than some reduced height of the interior ceiling. They may also include extended shielding of bogies, still more shielded air gaps between cars, as well as closed underframes also at the car-ends (i.e. outside bogies). Equipment on the roof (isolators, circuit breakers, etc) should have improved shielding and the pantograph should be designed for low air drag. These measures are expected to reduce air drag so that the following is achieved for a 6-car average train in the open air:

- Air drag and impulse resistance $\leq 80\, v + 4.7\, v^2$ (N), where v is train speed (m/s).

Some of the more ambitious measures can possibly also be applied to trains with a top speed of 250 km/h and lower.

Note that the above-mentioned measures are example proposals; alternative measures may also be considered by the train supplier making the final optimization. Also note that the impulse resistance (i.e. the first term in the formulas above) is partly due to the intake of ventilation air to the train.

Slipstream wind speed and pressure variations

The preferred performance is strictly according to TSI. An alternative might be to measure the slipstream wind speed at the same lateral distance from the side wall of a wide-body train as for a train with European continental width. The latter, however, is an exception from TSI and will require dispensation from the national authorities.

Adaption to winter climate

The adaption of the train in order to safeguard reliable operation in a harsh winter climate is partly due to the aerodynamic performance. In particular stagnation points and sharp edges should be avoided in open areas of the bogies and the underframe. See further Kloow [13] and the summary in Section 5.2.1.

8. Track friendliness and vehicle-track interaction

8.1 Overview

Vehicle-track interaction is one of the main performance issues for high-speed trains.

The performance of the vehicle-track system must safeguard:

- Safe operation
- Low deterioration of the track and low wheel maintenance costs
- Good ride comfort and low incidence of motion sickness
- Limited sway of the vehicle under the influence of lateral forces.

The dynamic behaviour of a rail vehicle running on the track is determined by

- Speed
- Curvature and cant deficiency (the latter being equivalent to mean lateral acceleration in the track-plane when curving)
- Wheel-rail contact conditions (geometry and friction)
- Mass, inertia and location of centre of gravity for carbody, bogies and wheelsets
- Suspension characteristics, both primary and secondary suspension
- Track irregularities (sometimes referred to as the inverse: track geometry quality).

Minimum legal requirements related to these issues are partly specified in TSI HS RST [N1] and EN 14 363 [N10], the latter specifying acceptance tests in detail. Evaluation of ride comfort is specified in EN 12 299 [N11]. An extensive summary of requirements as well as a discussion are presented in Sections 6.2-6.4 in Leander [5]. The specific legal requirements are briefly presented in the Sections 8.2-8.6 below.

Generally, the minimum legal requirements are modest and not necessarily optimum from an operational and economic point of view. The scope of the legal requirements is mainly to ensure safety and interoperability within Europe. Requirements on passenger ride comfort are either very low or considered as an open issue for railway operators.

8.2 Safety and dynamic stability

- Safety related to vehicle-track interaction has several aspects:
- Safety against **derailment** in normal operation (curve radius $R \geq 250$ m)
- Safety against **derailment on twisted track** (curve radius $R < 250$ m)
- Safety against **lateral track shift**
- Safety against **dynamic instability** (i.e. periodic lateral movements within the wheel-rail clearance)
- Safety against vehicle **turnover in strong cross-winds** (dealt with in Section 7.3).

8.2.1 Derailment in normal operation

There is a risk that the wheel flange may climb up the gauging side of the rail, if the lateral force Y is high in relation to the vertical force Q, the latter 'pressing down' the wheel onto the rail. Requirements according to TSI and EN shall be applied. The ratio between lateral force Y and vertical force Q shall meet the criterion

$$Y/Q \leq 0.8$$

This criterion must be fulfilled in normal operation in curves of radius R ≥ 250m, verified in acceptance tests on different track standards according to EN 14 363.

8.2.2 Derailment on twisted track

The risk of flange climbing is increased if the wheel is unloaded. A common cause of wheel unloading is twist in the track. Track twist is the difference in the track's cross level between two measuring positions along the track.

Requirements according to TSI and EN shall be applied. The ratio between lateral force Y and vertical force Q shall meet the criterion

$$Y/Q \leq \frac{\tan\gamma - 0.36}{1 + 0.36\tan\gamma}$$

where γ is the flange angle, i.e. the angle between the track plane and the steepest flange flank. For example, with a flange angle of 70° maximum Y/Q shall be 1.2.

New vehicle designs shall be subject to acceptance tests on a specially prepared test track at low speed. The applied track twist depends on the longitudinal distance along the track. For example, within a normal bogie (axle distance ≤ 4m) the track twist between axles shall be 7‰ in the tests, while the track twist within a 19m bogie centre distance shall be 3.05‰, i.e. 58 mm. The test track shall be 'dry' and also include a curve with radius R = 150 m. Further details are specified in EN 14 363 [N11].

Acceptance tests shall be made with air springs in both inflated and deflated condition. For vehicles with active systems (carbody tilt and/or active suspension) credible failure modes have to be considered.

8.2.3 Lateral track-shift forces

If the resulting lateral force on the track from any wheelset is too high, there is a risk that the lateral position (the alignment) of the track will be shifted permanently out of position. This force is thus the sum of lateral forces ΣY on the two wheels of the wheelset, see Figure 8-1.

If the track shift is small and occasional, this could cause some additional maintenance. With large lateral track shift – say more than specified as 'Immediate Action Limit' in EN 13 848-5 [N13] – the shift becomes a safety issue.

The following criterion on the permissible lateral track shift force from one wheelset is specified in TSI and EN 14 363, valid for multiple units, locomotives and passenger cars:

$\Sigma Y_{2m} \leq (10 + P_0/3)$ (kN) as sliding mean over 2 m, where P_0 is the static axle load.

New vehicle designs shall be subject to on-track acceptance tests with instrumented force-measuring wheelsets, measuring ΣY on different standards of track.

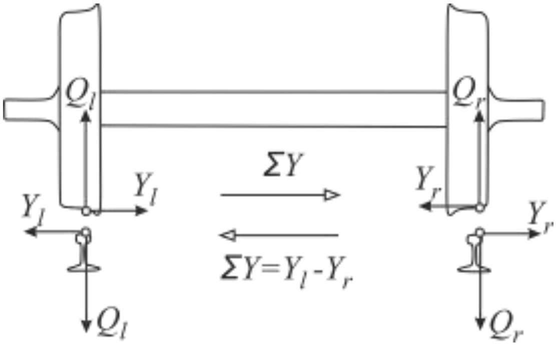

Figure 8-1 Track forces

Note: The established safety criterion shown above is determined for a non-stabilized track with mono-block sleepers, i.e. it is a 'worst case'. After some time and traffic load the track is stabilized and the resistance against lateral track shift is increased. After 0.1 million gross tonnes the track resistance is typically increased by 40–60% and after 1 million gross tonnes the track resistance is roughly doubled. In most cases, therefore, there are considerable margins. Nevertheless, the generally accepted criterion must be respected.

8.2.4 Dynamic stability

A conventional railway wheelset has conical wheel treads and a stiff axle between the wheels. Such a wheelset has an inherent **natural steering ability** both on straight track and on curves. On straight track and on large-radius curves it performs lateral, approximately **sinusoidal, oscillations** when they are rolling along the track after a lateral disturbance. The bogies and the carbody interact with these oscillations and sometimes the wheelset motions are amplified by this mutual interaction.

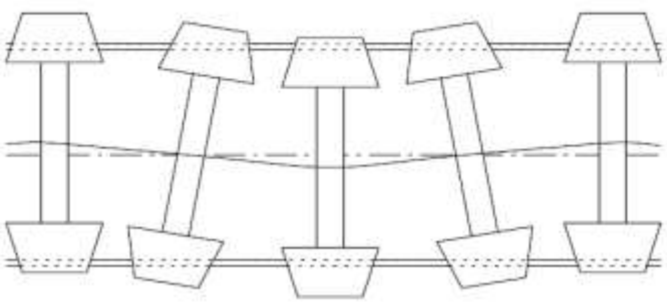

Figure 8-2 Sinusoidal lateral motion of a wheelset with conical wheels

The lateral oscillations may be damped or undamped. Above a certain speed, the oscillations usually tend to be sustained and sometimes violent, i.e. there is a so-called limit-cycle oscillation, limited by the wheel flanges striking the rails. This phenomenon is usually called **instability** or **hunting**, which is a potential problem for most rail vehicles that have normal wheelsets with conical wheel treads. Such hunting motions would produce both a poor ride and possibly excessive, unsafe lateral forces on the track. Hunting usually occurs on straight track but sometimes also on large-radius curves, say from R = 1,000 m and above.

The safety criterion for stability is that the r.m.s. (root mean square) lateral track shift forces are below a specified limit value, viz

$\Sigma Y_{rms,100m} \leq 0.5\ (10 + P_0/3)$ (kN) as r.m.s. measured over 100m.

This is half the numerical value of the permitted ΣY_{2m} sliding mean in Section 8.2.3.

Details on acceptance testing procedures are specified in EN 14 363. For example it is specified that acceptance tests shall be made in 'dry' track conditions as such conditions usually are 'worst case'. The maximum test speed is the maximum permitted operation speed (top speed) plus 10%.

A very decisive factor in dynamic stability is the so-called **equivalent conicity**, which (somewhat simplified) can be said to be the rate of change of rolling radius of the wheels when the wheelset is displaced laterally on the track. Equivalent conicity is dependent on a number of track and vehicle parameters, for example track gauge, wheelset gauge (between gauging faces on the flanges), rail profiles and inclination as well as wheel profiles. See for example Andersson et al [39].

A high equivalent conicity will cause a short wavelength of the above-mentioned sinusoidal oscillations, thus the frequency of the oscillation will increase (at constant speed) with higher conicity. A higher speed will also increase the oscillation (or hunting) frequency. Traditionally, the risk of hunting is considered be highest at high speed and high equivalent conicity, with hunting frequencies of 4–8 Hz. However, low equivalent conicity may sometimes also generate sustained lateral oscillations with a lower frequency of 1−2 Hz. The latter may involve considerable carbody motions.

The traditional and established awareness of 'high-frequency hunting' is reflected in the TSI and EN 14 363, which prescribe (upper) design limits for equivalent conicity that should be respected in cooperation between the train operator and the infrastructure manager. According to TSI, the minimum design limit values of equivalent conicity shall be according to Table 8-1, middle column.

Proposals

The minimum limit values according to TSI are to be determined in a number of ideal conditions with ideal rail profiles and rail inclination. It will, however, be difficult to maintain these conditions in real operations with modest rail and wheel maintenance costs. We therefore propose that vehicles and bogies be designed for at least the limit values as shown in the right-hand column in Table 8-1. This is not unique, as some railways (for example in Germany) require higher limit values than the minimum.

We also propose that the vehicle shall run stably **at any speed** up to maximum operating speed (plus a speed margin), at any conicity from 0.01 up to the proposed limit values in the right-hand column in Table 8-1.

Table 8-1 Equivalent conicity – minimum and proposed limit values for different maximum operating speeds (top speeds)

Max operating speed (km/h)	*Eq. conicity (minimum TSI)*	*Eq. conicity (proposed)*
≥ 190 and ≤ 230	0.25	0.40
> 230 and ≤ 280	0.20	0.30
> 280 and ≤ 300	0.10	0.25
> 300	0.10	0.20

Dynamic stability to prevent hunting is a necessary requirement of the vehicle-track system. It is not, however, advisable to design for maximum stability or excessive stability margins, but rather to achieve **sufficient stability** and then optimize for minimum track deterioration and vehicle maintenance a good ride comfort.

Note: If stability is dependent on devices which are not fail-safe, an on-board instability alarm shall be fitted on trains with a top speed higher than 220 km/h, according to TSI. For example, only one single yaw damper per bogie side would not be considered as fail-safe.

8.3 Forces and wear on wheels and rails

For reasons of maintenance cost it is necessary that lateral and vertical forces on track are limited. TSI HS RST defines such requirements which should be considered as minimum ones. All requirements regarding track forces must be verified in acceptance tests according to EN 14 363.

8.3.1 Nominal static axle load

For high-speed trains consisting of electric multiple units the following axle loads are permitted according to TSI HS RST:

- For top speeds ≤ 250 km/h: Axle load ≤ 18 tonnes;
- For top speeds > 250 km/h: Axle load ≤ 17 tonnes.

The axle load shall be measured in service condition with all seats occupied (80 kg per seat) and 2/3 of maximum mass of consumables.

8.3.2 Vertical dynamic wheel load

In addition to static axle load requirements, the maximum permissible dynamic wheel loads are also specified in TSI and EN 14 363:

- For top speeds ≤ 250km/h: Dynamic wheel load $Q \leq 180$ kN;
- For top speeds > 250 and ≤ 300km/h: Dynamic wheel load $Q \leq 170$ kN;
- For top speeds > 300km/h: Dynamic wheel load $Q \leq 160$ kN.

According to the TSI and EN standards, vertical dynamic wheel-rail forces shall be determined after low-pass filtering with 20 Hz limit frequency. This implies that peak forces of short duration will not be part of the evaluation and will thus be 'hidden' realities. The effect of un-sprung masses (i.e. the masses hammering on the track) as result of wheel and rail roughness from wavelengths below about 3 m is therefore ignored. High-frequency forces may deteriorate the track (and the wheels) as well. They are also part of the proposed track deterioration model developed by Banverket (now Trafikverket) according to Section 8.4 [42].

Proposal

We propose that the **higher frequency content of vertical dynamic wheel loads** also be evaluated in tests, as this is part of the track deterioration model developed by Banverket (Trafikverket) [42]. A suitable limit frequency may be the highest sleeper-passing frequency at the top speed plus 10%. For example: at a top speed of 250km/h and a sleeper spacing of 0.60 m, the limit frequency will be 127 Hz, say 130 Hz. At a top speed of 300 km/h the limit frequency will be about 150 Hz.

There are no strict limit values for the high-frequency vertical forces. For the Swedish high-speed train X2, the high-frequency forces have been determined to be about 160kN, although not statistically evaluated with the method that the current EN prescribes. In recent tests with the REGINA 250 test train (see Section 8.6), the maximum vertical dynamic forces at 140 Hz low-pass filtering were 25−40 kN above the 20 Hz forces at a test speed of 275 km/h. The highest 140 Hz forces would meet the TSI requirements for 20Hz filtering; i.e. the 170 kN limit value. See further Section 8.7.2.

The rate of track deterioration due to vertical forces (track settlement, component fatigue) is approximately proportional to about the third power of the applied force, i.e. to Q^3. This relation was established after a thorough literature study in Öberg [42].

8.3.3 Maximum lateral guiding force

In order to avoid excessive wear to rails and wheels in curves the TSI and EN specify an upper limit for the permissible lateral guiding force in curves. For constant geometrical and friction conditions, there is an almost linear relationship between wear and lateral force.

TSI and EN 14 363 take the mean lateral guiding force during a circular curve negotiation – usually called the quasi-static guiding force – as a measure of wear. This force is denoted Y_{qst} with a single limit value

$$Y_{qst} \leq 60 \text{ kN.}$$

This limit value shall be met in circular curves with radii 250–400m on dry track.

The linear relationship between guiding force and wear is a reasonable approximation as long as the contact conditions are constant. However, with changing contact conditions, i.e. varying contact geometry or friction, the linear relationship may not be true. Two examples: (1) two-point contact (instead of on-point) may increase wear much more than the guiding force; (2) with lubrication of the outer rail the natural steering ability of the wheelset may be reduced, which will produce a higher guiding force but less wear.

8.3.4 Friction energy dissipation

Creep is an important factor in the wear context. In the wheel-rail interface, creep is the ratio between the sliding velocity in the contact patch and the forward speed.

The dissipation of **friction energy dissipation** in the wheel-rail contact is considered to be a good overall determinator of the volume of wear and also partly of rolling contact fatigue (RCF). Energy dissipation includes the influence of many relevant factors, such as wheel-rail geometry, wheel-rail forces, creep and friction.

The total friction energy dissipation in curves is the same as the additional running resistance experienced in curves. However, the energy dissipation is not evenly distributed between the wheels; the outer guiding wheel of each bogie has usually the highest dissipation, while wheels on the trailing wheelset have less than average.

It is not straightforward to measure energy dissipation at each individual wheel. Instead, simulation with validated multi-body system (MBS) models is used. Simulated energy dissipation depends on the tangential friction force vector F (sometimes called creep force), and the creep v, if we omit the effect of rotation in the contact area. An approximate measure of energy dissipation is the so-called **wear index**:

Wear index $= \boldsymbol{F} \cdot \boldsymbol{v}$

i.e. the vector product of friction force and creep. Energy dissipation (wear index) is evaluated in energy per metre of running distance, i.e. Nm/m.

Wear and rolling contact fatigue are dependent on the wear index, although the relationships are not linear. Based on work done by the former AEA Technology for RSSB (Railway Standards and Safety Board, UK), a model for rail surface damage is reported by Burstow [41]. This model quantifies the cost of damage caused by abrasive wear and rolling contact fatigue, verified through comparison with measured field data on rail surface damage. It is presented in Figure 8-3. The RSSB model is also part of the Swedish Transport Administration's (the National Rail Administration's) track deterioration model [42].

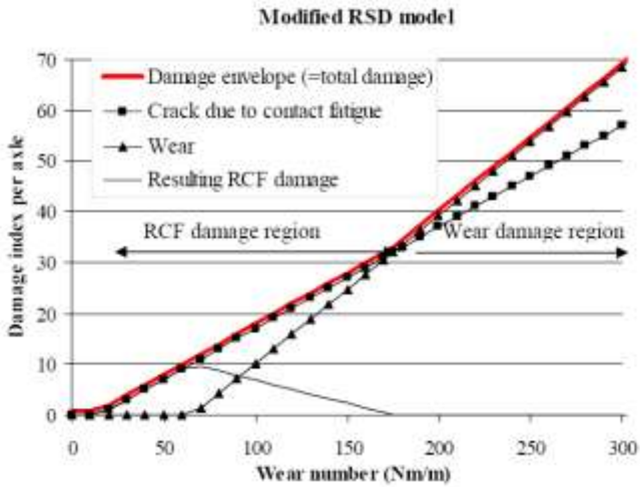

Figure 8-3 The Rail Surface Damage Model according to RSSB and the Swedish Transport Administration.

The total damage is a progressively increasing function of the wear index (also called wear number) from 15 Nm/m and up. For wear numbers up to about 90 RCF damage predominates, while abrasive wear predominates for higher wear numbers. Models that are more comprehensive also consider the contact pressure and sometimes also the type and composition of lubrication. High contact pressure, largely due to high static axle load, may result in more severe damage than indicated in the RSSB model. For high-speed trains with a maximum axle load of about 16 tonnes. only moderate average contact pressure is anticipated.

The Swedish rail network is quite curvy. About 8% of passenger operations (in tonne-km) are carried out in the curves radius interval 551–900 m (with a concentration around 600 m), while 2.4% are carried out in curves with smaller radius [42]. Considerable wheel and rail wear may be produced if wheels or rails are not lubricated. Most curves with radii less than 550 m are lubricated, larger radii usually not. Rail surface damage is estimated to account for 40% of the total maintenance and renewal cost for tracks of the Swedish rail network.

The situation is similar in Denmark and Finland, although with some variation. Norway, however, has a considerable share of narrow curves in the 250−550m curve radius range.

8.4 Track deterioration and vehicle maintenance

Track friendliness is an important part of vehicle-track interaction. Firstly, track friendliness means that the vehicles produce low or **moderate forces and wear on the track** to minimize track wear and fatigue, which necessitate maintenance and renewal with associated costs and interruption of train operations.

In the future, the marginal cost for track deterioration will most likely be included in the track access charges on a number of European rail networks. This is necessary for the internalization of the cost caused by the train operator when using the railway infrastructure. Rail vehicle operations causing a high rate of track deterioration should pay more than those that cause low or moderate track deterioration. This will highlight the need for track-friendly rail vehicles.

Secondly, track friendliness sometimes also means that the vehicle is **able to run on non-perfect track,** i.e. with considerable geometrical irregularities, with favourable response regarding forces on the track as well as ride quality. This aspect is also important in order to avoid excessive maintenance cost at higher speeds. Further, track friendliness is a prerequisite for tilting trains, running at extraordinarily high speed and cant deficiency.

Track friendliness usually also results in favourable properties regarding **damage and maintenance costs for the vehicles themselves**. For example, low rail wear will most likely be associated with low wheel wear. Regardless of the above-mentioned aspects, safety requirements must always be met.

As mentioned earlier, the Swedish Transport Administration has developed a model and a methodology for estimating track deterioration with respect to vehicle characteristics and operational parameters, see Öberg et al [42]. This model is yet not implemented (2011) but will likely be so in the future. It is based on comprehensive literature studies, where preference is given to models validated by full-scale testing and experience. The main sources are the former UIC ORE/ERRI expert committee D 161 as well as research done by RSSB and AEA Technology. For some issues Swedish data are also used.

Models for track deterioration and damage usually take one or two aspects into consideration, for example track settlement and fatigue in some track components. The model developed by the Swedish Transport Administration considers four different aspects and joins them together. These aspects are:

- Track settlement, being approximately proportional to the third power of the applied vertical force, i.e. to Q^3.
- Component fatigue due to forces and stresses (rails, rail pads and fasteners, sleepers, ballast etc.), also being proportional to Q^3.
- Abrasive wear of rails, being a function of the wear number (approximate energy dissipation) in the contact patch, with progressive dependence of the wear number; see previous Section 8.3.4.
- Rolling contact fatigue (RCF) of rails, also being a function of the wear index, (i.e. on friction forces and creep) although with its largest influence at relatively small wear indexes: see section 8.3.4.

Vertical forces Q with frequency content at least 10% above the highest sleeper-passing frequency have been used in the above estimations. At 200 km/h this is equivalent to a low-pass frequency window of about 100 Hz. A special model has been developed based on data measured in Sweden. Wheel-rail friction as well as wheel-rail geometric combinations are varied within realistic limits, resulting in an estimated average.

Forces and wear indices – and indirectly track deterioration – depend on different properties and features of the vehicles, such as axle load and unsprung mass, radial steering of wheelsets in curves, and height of centre of gravity. Operational parameters, such as speed and cant deficiency, also affect track deterioration.

The model is implemented in an EXCEL®-based software called DeCAyS. This software can also be used as a key for fair distribution of track access charges as far as the cost for track deterioration is concerned. The marginal cost of track maintenance and renewal was estimated to be about 0.75 SEK per gross-tonne-km in 2001, as an average over the whole Swedish rail network, see Andersson [43]. With some inflation up until today, the marginal cost is approximately estimated at some 0.009–0.010 SEK per gross-tonne-km on average.

The higher figure (0.010 SEK per tonne-km) corresponds to a total annual cost of about 650 million SEK in Sweden. Track settlement and component fatigue are estimated to account for 25% and 35% respectively of the total track deterioration costs, while abrasive wear and RCF are estimated to be responsible for 40% together.

Each type of vehicle, or train unit, can thus be debited a fair amount of track charge per kilometre, depending on the vehicle's features and its typical operational conditions. Average track conditions over the whole network are used for all vehicles irrespective of the actual track status. Track conditions are determined by the infrastructure manager, not by the operator.

Studies conducted for Gröna Tåget

A study of track friendliness, with respect to track deterioration only, has been conducted within the Gröna Tåget programme, see Öberg [45]. Two **reference trains** have been defined, together performing the majority of long-distance and fast regional passenger-km in Sweden:

IC A classic locomotive-hauled Inter-City passenger train (Rc-locomotive + 7 cars) with a maximum speed of 160 km/h; 399 tonnes service mass; "stiff" bogies; 388 seats. Permitted cant deficiency is 150 mm;

X2 The current high-speed tilting train *X2* (X2 loco + 6 cars) with a maximum speed of 200 km/h; 370 tonnes service mass; "extra-soft" bogies; 310 seats. Permitted cant deficiency is 245 mm.

For a definition of the different bogies, see Section 8.7.1. The reference trains are compared with a tentative **Gröna Tåget baseline** train:

GT A 4-car wide-body train unit with a maximum speed of 250 km/h, 230 tonnes service mass; "soft" bogies and 310 seats. Permitted cant deficiency is 275 mm as the baseline. Average operational axle load (incl. average passenger load) is 15.9 tonnes.

Track deterioration per seat-km is considered to be the most relevant measure for comparison between types of trains. Otherwise, different train concepts with different seating capacity cannot be fairly compared. On the other hand, this implies that trains with a higher load factor (i.e. a higher percentage of occupied seats) will have lower relative track deterioration per passenger-km than that indicated per seat-km. High-speed trains usually have a higher load factor than other trains, which will reduce the relative track deterioration for high-speed trains counted per passenger-km.

For Gröna Tåget (denoted GT as above), a sensitivity analysis for variation of the train concept has been made. With the Gröna Tåget baseline as a starting point, the following variations have been studied:

- Cant deficiency 168 mm (instead of 275 mm);
- Top speed increased to 280 km/h (instead of 250 km/h);
- 1 tonne higher axle load (16.9 t operational average instead of 15.9);
- 20% fewer seats (248 instead of 310, for one less seat abreast);
- "Stiff" bogies (instead of "soft"); see section 8.7.
- "Worst case" with a conventional train, combining the three last variations.

The most interesting and relevant results are summarized in Figure 8-4. The average cost of track deterioration is assumed to be 0.0090 SEK per gross-tonne-km, resulting from a cautious extrapolation (due to inflation) of the most relevant estimations [43].

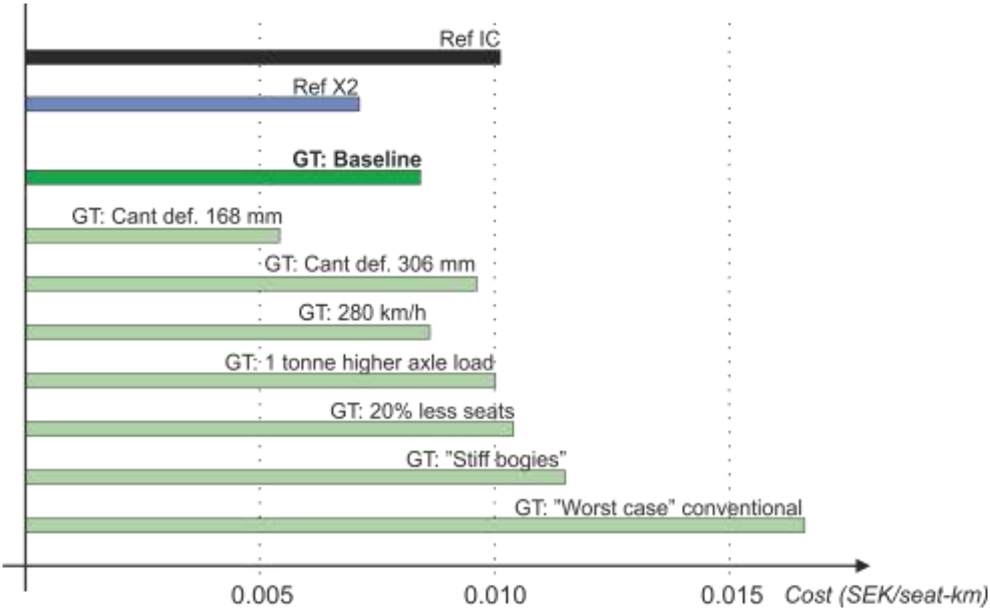

Figure 8-4 Track deterioration cost, estimated with the Swedish Transport Administration's DeCAyS, for different variations of Gröna Tåget and for the IC and X2 reference trains. Source: Trafikverket/Banverket [45].

Conclusions

In order to be as track friendly as previous long-distance trains it is concluded that the **axle load** must be modest and **bogies** should be of the **"soft"** type. It is also important that the train have a **high number of seats** per metre for distribution of track deterioration cost. Cant deficiency is also an important factor, but speed is not.

It should be noted that the estimated cost for track deterioration is not yet (2011) implemented in the track access charges paid to the Swedish Transport Administration. However, the cost is a reality. It is expected that a differentiated cost will be charged to train operators in the future. The Swedish Transport Administration has said that track friendliness is one of the main targets for development in the Gröna Tåget programme.

Low maintenance of trains

Track friendliness usually has a positive correlation with low maintenance cost for the trains, as many reasons for track deterioration (wheel-rail impact forces, abrasive wear, RCF, shocks and vibration) are also root causes of the need for maintenance of the vehicles. These issues are not elaborated in detail in the Gröna Tåget programme, but should be considered by rail operators in their acquisition of new vehicles. Operators should have access to detailed data concerning maintenance costs for different vehicles with different characteristics.

8.5 Ride comfort

Ride comfort, with criteria and targets, is described in Section 6.5. Implementation of technologies for achieving good ride comfort is covered in Sections 8.7.3 and 8.7.4.

8.6 Roll flexibility and vehicle sway

Vehicle sway is a combination of roll and lateral displacement, resulting in a rotation about a low centre. If a train is negotiating a curve at cant deficiency (i.e. the lateral acceleration causes a mass force directed outwards) the carbody will experience a sway outwards. With a passive suspension system, located below the centre of gravity, the roll motion will thus be in such a direction that it counteracts the cant of the track in the curve. In principle the same effect, but in the opposite direction, will occur at cant excess, for example when the train is standing still in a canted curve.

Vehicle sway can be identified and measured in different ways:

- If the vehicle is placed on a canted track with cant angle δ to the horizontal plane, the carbody experiences a roll angle η relative to the track.
- If the vehicle negotiates a circular curve at cant deficiency the effective cant of the carbody will be less than the track cant, due to the roll outwards. This causes an increased lateral acceleration in the carbody, parallel to the floor. With track-plane acceleration a_{yt} the resulting carbody acceleration is a_{yc}.

As a measure of the roll tendency, a **coefficient of flexibility *S*** can be determined as

$$S = \eta / \delta = (a_{yc} - a_{yt}) / a_{yt}.$$

Increased roll of the carbody thus causes a **higher lateral acceleration** (or mass force) experienced by the passenger. This may be uncomfortable, in particular when walking inside the train. It may also cause different objects to fall off the tables, for example cups of liquids, food, books, pencils, laptop computers, etc.

Excessive sway (including both roll and lateral displacement) may cause the vehicle to **hit obstacles** in the infrastructure. Excessive **lateral motion of the pantograph** on the roof may cause the pantograph to move upwards alongside the catenary, which usually causes severe damage with subsequent interruption of train operations.

In Section 9.5.3, a maximum lateral motion of the pantograph top of 0.25 m is proposed in the worst operational case with crush load, including also influence of poor geometry quality of the track, wheel-rail displacements and flexibility of the pantograph itself and its mounting brackets on the roof.

Proposals

The TSI HS RST requires that vehicles equipped with pantographs on the roof shall have a coefficient of flexibility (also called suspension coefficient) less than 0.25.

However, the lateral displacement of the pantograph would be a better measure as it directly relates to the critical properties. Combining reduced coefficient of flexibility with reduced lateral displacement is necessary to comply with requirements concerning pantograph displacements at the enhanced cant deficiency proposed in Section 2.4. Introduction of a Hold Off Device in the secondary suspension is recommended; see Section 8.7.3.

A reduced coefficient of flexibility will also have a positive influence on the lateral acceleration perceived by the passengers. From this point of view a coefficient of flexibility of the order of 0.15 is desirable at normal passenger load.

Note that most of these considerations are only relevant for non-tilting trains, or tilting trains operating in the non-tilting mode.

8.7 Bogie technology and its implementation

This section describes bogie technology in general, and in particular what is being developed and tested within the Gröna Tåget programme. It deals with bogies for low wheel-rail wear and good dynamic stability. This section also presents test results concerning track forces. Finally, the activities on active suspensions are described, in particular with respect to improved ride comfort and reduced displacements between bogies and carbody.

8.7.1 Bogies for low wear and dynamic stability

The issue of dynamic stability was presented and discussed in Section 8.2. It was also pointed out that maximum stability is not the main goal. Once sufficient stability has been achieved, optimization should rather be directed towards low wear and track forces as well as good ride quality; i.e. maximizing the benefits of other performance indicators.

A conventional railway wheelset has a common axle for the two wheels, each having a **conical shape** at the running surface, i.e. the radius increases at the flange side, see Figure 8-5. If the wheelset is displaced laterally outwards in a curve, the outer wheel will run at a larger rolling radius than the inner wheel. Since the **two wheels are firmly connected through the axle**, the two wheels are always rolling at the same angular speed. A larger rolling radius on the outer wheel will therefore force that wheel to run at a higher linear speed than the inner wheel. This compensates for the longer distance the outer wheel has to travel along the outer rail, allowing the wheelset to take an approximate radial position along the curve [39]. A free railway wheelset thus has an **inherent self-steering ability.**

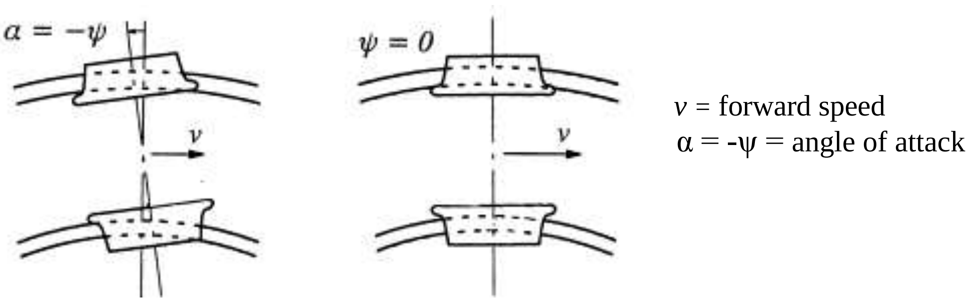

Figure 8-5 A radial attitude (*right*) of the wheelset has the potential to only produce limited friction forces and wear in the wheel-rail interfaces. A non-zero angle of attack (*left*) will produce larger wear.

A radial attitude approximately minimizes creep – the degree of sliding – in the contact patches between wheel and rail. Creep is closely related to the friction forces – or creep forces – in the same contact patches. Creep and creep forces produce wear and rolling contact fatigue (RCF).

In reality, all wheelsets in a rail vehicle are guided in and connected to a bogie frame or to the main frame of the vehicle. If these connections are stiff, they will prevent the wheelsets taking up radial positions. Cases with "stiff" and "soft" wheelset guidance are shown to the left and right respectively in Figure 8-6.

In order to allow radial self-steering, the **longitudinal stiffness** of the wheelset guidance is a most important issue. The flexibility must allow the friction-creep forces to set the wheelset in an approximate radial position in curves. Thus, in self-steering running gear the radial steering is to some degree dependent on the friction forces. If the friction is low, there is a lower degree of radial steering; however, with a low friction, the wear is usually low anyhow.

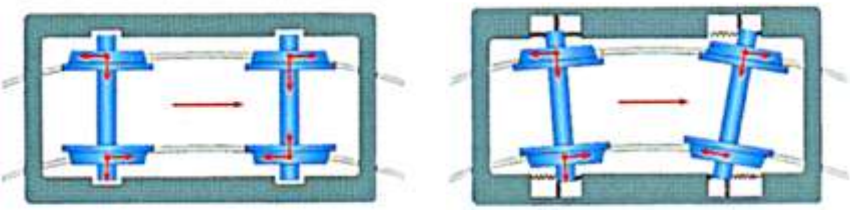

Figure 8-6 A stiff wheelset guidance (*left*) generates a considerable angle of attack between the leading wheelset and the track. More flexible (soft) wheelset guidance (*right*) allows the wheelsets to take up approximate radial positions in curves.

In the context of Gröna Tåget, running gears for fast passenger vehicles have been investigated, i.e. bogies for motor coaches and passenger cars for axle loads of 12-18 tonnes with permissible speeds of at least 160 km/h. These vehicles usually have two-axle bogies with axle distances of 2.5–3.0 m and axle journal bearings outside the wheels. The terms **'soft'** and **'stiff'** are here used to characterize the guiding stiffness of the wheelsets, in particular the longitudinal stiffness on each side between wheelset and bogie frame, Figure 8-7.

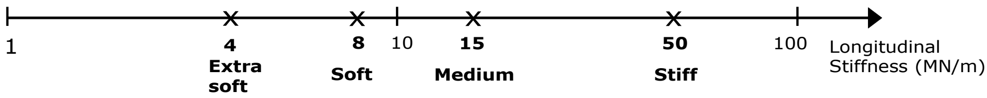

Figure 8-7 Longitudinal guiding stiffness (per axle box) for a vehicle with an axle load of 15 tonnes.

There are special cases where the self-steering ability is limited or non-existent, for example on very narrow curves ($R < 300$ m) or with high traction forces acting on the wheels. In such cases some steering linkage, or even active mechatronic means, may help to steer the wheelsets radially; see for example Schneider et al [46, 47].

"Soft" or "extra soft" bogies are usually also quite flexible in their **lateral wheelset guidance**.

Another important matter is dynamic stability; see Section 8.2.4. Generally, the natural wheelset oscillations need to be restricted by the bogie frame, by a steering linkage and/or by appropriate damping means. A certain amount of stiffness in the wheelset guidance is necessary to prevent hunting. Another very efficient way to avoid hunting is to arrange so-called **yaw damping** of the bogies in relation to the carbody, i.e. longitudinally directed dampers placed between each side of the bogie frame and the carbody. Such yaw damping stabilizes the yaw motion of the bogie (i.e. the rotation about a vertical axis) as well as the lateral oscillations.

A widespread opinion in Europe is that bogies intended for high speed need a very high guiding stiffness for the wheelset connections; otherwise there is a risk of unstable hunting oscillations. Above a certain amount of guiding stiffness however, the benefits (in terms of stability) of having additional guiding stiffness are only marginal or non-existent, according to our experience. If necessary, a lower guiding stiffness may be compensated by a higher amount of damping – in particular yaw damping – from a stability point of view. It should be noted that "stiff" bogies also need yaw damping to prevent hunting, at least at speeds around 200 km/h and above.

Research and development conducted for Gröna Tåget

Two types of track-friendly bogies have been developed and tested within the Gröna Tåget programme:

- Radial self-steering (RSS)
- Active radial steering (ARS)

Both have the objective of minimizing wear and maintenance on rails and on wheels, at the same time as sufficient dynamic stability is achieved.

The main part of the theoretical analysis and dynamic simulations on RSS was done by KTH, while Bombardier designed and built the hardware, see Figure 8-8. The newly-developed bogies have been subjected to certification testing according to EN 14363 (or the older UIC 518) as well as long-term service testing in the REGINA 250 test train. The ARS bogies were analysed, designed and manufactured by Bombardier; however, ARS was built into the same bogies as RSS, just by replacing the passive wheelset guidance by electric actuators and a control system, plus removing the yaw dampers. Parts of the ARS technology are confidential.

Tests for development and certification (EN 14363) have been conducted each year between 2006 and 2010, on different tracks and curve radii, and at different speeds, see the map in Figure 8-9. In September 2008, a new Swedish speed record of 303 km/h was set on ordinary track between Skövde and Töreboda, otherwise used for 160-200 km/h. In the high-speed tests, the track geometry quality was close to the limit for what is accepted for lower speeds.

Figure 8-8 The radial self-steering bogie (RSS) being developed and tested. Note the longitudinally directed yaw damper that stabilizes the bogie at high speed. Source: Author

Curve class	Section	*R* (m)
Small-radius	Ånge – Sundsvall Hudiksvall – Sundsvall Järna – Nyköping	300 500 600
Medium-radius	Järna – Töreboda	1 000
Large-radius	Örbyhus – Skutskär	3 000
Straight track	Skövde – Töreboda	—

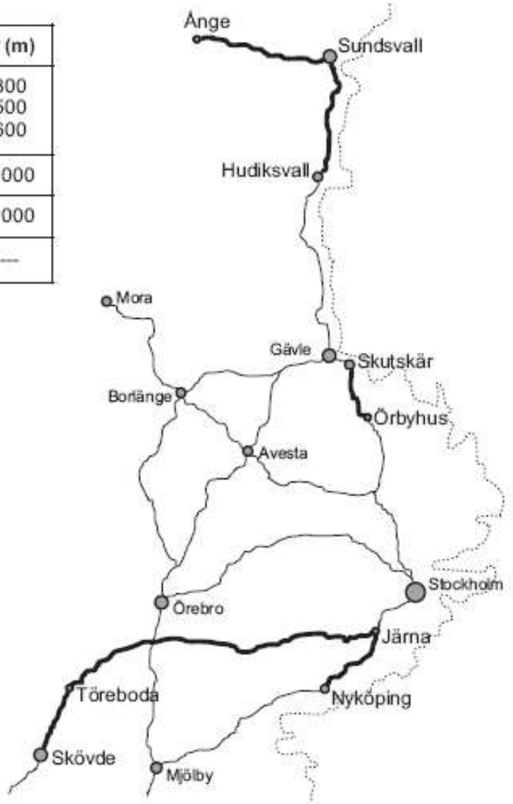

Figure 8-9 Track sections for REGINA 250 research and certification tests

The RSS bogies have been in regular service since 2008. Until the summer of 2010 they were used on winding low-speed routes and were then moved to the newly-built Bothnia Line, with speeds up to 200 km/h. The mileage has (Dec 2011) passed 500,000 km without reports of poor running behaviour or wheel re-profiling due to wear. It should also be noted that the two winters 2010 and 2011 were unusually severe in Sweden with challenging conditions regarding snow and cold.

One of the first activities in the RSS bogie development was a theoretical analysis of the bogie and the test train by means of simulation; see Orvnäs et al [48]. As stated earlier, many curves have radii in the range of 550–900 m, with a concentration around 600 m, usually without lubrication. It is therefore important that vehicles can negotiate these curves with appropriately low wear. It is not a matter of minimizing wear, but rather of achieving the right balance between flange wear and tread wear. Too little flange wear risks causing hollow wheel treads and increased flange thickness, which will subsequently produce high equivalent conicity, which in turn would require wheel turning to restore a proper wheel geometry.

Figure 8-10 shows simulation results for different stiffnesses of the longitudinal wheelset guidance. The examples shown are for nominal wheel and rail profiles at dry friction, although other cases have also been studied.

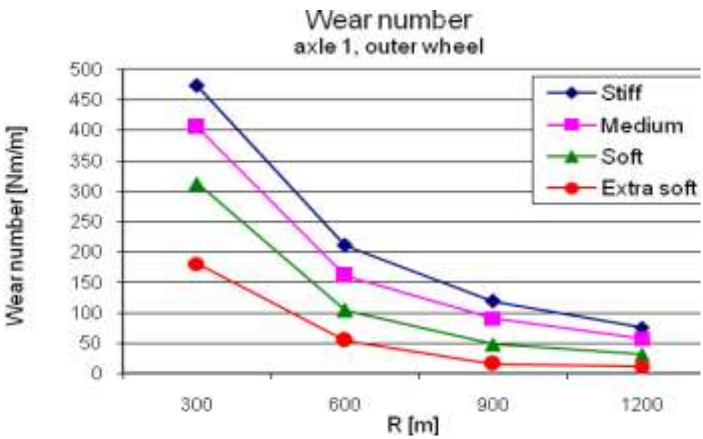

Figure 8-10 Simulated wear index (approximate energy dissipation) of the leading outer wheel for bogies with different wheelset guidance.

In this case simulations are made for dry track with S1002 wheels and UIC 60 rails. Source: KTH

The next step was to ensure the dynamic stability of the bogies within a large range of equivalent conicity (0.01-0.40), at speeds up to 300 km/h. Most simulations were made on straight track at a speed of 275 km/h, 10% higher than the intended permitted speed of 250 km/h. A number of wheel-rail combinations, within the mentioned range of conicities, were selected. This process was also carried out by means of simulation, where the SIMPACK software was used [51]. The model used was highly non-linear. For details, see Orvnäs et al [48].

A number of parameter variations were made to systematically explore the possibilities to achieve stability with a "soft" setting of the wheelset guidance. One of the most decisive parameters is the "blow-off" force level for the yaw dampers, i.e. the almost constant damper force at higher piston velocities. A great many wheelset guidance alternatives were investigated. Longitudinally stiffer alternatives than "soft" did not improve stability margins if other parameters were given optimum values.

With optimum suspension and damping parameters, running stability can be achieved with "soft" setting of the wheelset guidance.

As mentioned in Section 4.2.4, the main criteria for dynamic stability is the sliding r.m.s. value of lateral wheelset forces ΣY measured over 100 m. For the test train having an axle load of 154 kN, the limit value, as given in EN 14363, is 30.7 kN.

Simulation and test results

Results for the stability criterion $\Sigma Y_{rms,100m}$ in simulation and tests are shown in Table 8-2. Simulations produce higher maximum ΣY_{rm} than the tests. This is due to the large local lateral track irregularity being used in simulations. The extreme track disturbance is well motivated in simulations as a trigger for potential instability, but simulations may consequently show higher ΣY_{rms} than for the actual test tracks, which have normal track irregularities.

Table 8-2 Simulation and test results on stability criterion $\Sigma Y_{rms\ 100m}$
Radial self-steering "soft" bogies. Sources: [48, 49, 50]

Speed (km/h)	**Simulation $\Sigma Y_{rms\ 100m}$** (kN)	**Test $\Sigma Y_{rms\ 100m}$** (kN)	**Limit value** (kN)
275	13–26 (depending on conicity)	–	30.7
269–276	–	10–16 [a]	30.7
298–303	–	18	30.7

a) Maximum $\Sigma Yrms,100m$ were slightly different in the tests in 2006, 2007 and 2008. It is believed that the differences are due to changing track conditions (irregularities, friction, etc.) and to different suspension systems (passive and active).

Testing for high-speed stability was done on a straight track between Skövde and Töreboda on the Stockholm-Gothenburg line. Equivalent conicity was occasionally up to 0.8, with 0.4-0.6 over a considerable part, otherwise 0.2-0.4; see Figure 8-11.

Stability tests were also made on large-radius curves with cant deficiency up to 200 mm (1.3 m/s²). With passive suspension, low-frequent (1.5-2 Hz) periodic lateral motions appeared in some locations. The measured maximum $\Sigma Y_{rms,100m}$ was however low, i.e. up to 10 kN. With active lateral suspension (see Section 7.2.3), these tendencies disappeared.

The "soft" self-steering bogie has passed on-track certification tests according to EN 14363 or UIC 518. This bogie under the test train meets all requirements for an operational speed of 250 km/h and a cant deficiency of 183 mm. This is also the case for a bogie with "medium" wheelset guidance (see Figure 8-7) which was tested in 2006.

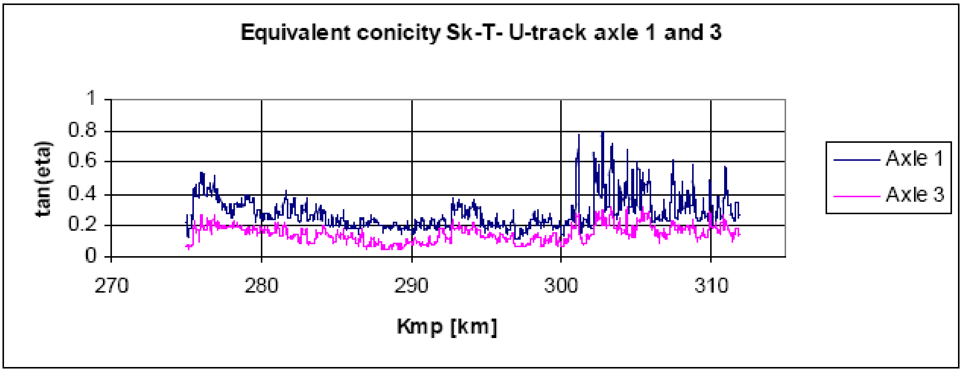

Figure 8-11 Equivalent conicity on the "up" track Skövde-Töreboda.
The high-speed test section (> 250 km/h) is km 290–308.
Axles 1 and 2 with instrumented force-measuring wheels have intentionally larger distance between wheels, in order to perform tests at high conicity. Axle 2 is similar to axle 1 shown above.
Track gauge on this test section was 1,429–1,435 mm. Source: [50]

Conclusions and proposals

It is shown that "soft" wheelset guidance introduced for modest rail and wheel wear in curves can be combined with dynamic stability at high speed as well as high equivalent conicity. The developed and tested bogie has been subjected to certification testing according to EN 14363 (or UIC 518) with favourable results.

The optimization process is critical for a favourable outcome and should consider a large number of parameter variations, regarding wheel-rail combinations (eq. conicity), wheel-rail friction, track irregularities and track flexibility. The necessary simulations require an appropriate non-linear model of the vehicle and its interfaces with the track.

It is proposed that this type of "soft" high-speed bogie be used for future trains, at least for operational speeds up to 250 á 275 km/h.

8.7.2 Track forces

Two wheelsets (Nos. 1 and 2) of the REGINA 250 test train were equipped with instrumented wheels, capable of continuously measuring high-frequency forces between wheels and rails. The instrumentation was provided by Interfleet Technology (Sweden) who also evaluated the test results.

KTH has simulated the track force performance prior to the tests, as part of bogie optimization [48]. A "safety track" was used in the simulations, with track irregularities as for the worst case QN3 in EN 14363.

Lateral track-shift forces

Simulations and tests are made on **lateral wheelset-to-track forces** ΣY_{2m} (also called track-shift forces); see Figure 8-12. They are here shown for small- and medium-radius curves at a modest cant deficiency (135–150 mm). Simulation and test results show good agreement, although track irregularities are not exactly the same. Due to different tracks with varying geometry quality, there is some spread in the measured results.

Lateral guiding forces

No particular requirements have been called for, except that the quasi-static guiding forces Y_{qst} must meet the limit value of 60 kN, according to EN 14363. This criterion is met with margins of 25-40% in the tightest curves with radii around 300 m [49]. The lower values ($Y_{qst} \approx 35$ kN) are in accordance with simulation predictions on dry track. Higher measured values ($Y_{qst} \approx$ 40-45 kN) were achieved on a track with rail lubrication on the high rail, thus limiting the self-steering ability of the leading wheelset. However, on lubricated track the wear should be low anyhow. Further, EN 14363 requires that acceptance testing be performed on dry track. Guiding forces in larger curve radii (R = 600 m and above) are 18-23 kN, which is also in accordance with simulation predictions.

There is a strong linear relationship between quasi-static guiding force Y_{qst} and the wear number, if the contact conditions are the same. As the predictions of Y_{qst} are close to reality, we draw the conclusion that the predicted levels of wear index and wear (Section 8.4 and Figure 8-10) should also be approximately correct.

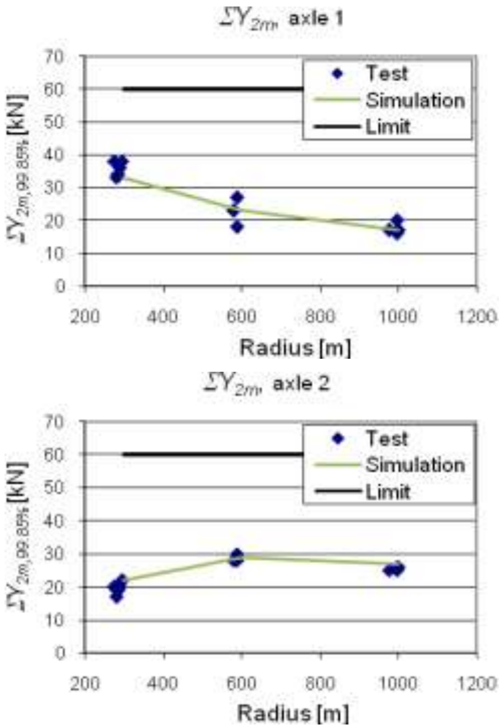

Figure 8-12 Simulated and tested ΣY_{2m} (99.85 percentiles) on the leading bogie wheelsets 1 and 2, in small- and medium-radius curves.
Source: [48]

Vertical wheel-rail forces

Considerable testing of track forces has been done, partly for EN 14363 (or UIC 518) compliance, partly for research purposes. One of the most interesting research activities was to evaluate measured track forces versus track geometry quality; see Karis [12]. An example of results from such an evaluation is shown in Figure 8-13.

The correlation is usually, but not always, between 0.6 and 0.9 for vertical forces which is considered good. For lateral forces, correlations are usually lower, sometimes very low. Obviously there is not always a straightforward relation between vehicle response and the quantities presently describing the geometry quality of the track. Not only track forces but also ride comfort was evaluated.

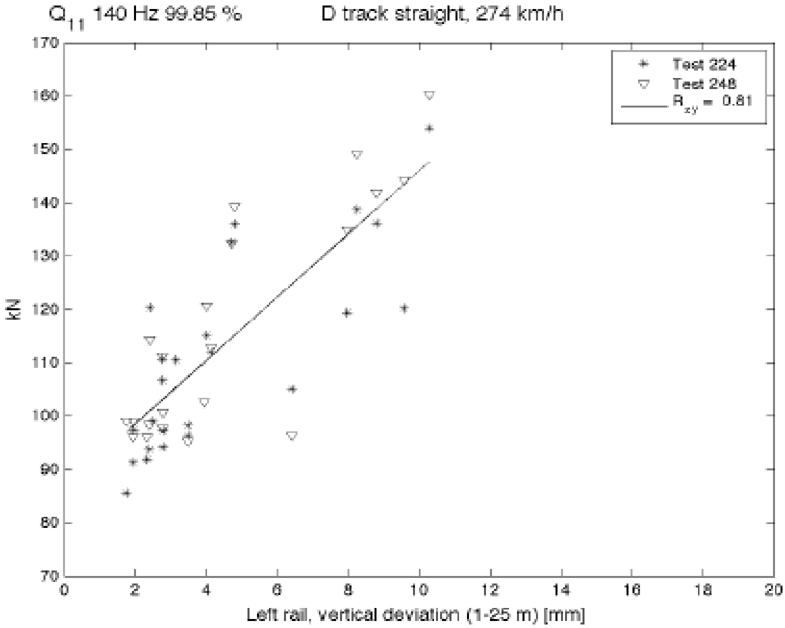

Figure 8-13 Measured vertical wheel-rail force *Q* versus vertical deviations (mean to peak) of the track geometry (average for 500 m sections). Q has a frequency content up to 140 Hz. Source: [12]

Conclusions

- From the correlation studies some interesting and valuable conclusions can be drawn:
- In a majority of cases there are correlations between 0.5 and 0.9;
- Vertical forces are mainly correlated with short-wave vertical track irregularities;
- Ride comfort is mainly correlated with longer wavelengths (vertical and lateral);
- A small track gauge (less than 1,434 mm) may cause some increase in ΣY forces at speeds above 270 km/h, although much less than the limit value;
- Dynamic vertical forces are sometimes influenced by the sleeper-passing effect, which negatively affects the correlation with track geometry irregularities.

Overview of measured track forces

Table 8-3 below presents an overview of measured and evaluated track forces, both lateral and vertical. The upper part shows safety-related maximum forces and force combinations. The lower part of the table shows maximum forces related to track fatigue and deterioration. Vertical forces *Q* are estimated with 20 Hz low-pass filtering (as in EN 14363) as well as with 140 Hz (as is here proposed for estimation of track deterioration).

Estimated values are according to a statistical method based on the assumption that the evaluated quantities have normal Gauss distributions. These values are very often higher than the maximum force measured in the tests.

Table 8-3 Measured and statistically evaluated wheel-rail forces.
Source: Interfleet [50]

Quantity tested	Test zone	Max Estimated Value [kN]	Percentage of Limit	Max Measured Value [kN]
Y/Q	250 m ≤ R < 400 m	0.68	85	0.61
	400 m ≤ R ≤ 600 m	0.65	81	0.61
	900 m ≤ R ≤ 1500 m	0.46	58	0.45
	Large-radius curves	0.28	35	0.24
ΣY [kN]	Straight track	34	55	28
	250 m ≤ R < 400 m	40	65	37
	400 m ≤ R ≤ 600 m	40	65	36
	900 m ≤ R ≤ 1500 m	40	65	42
	Large-radius curves	44	71	37

Quantity tested	Test zone	Max Estimated Value [kN]	Percentage of Limit	Max Estimated Value 140 Hz (1-dim) [kN]
Q[kN]	Straight track	100	60	169
	250m ≤ R < 400m	113	67	127
	400 m ≤ R ≤ 600 m	118	70	176
	900 m ≤ R ≤ 1500 m	121	72	168
	Large-radius curves	119	71	141
$Y_{qst}[kN]$	250 m ≤ R < 400 m	44	73	-
	400 m ≤ R ≤ 600 m	27	44	-
	900 m ≤ R ≤ 1500 m	18	30	-

Comments and conclusions

Tests were made in various curve radii at various speeds, according to the specifications of the former UIC 518, now EN 14363 [N10]. Curves of radii between 900 and 1500 m are however not part of the required mandatory testing, but were included in Gröna Tåget tests because of their significance for Scandinavian conditions.

Tests were mainly made for certification up to an operational speed of 250 km/h (i.e. 275 km/h testing speed), and a maximum operational cant deficiency of 183 mm (i.e. 200 mm during testing). However, some tests were also made for research purposes at speeds up to 303 km/h. It should be noted that condition of the track and the catenary in these very-high-speed tests was close to the limits for 160–200 km/h.

Simulations and test results agree very well, not only for track forces but also for dynamic stability. This is despite no attempts being made to reflect the exact track conditions (irregularities, conicity, etc.) in the simulations. Such an agreement has been demonstrated several times before, which gives confidence in the simulation models and methodology.

The measured track forces are in general safely below required limit values for an operational cant deficiency up to 183 mm (corresponding to a track-plane acceleration of 1.2 m/s^2), to be used without carbody tilt.

The test train was not equipped with carbody tilt due to the cost and for practical reasons. Gröna Tåget as a concept for a future Scandinavian train is however intended for carbody tilt as the main alternative. This raises the question of whether track forces will stay within the required safety limits when the cant deficiency is further increased. The most critical issue is considered to be the track-shift forces ΣY_{2m}. For an approved operational cant deficiency of 306 mm (track-plane acceleration 2.0 m/s^2), the cant deficiency at certification test must be 336 mm, i.e. 10% higher. This is considerably more than the tested 200 mm.

A limited simulation study has recently been made. It was assumed that the tilt was shut off, but over-speed in the curve remained for a while. This implies that the carbody will be forced into the lateral bump stops, which will cause poor dynamic behaviour with high lateral impact until the speed is reduced. The simulated curve radius was 1,200 m and the speed 222 km/h. The track was a "safety track" with the largest required track irregularities QN3 according to EN 14363. This should be considered a "worst case". Simulation results show that ΣY_{2m} forces at the 99.85 percentile were just around the limit (±5%) for different simulated cases. No attempts were made to optimize performance at this stage.

It is concluded that the future Gröna Tåget will also most likely meet safety requirements regarding track forces for very high cant deficiency in combination with a carbody tilt failure. This is on condition that "soft" bogies are used, with considerable flexibility in both longitudinal and lateral wheelset guidance. Further detailed studies of these issues are proposed.

8.7.3 Active lateral suspension (ALS)

Up until recently, most trains have had passive suspensions, i.e. ordinary springs and dampers without any assistance from powered and controlled active systems. However, on some of the latest Japanese Shinkansen trains active lateral secondary suspension has been introduced. Earlier version so the Italian Pendolino tilting trains had a lateral centring device (a so-called Hold-Off Device; HOD). This was made in order to limit suspension travel and carbody lateral displacement when running at high cant deficiency with high lateral forces in the secondary suspension, because suspension was earlier located below the tilting plane.

A fully active lateral suspension has essentially two functions

- Improve **ride comfort**, in particular at high speed and/or on non-perfect track;
- Reduce the **lateral displacement** of the carbody, in particular at high track-plane acceleration (high cant deficiency), thus enabling increased carbody width and improved cross-wind stability.

In order to make this possible, a control loop must be arranged and built into the train. This loop includes **sensors**, a **controller** and **actuators**. A schematic of the layout of the system is shown in Figure 8-14.

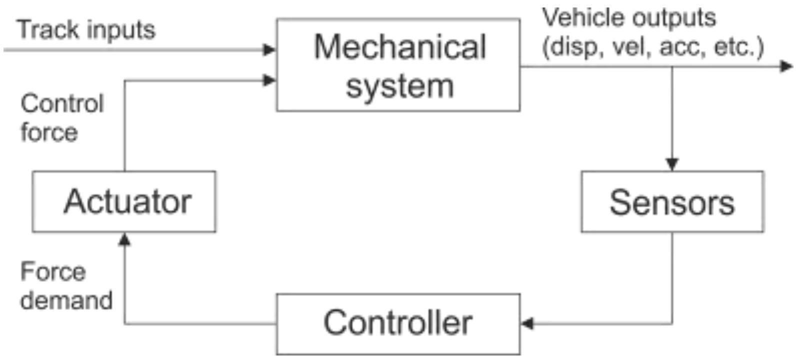

Figure 8-14 Basic principle of an active suspension system
Source: KTH [52]

Research and development conducted for Gröna Tåget

In addition to performance for improving ride comfort and reducing carbody lateral displacement, it is of great importance that the system is robust, reliable and affordable. All of these are objects of research and development within the Gröna Tåget programme.

Basic analysis of control strategies as well as optimization was done by KTH, while Bombardier designed, built and tested an ALS system. Liebherr in Germany also participated in the delivery of electro-hydraulic actuators. In addition to performance testing, the system has been subjected to long-term endurance testing in commercial service, using the REGINA 250 test train since March 2009, including the harsh and challenging winters of 2009/10 and 2010/11. The ALS has also been part of the certification testing according to EN 14363, as described in Sections 4.7.1 and 4.7.2.

It should also be noted that the developed ALS system is planned to be introduced commercially on trains in Italy and Switzerland (status in December 2011).

The hardware used is an electro-hydraulic actuator, designed for a maximum lateral force of 30 kN with a frequency range up to 6 Hz; see Figure 8-15. The actuator replaces one of the lateral dampers between bogie and carbody.

Figure 8-15 The actuator developed for Gröna Tåget.

The valves on the actuator are controlled by varying current, determined by the force demand delivered from the controller. So-called **sky-hook control** is used, which (simplified) means that measured carbody accelerations are integrated to produce velocities, which are then to some degree suppressed by the applied actuator force. The suppressed carbody motions bring about improved ride comfort.

Another control chain is provided in order to centre the carbody over the bogie, i.e. for the Hold-Off-Device (HOD). For this purpose the accelerometers measure the lateral acceleration when entering a curve, thus providing a reference for the applied mean force in the actuator.

As stated earlier, the ALS system has been on-track tested in various conditions along the Swedish rail network (Figure 8-9). Depending on the tested case (curve radius, speed and track geometry quality) the active suspension is able to reduce carbody dynamic accelerations by 10-50%, with an average of 30-35%. Very significant improvements are realized in large-radius curves where earlier sometimes low-frequent (1.5-2 Hz) lateral motions occurred at high cant deficiency (170-200 mm) and high speed (220-70 km/h). This is very important, because it makes possible to run on many of the upgraded and new lines with very good performance at full speed and cant deficiency. Figure 8-16 shows examples of improved ride comfort on various curves at tested speeds.

At normal operating speeds (excluding speeds above 250 km/h on these tracks), the ISO-weighted lateral r.m.s. accelerations are around 0.10 m/s^2, with peaks up to 0.12 m/s^2. This is considered to be very good ride comfort, cf. EN 12299 [N11].

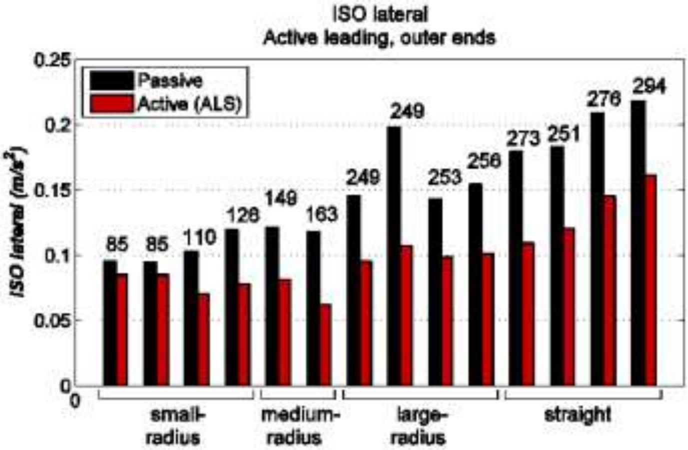

Figure 8-16 **ISO (EN 12299) lateral ride comfort evaluation for a number of tests.** Testing speeds are indicated above the bars. Source: KTH [52].

Lateral displacements in the suspension between bogie and carbody are also very significantly reduced. Figure 8-17 shows evaluations of the lateral displacements in a large number of curves with different radii and speed. Displacements are plotted against the lateral track-plane acceleration in the circular part of the curve. It is seen that maximum lateral displacements are reduced by 40-45 mm if ALS is compared with the ordinary passive suspension.

The specific actuators on the test train were able to counteract track-plane acceleration up to 1.1 m/s² and the shown displacements are merely a result of dynamic movements. An increase to 1.2 m/s² would only require a minor actuator upgrade. Setting the soft bump-stops at 10-15 mm and the hard stops at 30 mm is judged to be feasible.

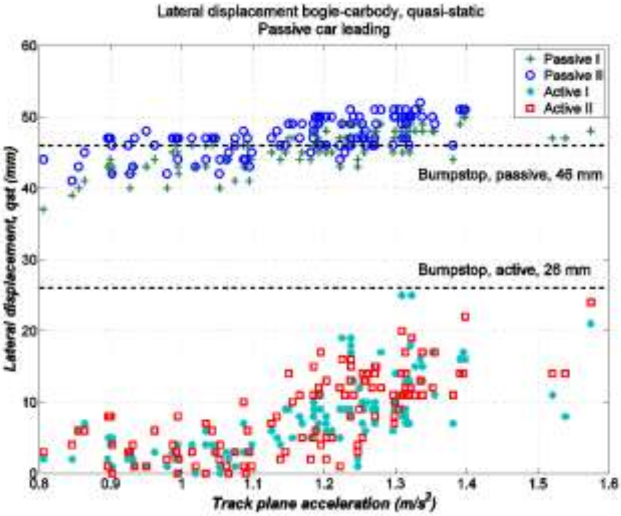

Figure 8-17 **Lateral displacements carbody-bogie for the two bogies in a large number of curves plotted against lateral track-plane acceleration.** Lower plots are ALS; upper plots are passive. Source: KTH [52].

8.7.4 Active vertical suspension (AVS)

Active vertical secondary suspension has a number of potential advantages:

- Improved ride comfort;
- Reduced roll and sway of the carbody, thus making it possible to increase speed on curves and/or improve cross-wind stability, or to reduce the perceived lateral forces on travellers;
- Active control of carbody vertical bending vibrations, making it possible to use a more flexible, lighter and less expensive carbody structure;
- More flexible choice of air suspension, for example making it possible to reduce or omit their auxiliary volumes.

Thus, besides improved ride comfort there is a potential to reduce weight and cost. The principle layout of an AVS system is about the same as for ALS. Four actuators are needed instead of two, but actuators can be smaller because less actuator forces are needed. Smaller actuators also make it possible to control higher frequencies, say up to 9-10 Hz. The latter is necessary for active control of carbody bending vibrations.

Research and development conducted for Gröna Tåget

The potential of active vertical suspension (AVS) has been investigated by simulation. No tests have been made to date (December 2011). System design, test train modification and on-track tests are planned for 2012, but will be beyond the current scope and timeframe of Gröna Tåget.

Simulation studies were made by KTH as part of the current Gröna Tåget programme, see Orvnäs [52]. The simulations report that the AVS system offers the advantages indicated in the introduction above. Figure 8-18 shows vertical ride comfort as a function of the carbody's first vertical bending eigen frequency. It can be seen that AVS makes ride comfort independent of the bending frequency, at least in the investigated range of 8–11 Hz (example: *X2* has a very stiff carbody of 11 Hz). The lower carbody frequency is a great advantage as regards weight, complexity and cost. Larger windows could also be provided, without large wall sections between the windows that obstruct traveller view.

Vertical vibrations are still higher in the middle of the car, but at a quite low level.

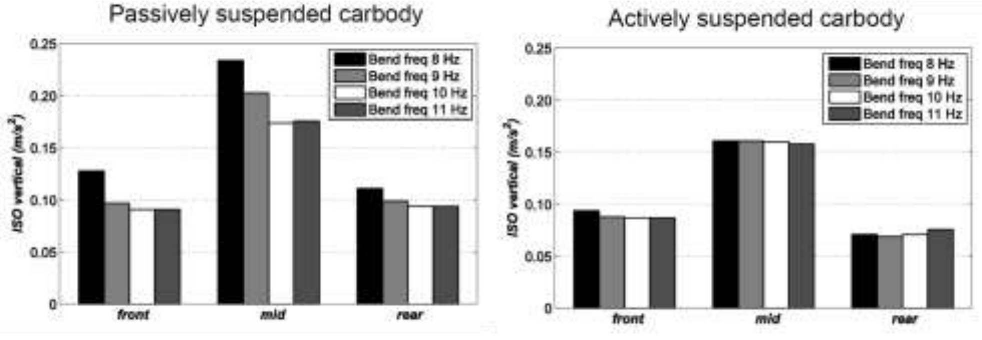

Figure 8-18 ISO (EN 12299) vertical ride comfort at different locations in the carbody as a function of the first vertical bending frequency [52].

Figure 8-19 shows the difference in ride comfort when using active ALS and AVS suspension compared to passive suspension. Ride comfort is shown for two speeds; 200 (passive) and 250 km/h (active). The track geometry quality is the same; i.e. a "comfort track" corresponding to the current standard for track maintenance at the Swedish Transport Administration. It is concluded that ride comfort can be better at 250 km/h with active suspension than at 200 km/h with conventional passive suspension, assuming the same track geometry quality.

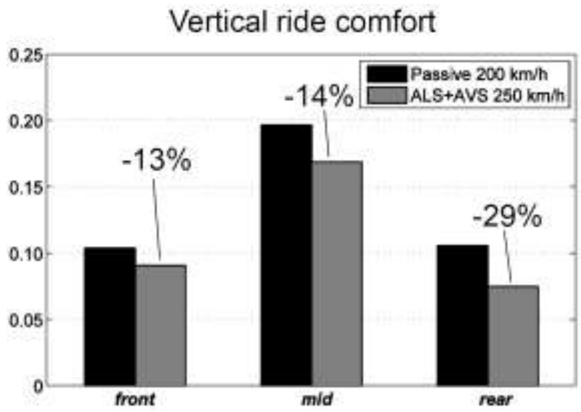

Figure 8-19 ISO vertical ride comfort (EN 12 299) at 200 km/h (passive suspension) and 250 km/h (ALS+ AVS).
Straight track. Track quality is the same for the two cases. Source: KTH [52].

It is currently (Dec 2011) not proven that the simulated performance of active vertical suspension (AVS) can be achieved in a real application. However, earlier simulations have in principle shown very good agreement between simulation and test, so the confidence in the simulation technique is high. The main uncertainty may be the possibility to realize the necessary high-frequency performance of the actuators, as well as funding for design, modification and testing of the AVS system.

8.8 Carbody tilt and motion sickness

Reducing the risk of motion sickness on tilting trains has been a subject of discussion since they were introduced. A thorough literature study within the Gröna Tåget programme on the subject is reported in Persson [57]. The difference in risk of causing motion sickness relative to non-tilting trains has attracted particular interest and also initiated the EU-funded research project Fast And Comfortable Trains (FACT), [58]. Further enhanced speeds, as suggested in Section 4.3, tend to increase the risk of motion sickness if no countermeasures are applied.

Decreasing the risk of motion sickness has until now been equal to increasing the discomfort related to quasi-static (mean) lateral acceleration at curving, i.e. to have less tilt compensation and tilt angle. But there is a difference in time perception between discomfort caused by lateral curving acceleration and motion sickness, which opens up for new solutions. Motion sickness due to tilt action is a result of several minutes of exposure, while discomfort due to high acceleration is an immediate perception.

The measures can in scope be divided into four groups: tilt control, reduced tilt, speed restrictions and track design geometry. Measures from the four groups can and should be combined for best effect.

Research and development conducted for Gröna Tåget

A **track-data-based tilt control** was developed to reduce the low-frequency lateral acceleration that may otherwise induce motion sickness in sensitive passengers. These low-frequency accelerations are due to tilt action delay and tend to have a dominant frequency where sensitivity to motion sickness is high. Track-data-based tilt control was one assumption in the on-track tests made within the Gröna Tåget programme. Another advantage of track-data-based tilt control is significant improvement of the *objective* lateral ride comfort (according to EN 12299) compared to the original, which could be due to the absence of track irregularity influence on the tilt reference.

Making the motions of tilting trains more like non-tilting is equivalent to reducing tilt and letting the passengers feel somewhat more lateral acceleration on curves. One proposed strategy is to let the local track geometry influence the tilt and give each curve its own optimised tilt angle. This is made possible by new tilt algorithms, storing track geometry data and using a positioning system to select the appropriate data.

On-track tests involving more than 100 human test subjects on board a tilting train have been performed within the Gröna Tåget programme to evaluate the effectiveness of the new tilt algorithms and the different requirements regarding quasi-static lateral acceleration and jerk; see Persson [59]. The tests involved four test cases, Case 1 was a reference case as the trains run today and the three others were alternatives aiming to make the motions more like the ones on non-tilting trains. Cases 3 and 4 utilized track-data-based tilt control, see Table 8-4. Differences in motions (frequency-weighted accelerations according to EN 12299) are presented in Figure 8-20.

Table 8-4 Cases in on-track human tilting tests

Test case	*Quasi-static lateral acceleration perceived by the test subjects*	*Tilt reference*
1	Normal [a)]	Measured [c)]
2	Increased [b)]	Measured [c)]
3	Normal [a)]	Track data based [d)]
4	Increased [b)]	Track data based [d)]

a) 0.6-0.7 m/s² lateral acceleration on speed-limiting curves (*X2* has about 0.6 m/s²)

b) 0.8-0.9 m/s² lateral acceleration on speed-limiting curves.

c) With linear relation between bogie lateral acceleration and tilt angle.

d) Tilt applied individually to each curve to meet requirements regarding quasi-static lateral acceleration and jerk perceived by the test subjects.

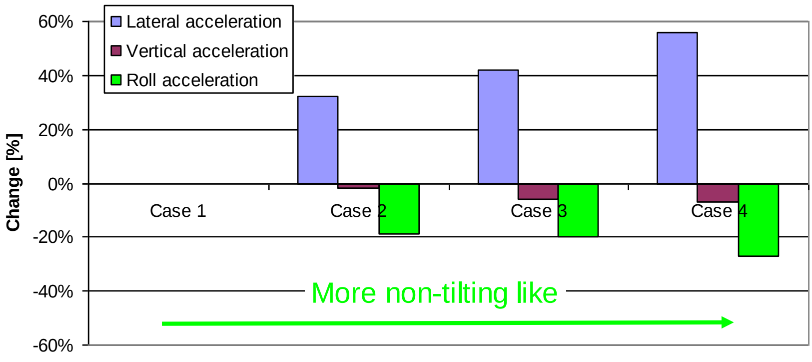

Figure 8-20 Frequency-weighted accelerations (EN 12299) for the four test cases. Source: KTH [59].

The evaluation showed that the lowest risk of motion sickness was recorded for Case 2, which was an intermediate case in a frequency weighted motion quantity perspective. The motion sickness score was about 40% lower for Case 2 than for the reference case. It should be noted that frequency of motion sickness was low for all test cases, despite the test subjects mainly being recruited among candidates who declared themselves to be prone to motion sickness.

The *subjective* comfort was judged to be about 6 on the 7-grade scale (1-7) for all test cases. The best subjective comfort was recorded for Case 1 and 3, which both had the normal level of quasi-static carbody lateral acceleration. The difference compared to the two other test cases was significant, but still rather small. Subjective ride comfort as function of motion sickness score is shown in Figure 8-21.

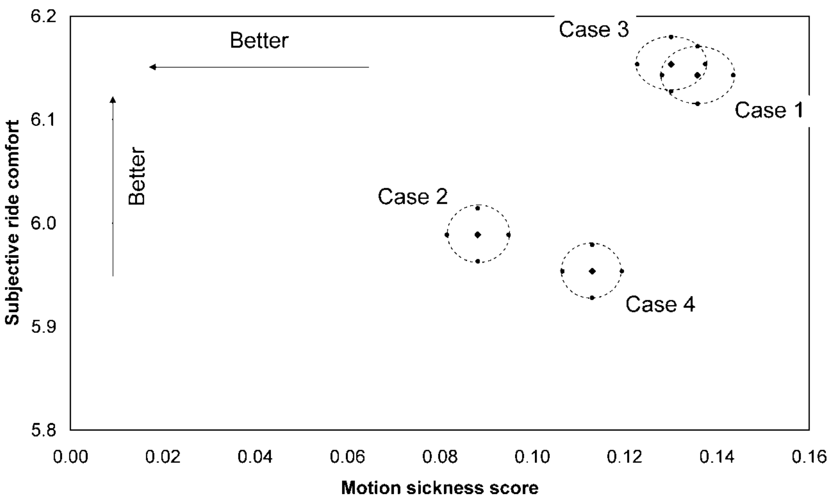

Figure 8-21 Subjective ride comfort as a function of motion sickness score with approximately 95% confidence intervals for the four test cases [59].

A third measure to reduce motion sickness is to **reduce speed.** Speed restrictions are of course contradictory to the main purpose of tilting trains, which is to reduce travel time. However, the speed restrictions needed to reduce the risk of motion sickness can often be made quite locally with little influence on the total travel time.

There are two cases where **track design geometry** cannot be compensated by advanced tilt control. The first is to avoid adding vertical accelerations from carbody tilt to those from vertical track design geometry. In practice, this means that horizontal curves should not coincide with concave vertical curves, which is not a practical option for existing railway lines.

The second case is to extend curve transitions as a way of reducing the carbody's roll velocity. This could sometimes be done on existing lines, in particular at more extensive track upgrading.

Conclusions

From the research and experiments conducted in the programme – or were conducted earlier – it is clear that the tendency for motion sickness can be influenced by a number of different means. The optimum solution will probably not be found in the present Gröna Tåget programme, but a combination of several means have prospects to further reduce motion sickness, despite the fact that some higher curving speeds are proposed.

9. Traction and power supply

Traction deals with the issue of producing the necessary forces for train haulage, i.e. to overcome the resistance to train motion and for accelerating the train. The traction system in modern trains is usually also used for electric braking. Traction is sometimes called '**propulsion**'. For electric train operation the traction system also includes the power supply. Power supply as part of the railway infrastructure is briefly described in Section 2.5. Power supply also includes the pantograph, i.e. the train's current collector. The latter is dealt with in Sections 9.4-9.5 below.

9.1 Adhesion utilization and adhesive mass

The term 'adhesion' means roughly the same as 'friction'. Adhesion should be interpreted as that part of the friction that can be used for transmitting longitudinal forces between wheel and rail for traction or braking. '**Adhesion**' or '**coefficient of adhesion**' α is defined similar to 'friction', i.e.

$$\alpha = F / Q$$

where F is transmitted longitudinal force and Q is vertical load.

The definition of 'adhesion' is usually related to the sum of forces (longitudinal and vertical) of all powered (or braked) wheelsets on a train. The sum of axle loads for all powered wheelsets on the train is referred to as the 'adhesive axle load' (measured in kN) or, more commonly, the corresponding sum of masses carried by the powered wheelsets, referred to as the '**adhesive mass**' (tonnes).

Adhesion utilization is dependent on the transferred longitudinal forces, which varies considerably between different operational conditions. Very often, the term '**adhesion utilization**' is related to the sum of **maximum** longitudinal forces that have to be transferred at the speed in question, thus depending on the traction or braking performance of the train. If a larger longitudinal force is applied to a wheelset than what the actual adhesion allows, the wheels will begin to slip

At low speeds (say up to 70-100 km/h) and in dry wheel-rail conditions, the adhesion level is usually around 0.25-0.35. However, rails may be contaminated with water drops and/or a thin layer of oil. With wet or otherwise contaminated rails, the adhesion is usually lower. However, at low speeds the level of adhesion can be restored to almost 'dry', i.e. at least in the order of 0.25, by using **sand** which is injected by a hose into the wheel-rail interface. At higher speeds, this is usually not possible, because the relative wind speed risks spreading the sand to other locations than the wheel-rail interface. Another factor that contributes to reduce adhesion at higher speed is the increased dynamic variation of the vertical load, i.e. the vertical wheel loads may be momentarily reduced (for some milliseconds) to a low level, sometimes close to zero. Some aquaplaning may also occur. All this makes it easier for the wheels to slip, reducing the effective adhesion level.

At higher speeds, the available effective adhesion level may therefore be considerably lower than at lower speeds, in particular with wet or otherwise contaminated rails. Japanese practices allow adhesion utilization as low as 0.048 at 200 km/h and 0.038 at 270 km/h [22]. These practices are related to wet rail conditions. As these levels of adhesion are used for braking, they include some safety margins, as adhesion has a statistical distribution. Although the exact levels can be discussed for Nordic and European conditions, this is a clear indication that adhesion levels may be very low at high speed onwet rails.

The lower available adhesion at higher speeds is also reflected in the TSI specifications for high-speed trains' braking performance. In TSI HS RST [N1], deceleration during normal service braking is permitted to be as low as 0.6 m/s^2 at 170–230 km/h and 0.35 m/s^2 in the interval 230–300 km/h. These decelerations correspond to an approximate adhesion utilization of 0.06 and 0.035 respectively, with all wheelsets used for braking. The latter level is similar to Japanese practices, while the former level is somewhat higher. In emergency braking, higher levels of deceleration are required, but in this case it is permissible to include the contribution from brakes that are independent of adhesion, i.e. electromagnetic brakes or eddy current brakes.

Adhesion utilization is, of course, most crucial during braking because braking is a most important safety issue. But adhesion utilization during traction is also important, although the safety margins can be reduced.

Attempts to use considerably higher adhesion levels than the above-mentioned risk not being appropriate:

- Wheels risk being subject to considerable slip, which will produce heat and hollow wear on the wheels, which - in turn – risks producing high equivalent conicity, subsequent bogie hunting and frequent wheel turning (cf. Section 8.4). Other wheel damages (surface fatigue and cracks) may also occur.
- Running time performance risks being poorer than predicted, i.e. punctuality may be negatively affected.
- Electric regenerative braking risks being less effective than predicted, leading to higher energy use and increased insertion of mechanical brakes leading to excessive wear on brake pads.

High-speed trains are usually designed to have low or modest adhesion utilization at higher speeds. An important matter is the adhesive mass (i.e. train mass on powered wheelsets) in relation to the total train mass. High-speed trains around the world have various fractions of powered wheelsets. Some early European loco-hauled high-speed trains have only 18-20% of train mass on powered axles, while most of them have 35-50%, with the higher values for multiple unit trains (EMUs) with distributed power along wheelsets in the train. Japan's Shinkansen trains, however, have about 75% of train mass on powered axles.

Modern high-speed trains – with the exception of the first European generation of loco-hauled trains (German ICE 1 and Swedish X2) built during the 1990's – have a maximum adhesion utilization of about 0.15 at low speed; in most cases however only 0.10–0.12. At speeds of around 200 km/h, most European trains utilize an adhesion of 0.06-0.08 maximum, with the exception of TGVs (which have a power-unit at each end) which use about 0.12. Japan's Shinkansen trains utilize an adhesion of less than 0.05 at 200 km/h.

Proposal

It is proposed that Gröna Tåget will have at least 50% of the train mass on powered axles. This will provide a starting acceleration of about 0.6 m/s^2 with an adhesion utilization of slightly more than 0.12. With proposed short-duration tractive power in the order of 4800 kW for a 4-car train (about 20 kW per tonne train mass), adhesion utilization at 200 km/h will be about 0.07.

These levels of adhesion have proven to be appropriate for European conditions. This will facilitate punctual, reliable train operations, low wheel wear and also high-performance eco-driving techniques to save energy and mechanical brake wear.

A solution with about 33% of the train mass on powered axles, resulting in an adhesion utilization of around 0.18 at start, might be considered if the train investment cost is very important. However, the latter option risks causing excessive maintenance on wheels due to slip with high tractive or braking forces as well as increased brake maintenance and higher energy costs.

9.2 Electric traction technology

Since about 1990 the configuration of electric traction systems is by and large almost the same for all major train suppliers. This is due to the available technology. The principal configuration is shown in Figure 9-1. It is anticipated that railway electrification will use alternating current (AC), as on most high-speed railways. AC is used in all electrification on mainline railways in the Nordic countries. Denmark and Finland use 25 kV - 50 Hz, while Norway and Sweden use 15 kV - 16 2/3 Hz. The latter is also used in Germany, Austria and Switzerland.

The main components of a high-speed train's traction system are:

(1) **Power supply** from transformers and frequency converters through the **catenary;**

(2) **Pantograph** and main circuit breaker;

(3) **Transformer** (transforming high voltage to lower voltage for internal use in traction vehicles);

(4) **Converters** - consisting of a **line converter** (rectifier), a direct current (DC) **voltage link** (with smoothing capacitor) and **motor inverters**, the latter providing **3-phase current** of variable voltage and frequency to motors;

(5) **Traction motors** – up till now usually **induction (asynchronous) motors**, but **permanent magnet (PM) synchronous motors** are under commercial introduction 2011-2012;

(6) **Mechanical transmission** between motor and wheels, where the comparatively high rotational speed of the motor (4,000−6,000 rpm maximum) is reduced to what is required for the wheels (1,000−2000 rpm) at maximum permissible vehicle speed.

The size and power of traction motors vary, depending on application (distributed power in passenger cars or separate heavier power units). The design of the mechanical transmission also differs. Heavy motors are often mounted dynamically in the carbody to improve the dynamic properties of the running gear (bogies) at high speed. However, lighter motors can be hung directly in the bogie, which is simpler. The choice also depends on the dynamic performance of the bogies that will be used.

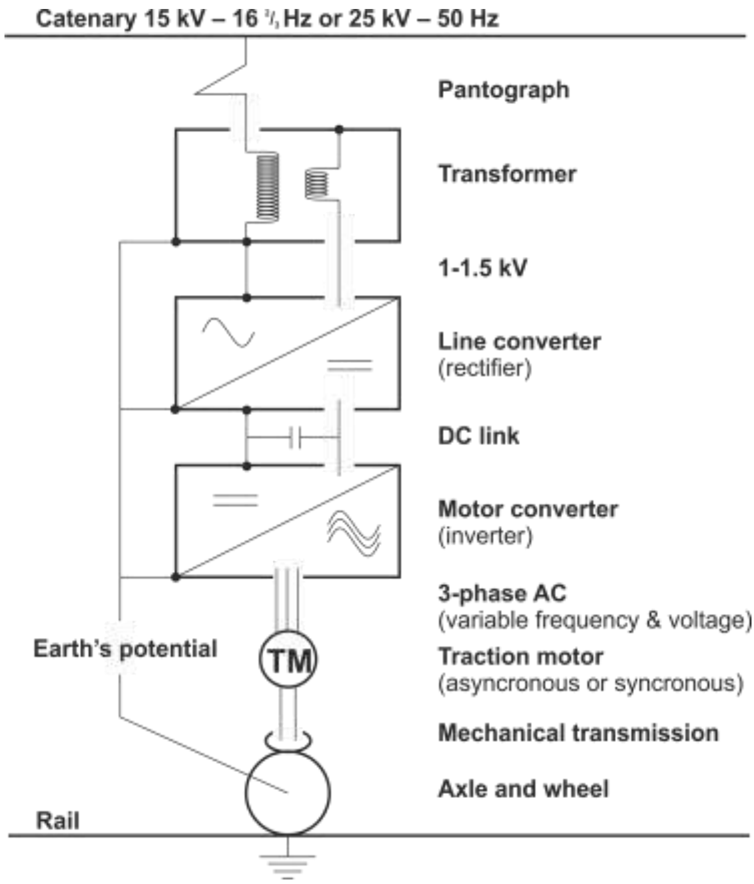

Figure 9-1 Configuration of modern electric traction systems
- With induction (asynchronous) motors (1990–)
- With PM synchronous motors (2012–)
AC = Alternating current; DC = Direct current

Some comparisons have been made between induction (asynchronous) motors versus the newly introduced PM synchronous motors. This is shown in Table 9-1. Some comments and conclusions are made below the table.

It should be noted that PM synchronous motors are not new as a principle, but it is new in the high-power application that is typical for railway traction.

Table 9-1 Comparison of induction motors and PM synchronous motors

	Induction (asynchronous)	***PM (synchronous)***
Stator magnetization	Rotating field excited by 3-phase current	Rotating field excited by 3-phase current
Rotor magnetization	By induction in rotor winding at rotation asynchronous to rotating stator field	**By permanent magnet (PM)** in rotor
Rotor in drive mode	Lower rotation speed than stator field	Synchronous to stator field rotation, but an angle behind
Rotor in braking mode	Higher rotation speed than stator field	Synchronous to stator field rotation, but an angle in front
Stator energy losses	Yes	Yes
Rotor energy losses	Yes	**Very small**
Energy efficiency (typical) [a]	**91–94%**	**95–97%**
Power density (kW/kg) [b] (typical, short time)	**0.8−1.1**	**1.3−1.8**
Two motors supplied from the same converter	**Yes,** rotation speed may deviate within certain limits	**No**

[a] Energy efficiency figures include the internal losses in the motor as well as the additional typical auxiliary power needed for cooling. The lowest figures are approximate for an average duty cycle, while the highest figures are for the most favourable operational conditions regarding power and speed.
Energy efficiency is determined as the ratio between output mechanical energy and input electric energy.

[b] Power density varies over a wide range, depending on a number of design parameters and operational conditions. Figures shown in the table should mainly be seen as relative measures in comparison between the two motor types, although the figures are within a realistic range.

Comments: There are two major advantages with the PM synchronous motor:

- The **lower energy losses** can provide higher energy efficiency. This facilitates **simpler cooling;** only the stator must be cooled, which is much simpler than cooling the rotor inside the motor. In the asynchronous motor, the typical amount of total losses requires external air to be taken into the motor through fans and ducts in the carbody. In the PM motor, the stator can be cooled by self-ventilation using a fan on the motor axle to blow cooling air into ventilation channels in the stator. No auxiliary power is needed in this case.
- The **power density** can be considerably higher, which results in reduced motor mass and/or higher power for equivalent mass and space. For several reasons the PM motor can be designed to deliver considerably higher torque.

There is also a potential disadvantage with the PM motor:

- As the rotor follows the rotating stator field, two motors fed from the same inverter will have exactly the same rotational speed. This is not compatible with the advantage of allowing slightly different wheel diameters on different wheelsets, caused by different wheel wear and wheel turning intervals.
  The practical implication is that **a separate inverter is needed for each motor**. This would increase costs and require more space. However, in high-powered traction systems for high-speed operation, one inverter may usually not be able to feed two motors anyhow. This of course depends on the motor power and the size and concept of the inverters and motors.

Development conducted for Gröna Tåget

In the Gröna Tåget programme permanent magnet (PM) synchronous motors have been developed and tested in cooperation between Bombardier Transportation and KTH. This type of motor is quite new in railway traction applications.

The advantages with PM motors described in the previous pages were confirmed in the tests. In the test train (see Section 1.1), two PM synchronous motors deliver higher maximum power than four induction motors did previously. The new PM motor has approximately the same mass and exterior dimensions as the older induction motor; they were also mounted in the same brackets and space in the test train's bogies. The maximum power was thus more than twice that of the older motor. Each of the PM motors is fed with 3-phase AC current from the same inverter as two induction motors previously.

Each PM motor has a defined maximum power of 950 kW, which corresponds to 1.7 kW per kg. The continuous power is in this case considerably lower, mainly due to the modest cooling with a very simple self-ventilation of the stator.

Figure 9-2 Permanent magnet (PM) motor developed and tested for Gröna Tåget
Source: Bombardier

Motors for railway applications must cope with a number of conditions that are usually much less severe in normal industrial applications. These conditions include shock and vibration, sudden slip between wheel and rail as well as interruption of power supply. They are also subject to severe climate conditions. In railway applications there is also a need to minimize mass, space and noise for a given power and torque.

Both type-testing, i.e. verification of anticipated performance, and long-duration endurance testing are part of the Gröna Tåget programme. Endurance testing was done in commercial service from early 2009 until the end of 2011. So far, the motors have passed all the tests, reportedly with very good outcome. Similar motors will be introduced in new trains in France, Switzerland and other countries.

Proposals

It is proposed that synchronous PM motors be used for future high-speed trains based on the Gröna Tåget concept. For simplicity and cost reasons, it is preferred that a self-ventilated motor be used, so that auxiliary power and air ducts through the carbody can be avoided.

The traction system must also be thoroughly adapted to the harsh Nordic winter climate. See further Kloow [13] and Section 5.2.8 for details.

9.3 Traction performance

Traction performance influences travel time and also the degree of electric braking that can be achieved. In the Gröna Tåget programme, the importance of tractive power and starting acceleration has been thoroughly elaborated in Sipilä [9] for a number of future train services in Sweden. The benefits of power and regenerative braking have been shown by Sjöholm [6]. A summary was given in Section 4.3. In summary, high power is advantageous during both driving and electric braking.

It is usually the responsibility of the train supplier to propose, design and build a traction system that meets the specified demands concerning travel time, energy use and others. In the Gröna Tåget programme, a train concept has been proposed – with optional alternatives – where a combination of performance data is anticipated in order to meet the overall demands. The anticipated properties will be presented and motivated below and will be part of the following discussions, accompanied by major simulation results rather than by very detailed investigations.

Mainly two performance quantities will be discussed: (1) starting tractive force and (2) tractive power. These quantities are shown in Figure 9-3.

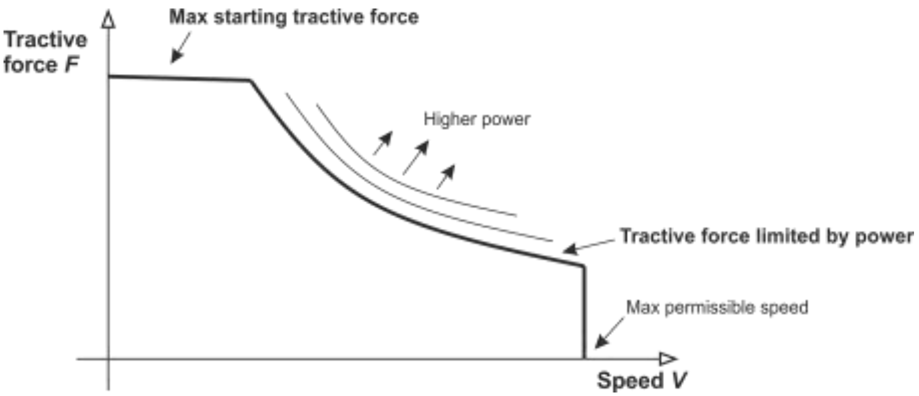

Figure 9-3 Tractive force characteristic versus speed

Note that the tractive force characteristic may differ to some extent between **drive mode** and **electric braking mode,** respectively (see further Section 9.3.2 below).

9.3.1 Starting tractive force

Proposal

As a main reference alternative for Gröna Tåget it is proposed that the starting tractive effort be chosen such that a **starting acceleration of** at least **0.6 m/s²** is achieved. This is for long-distance service with relatively few intermediate stops, i.e. the shortest average stopping interval is about 50 km. For this type of service, a higher starting acceleration (0.8 m/s²) results in less than 1 minute gain in travel time (of about 150 minutes as the baseline). For non-stopping trains the gain would be only some 5-10 seconds.

For a 4-car train with a service mass of 232 tonnes, carrying an average of 186 passengers, this requires a starting tractive force of the order of 160 kN.

Versions of Gröna Tåget intended for fast regional service may be able to use higher starting acceleration. This can be provided by changing the gear ratio between traction motor and wheels, on condition that a lower top speed can be accepted than for the long-distance version. Alternatively, a higher motor torque must be provided. With the same top speed (250 km/h) and the same tractive power (20 kW/tonne), but with starting acceleration increased from 0.6 m/s² to 0.8 m/s², some 2 minutes travel time is gained on the 340 km Gothenburg-Copenhagen route with 14 intermediate stops.

9.3.2 Tractive power

At a certain speed the starting tractive force must be reduced from the level attained at low speed, because of limited available tractive power. Tractive power P (kW) is tractive force F (kN) times speed v (m/s),i.e.

$$P = F \cdot v$$

and therefore, as also shown in Figure 9-3:

$$F = P / v$$

at speeds where maximum available power is delivered.

Proposal and discussion

As a main reference alternative it is proposed that a short-duration power of the order of **20 kW per tonne train mass** be provided in drive mode. This is for a train intended for top speeds of 250–275 km/h. For a 4-car train this is equivalent to about 4,800 kW. For a 6-car average train size, the corresponding figure is 7,200 kW. It is further assumed that the maximum power is constant or almost constant throughout the speed range where power limits tractive force.

It is assumed and proposed that trains for top speeds of at least 280 km/h will have a maximum power of the order of 25 kW per tonne of train mass, although the main discussion in this section will focus on a traction system for the lower speeds, i.e.250-275 km/h.

The power assumed above relates to the maximum **short-duration power**, to be delivered for1–3 minutes during full acceleration or electric braking. Another measure, which is most often referred to, is the **continuous power** that can be delivered for an infinite time without overheating or otherwise over-stressing the traction system.

In the Gröna Tåget programme we have made preliminary estimations of r.m.s power with different durations, using the computer simulation system STEC – Simulation of Train Energy Consumption; ref [25]. According to these investigations the most demanding case is for a fast regional train service with fairly frequent stops from top speed, also including a number of unplanned stops at restrictive signals or track work. The conditions are

- Fast regional service on the Gothenburg-Copenhagen route (342 km), top speed 250 km/h; see section 4.3;
- 14 planned and 4 unplanned stops or severe speed restrictions underway, plus one stop at final destination, i.e. 19 stops in all (or close to stops);
- Of the 19 stops, 13 start braking at a speed of at least 200 km/h.
- Average interval between stops (or severe speed reductions) is 18 km;
- The electric brake is mainly used, providing 90% of braking energy.
- Tunnels (about 8% of the route) increase the average air drag by 5%.

This example should be close to the worst case for the Gröna Tåget type of train.

The maximum r.m.s. power at the wheel-rail interface for an average 6-car train is:

- During 1 minute 7,420 kW (during electric braking)
- During 2 minutes 7,348 kW (during electric braking)
- During 60 minutes 4,980 kW
- Over the entire run 4,555 kW

It is noted that the long-duration r.m.s. power is much lower than the short-duration power. For at least traction motors and the transformer (with comparatively slow temperature rise) this fact will favourably affect the thermal dimensioning.

It can be seen from the above figures that the short-duration power is higher than the nominal short time power of 7,200 kW for a 6-car train. This is because the power shown is related to the **wheel-rail interface** and not to the motor or the converter. With the same output power from the traction motors, the power at the wheels will be 3% higher in electric braking mode than in drive mode, assuming 1.5% losses in the mechanical transmission from motor to wheel and vice versa. In the above estimation it was assumed that the motor was the power-limiting component. The difference will be larger if the converter is the short-duration power-limiting part of the traction system (and motors are not). For example, assuming an average efficiency of 95% for the motor and 98.5% for the mechanical transmission, the electric braking power (at wheels) will be about 8,200 kW, with the same power delivered from the converter. The power in drive mode will remain at 7,200 kW at wheels.

This difference opens up for higher power (at wheels) in electric braking mode than in the drive mode. As the train's performance regarding travel time and energy usage depends on both driving and electric braking, performance in drive mode might possibly be compromised to some extent. Certainly, motors and the transformer (with slower temperature rise) can be dimensioned for lower continuous power than the short-duration power.

Studies have also been made for a 6-car very high-speed train (VHST) running on the proposed Eastern Link/Götaland (high-speed) Line in Sweden. Its top speed is 320 km/h and the line has frequent up and down gradients (20–30‰) in which drive and braking modes alternate. This contributes to a comparatively high utilization of the traction system, if the electric brakes are used as the normal operational braking. In this case the 60-minute r.m.s. power is about 80% of maximum power (9,000 kW in drive mode and 9,280 in electric braking mode), while the entire run r.m.s. is about 75% of maximum. Although these figures are more demanding than for the previous case at lower speed, there is still a considerable difference between short-duration and long-duration power.

In all cases it is preferred that a simple self-ventilation of the motors can be used. As stated earlier it is, however, the responsibility of the train and traction system supplier to make the final estimations and decisions, taking into account all the performance requirements and all parts of the traction system.

9.3.3 Notes on TSI requirements

The proposals in Sections 9.3.1 and 9.3.2 have large margins to TSI requirements, as expressed in TSI HS RST, clause 4.2.8.

For Class 1 trains, TSI requires a minimum starting acceleration of only 0.40 m/s^2 on horizontal (level) track at nominal supply voltage. For Class 2 trains (top speed below 250 km/h), the minimum requirement is 0.30 m/s^2. These very modest requirements are not compatible with the permissible maximum gradients (35‰) according to TSI HS INF, not even with full traction performance, and even less at reduced traction performance in case of an equipment failure of 25% or 50% – that is also specified in TSI HS RST. Such an equipment failure – following the minimum requirements of TSI – will cause the train to stand still on a maximum gradient as specified in TSI HS INF. We do not consider this to be acceptable for a train intended to have good reliability and punctuality.

Another example is that the required minimum acceleration on horizontal track at maximum service speed is only 0.05 $m/^2$ in TSI. This very modest performance may be sufficient for non-stop services over large distances (which is to a large extent the case in France), but for trains with more frequent stops such modest performance would lead to significantly longer travel time. With the power (of the order of 20 kW/tonne) and running resistance performance proposed for Gröna Tåget, the residual acceleration will be in the order of 0.17 m/s^2 at 250 km/h.

9.4 Power supply

For general use in the Nordic rail networks a dual-system is necessary with respect to power supply. Denmark and Finland have nominally 25 kV – 50 Hz, while Norway and Sweden have 15 kV – 16 2/3 Hz. The voltage is measured as r.m.s. It is considered as necessary that future trains based on the Gröna Tåget concept must be interoperable in Denmark, Norway and Sweden.

With the desired flexible operational concept, the three pantographs will work at intermediate distances of 100, 108 or 116 m for 4-car trainsets with full-length cars. With 5- or 6-car trainsets, the two latter distances will be increased accordingly. Characteristics of the electric power supply system in Sweden are specified in Section 2.5. Characteristics for other Nordic countries are specified in EN 50 367 [N16].

At least the following specific requirements are necessary for the Nordic networks:

- The highest allowed non-permanent voltage for rolling stock is 17.5 kV in Sweden. This is due to limitations in existing rail vehicles, and is mentioned as a specific case in TSI.
- A number of detailed specific requirements for electric rail vehicles intended for Finland, Norway and Sweden are stated in NES TS 01 [N17]. These requirements deal with the inrush current of the transformer, telecommunication disturbances, exterior antennas, neutral sections of the catenary, line voltage distortion, allowed power factor, low-frequency power oscillations, current harmonics and others. See also Leander [5].
- For unrestricted use everywhere in Sweden, the current drawn by a train is limited to 900 A. This is compatible to a train consist of two 4-car units having a traction max power of 9,600 kW. For three 4-car units having a maximum traction power of 14,400 kW, plus losses and auxiliary power, the max current will be in the order of 1200 A at a supply voltage of 14.5 kV. This would be acceptable for modern electrified lines in Sweden. It is proposed that the train be equipped with a current limitation being active at voltages below a certain value, possibly 15 kV. The exact setting of this limitation should be agreed between the infrastructure manager (Trafikverket) and the train supplier or the operator. For Denmark, Norway and Finland, other limits and settings may apply.

Other Nordic networks (DK, N, SF) have their own specific requirements.

9.5 Pantograph

9.5.1 Conditions and targets

Current collection at high speed is one of the most demanding tasks, in particular if the catenary is designed and maintained for lower speeds than the target speed for the intended train operation.

Up to **three pantographs may operate in multiple** on the catenary in the same train, according to the Gröna Tåget concept. Pantographs are proposed to be placed above the fourth bogie in the train; see Figure 3-4.

A preliminary target is to make it possible to operate with good reliability

- At 200 km/h in multiple operation with three pantographs on catenary of today's standard for 200km/h, i.e. SYT 7.0/9.8 or ST 9.8/11.8
- At 250 km/h in multiple operation with three pantographs on catenary of today's standard for 250 km/h, i.e. ST 15/15 or SYT 15/15.

  It should be noted that SYT 7.0/9.8 is today (2011) operated at 200 km/h with two pantographs, normally with an intermediate distance of 140 or 165 m. Occasionally, there are also short catenary sections with lower standard – ST 7.0/9.8 with sagged simple catenary – usually when passing yards with deviating tracks and catenary wires.

9.5.2 Contact force and catenary uplift

The general requirements for the Swedish catenary are as listed below; see EN 50 367 [N16], where national specifications for other Nordic countries are also given:

- Nominal force at standstill: 50–60 N
- Maximum mean contact force at any speed: 110 N
- Maximum contact force at any speed (mean + 3 stddev) 200 N
- Minimum contact force at any speed: 0 N

These targets were for example developed for a maximum speed of up to 250 km/h. However, at 250 km/h and according to [N17] the allowed maximum mean contact force is 120 N, while the allowed maximum contact force is 220 N. The above targets are based on a maximum permitted uplift of the catenary of 120 mm and a minimum of arcing.

It is concluded that the above-mentioned conditions and targets are very demanding and require very good dynamic behaviour of the pantograph.

No target or development programme has yet been defined for catenary and pantographs at speeds above 250 km/h. As speeds above 250 km/h will mainly be applied on newly built high-speed lines, it is anticipated that catenary and pantograph will use proven technology from other very-high-speed railways in the world.

Development and studies conducted for Gröna Tåget

In the Gröna Tåget programme, two main activities are conducted regarding pantograph-catenary interaction:

- On-track testing of a pantograph with a newly developed head (Schunk WBL 88 with head SSS 400), using the REGINA 250test train.

  Tests were conducted on the old Stockholm-Gothenburg main line, specifically the Skövde-Töreboda section in both directions, at speeds of up to 303 km/hand mainly on straight track. The catenary standard was usually SYT 7.0/9.8, but ST 7.0/9.8 also existed occasionally according to the national Swedish infrastructure data base (BIS).

  Tests were also conducted on the Stockholm-Sundsvall line, specifically the upgraded Örbyhus-Skutskär section, at speeds of up to 270 km/h, on straight and curved track. The catenary was usually the standard ST 15/15 type, although ST 9.8/9.8 also existed occasionally over station yards.

  Tests were made in both 'closed knee' and 'open knee' directions. A single pantograph was tested on the train, due to the fact that only one test train was available. Pantograph testing was done in co-operation between the Swedish Transport Administration, Bombardier Transportation and Schunk Nordiska.
- Development and validation of improved models for simulation of pantograph-catenary interaction. Special consideration should be taken to **multiple operation** of pantographs on arbitrary distances (see above). **Section points** where two catenary wires diverge in different directions with considerable height variation are of special interest, as these parts of the catenary may generate the highest or lowest contact forces.

Both tests and simulation models use the WBL 88 pantograph with head SSS 400 as a reference. The head and its suspension are light; the suspension has a large stroke. The aerodynamic influence of head suspension is minimized by separation of the wind pressure direction and the working direction of the suspension: see Figure 9-4. There are aerofoils in order to minimize the influence of running direction (open or closed pantograph 'knee') and to achieve an even distribution of the contact forces between the two carbon strips.

Test results

Although the maximum testing speed was 303 km/h, the main focus was on speeds up to 270 km/h. This is 20 km/h above the target speed for catenary ST 15/15 and 70 km/h above the target speed for SYT 7.0/9.8. As stated earlier, the test sections also occasionally included parts with a lower catenary standard.

Despite the low standard of the catenary on the Skövde-Töreboda section in relation to the test speed, the contact force targets were essentially met at speeds up to 270 km/h. At this speed, the maximum contact force was measured up to 116 N, which is within the 120 N limit prescribed in [N16]. At 250 km/h, the mean contact force met the target of 110 kN maximum prescribed in [N15].

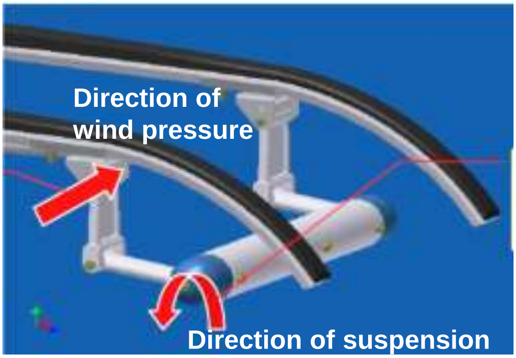

Figure 9-4 Pantograph head SSS 400

The maximum contact force stayed well within the 200 N upper limit in all cases. The standard deviation at 270 km/h was about 25 N on the Skövde-Töreboda section and 20 N on the Örbyhus-Skutskär section –the latter with higher catenary standard. For a more detailed description, see Bustad [26].

These results for single pantograph operation are very promising. Some further improvement could possibly be made for the average force in the 'open knee' direction.

Figure 9-5 Pantograph testing – view of the visual display in the train

Development of simulation models

Despite the promising test results, questions still remain with regard to performance in multiple operations, as these cases could not be tested. It is well known that multiple operation of pantographs may not be as good as with a single pantograph, with higher dynamic forces (i.e. larger standard deviation). This is one of the main reasons why improved simulation models are also being developed.

There are several goals and questions to be answered, both from a practical and scientific point of view:

- What type of catenary is needed to meet the target of running with up to three pantographs with arbitrary distances from about 60 m and up?
- Can this target be met with a pantograph with passive suspension, for example the tested one WBL 88 and head SSS 400?
- Are pantographs with active suspension, or at least controllable mean force, necessary or desirable?
- Can simulation models be developed, having good agreement with real performance? In this context it should be mentioned that tests with three pantographs have been conducted with 'Regina' trains in Sweden (although not with the Gröna Tåget test train), at speeds up to 210 km/h. Simulation models must thus be validated.

The last point is the starting point; when this has been completed with satisfactory results, the three other issues can be subjected to parametric studies. Development of simulation models – and the succeeding parametric studies –is being carried out by KTH in co-operation with the Swedish Transport Administration.

Due to a high work load, this part of Gröna Tåget is delayed. The final report is estimated by 2012. To date (November 2011) some important steps have been taken:

- The two-dimensional Finite element model has been validated against Gröna Tåget measurements. Up to 250km/h the results are quite satisfactory. For higher speeds, the deviations increase. Comparisons with a similar simulation program developed at Politecnico di Milano also show good agreement.
- To achieve even better agreement between simulation and measurement, a three dimensional FE model is also being developed, including for example the zigzag motion of the catenary and the roll degree of freedom of the pantograph head. This model has not yet been validated, however. When the model has been validated, parameter studies for relevant operational cases will be carried out.
- Together with Politecnico di Milano, a study regarding operation with two pantographs has been carried out. A reduction in the quasi-static uplift force on the leading pantograph with a simultaneous increase in the uplift force on the trailing pantograph was tested. Both simulation results and on-track tests on a high-speed line in Italy indicate a potential for improved current collection [26].
- In parallel, a simple three-degree-of-freedom model for the dynamic pantograph catenary interaction is being developed with the MBS program GENSYS. This model shows surprisingly good results regarding calculated standard deviation of contact forces. With this model also the first studies of an active control, working

in parallel with the air spring at the lower arm of the pantograph, are also being carried out. Initial results indicate a 15–20% reduction of standard deviation of the contact force.

9.5.3 Geometric and other considerations

Pantograph width

The TSI and EN 50 367 [N16] specify a total pantograph width of 1,600 mm. EN 50 367 states in Clause 1 that such a pantograph achieves 'free access to the European railway network'. This is however not true, because many railway networks have their own national standards, which are also specified in EN 50 367, Appendix B.

In Denmark, Norway and Sweden a **pantograph width of 1,800 mm** is necessary, although Denmark also allows a width of 1,950 mm (as also Germany and the Öresund Link). The 1,800 mm pantograph is necessary to be compatible with the lateral deviation of the catenary above the track centre line. These conditions will certainly prevail for a long time, as it would be very expensive to change.

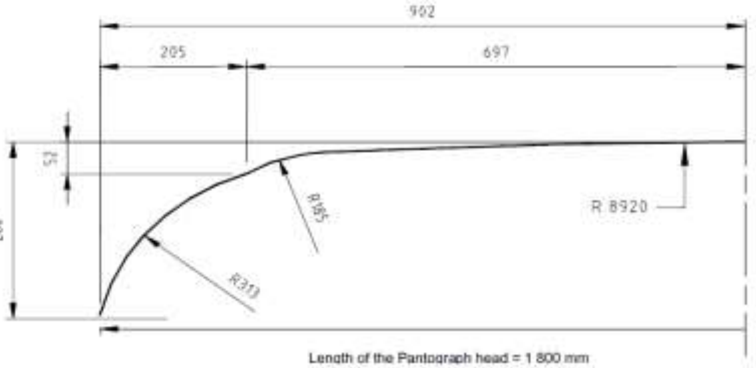

Figure 9-6 Pantograph head for Sweden and Norway, also allowed in Denmark.
Source: EN 50 367

Pantograph sway

Sway is a combined lateral and roll motion of the vehicle. As the vehicle is subject to lateral forces (or acceleration) the suspension of the vehicle causes sway and lateral displacement of the vehicle body and its roof-mounted pantograph. The flexibility of the pantograph itself may also contribute. To be compatible with the possible lateral deviation of the catenary above the track centre line, this sway must be limited; otherwise the pantograph may deviate laterally outside the range of the catenary, which will cause severe damage and probably complete interruption of train services.

Special attention must be paid to the this issue in the case of trains with tilting carbodies, as these operate with extra high cant deficiency (lateral acceleration) and also in the case of trains running at higher cant deficiency in curves. Gröna Tåget is such a train concept.

It is proposed that the **maximum lateral sway of the pantograph**, relative to the actual centre line above the track **be limited to 250 mm in the worst case.** The same figure is specified in the national requirements for Norway [N17], and is here also proposed for Denmark and Sweden.

If the pantograph is mounted on top of a tilting carbody, an **anti-tilt system** must be applied to the pantograph. Regarding estimation of maximum sway, see Section 8.7. The flexibility of the pantograph and its support must also be included in all cases.

Working range

The necessary **working range** for pantographs of trains interoperable on the whole network of Denmark, Norway and Sweden is **4.60–6.10 m** [N17, N18]. It may be that the extremes can be eliminated after a thorough investigation.

Redundancy

It is proposed that each trainset with 4–6 cars has **two pantographs**, of which one is used as a spare in case of damage or other malfunction. It is also proposed that the corresponding circuit breaker and other high-voltage equipment be doubled. This is to increase availability of the train. Redundancy is also a safety issue when running in tunnels. This is also a requirement for Class 1 trains according in TSI HS RST.

Adaption to winter climate

The pantograph and its maintenance must be adapted to the harsh Nordic winter climate in order to ensure reliable winter operation. See further Kloow [13] and the summaries in Section 5.2.9 and 5.2.10 for details.

10. Braking

10.1 TSI and additional braking performance

TSI minimum requirements

TSI HS RST [N1] has moderate or low minimum demands regarding braking performance. In Section 4.2.4 of the TSI and in Leander [5], the following **emergency braking requirements** are stipulated:

	t_e	Minimum mean deceleration [m/s²] measured between end of t_e and reaching the target speed.			
	[s]	350-300 (km/h)	300-230 (km/h)	230-170 (km/h)	170-0 (km/h)
Case A	3	0,75	0,9	1,05	1,2
Case B	3	0,60	0,7	0,8	0,9

t_e [s] = Equivalent time of application: the sum of the delay period and half of the brake force build up time, where the build up time is defined as the time needed to reach 95% of the braking force demanded.

Case A: Emergency braking with specific equipment isolated:

Case B: Emergency braking with specific equipment isolated and unfavourable climatic conditions;
- reduced wheel/rail friction
- reduced brake pad/brake disc friction

The specified braking performance shall be achieved on horizontal track at normal load (train in service condition and all seats occupied). Details regarding braking conditions, braking calculations and tests are given in Annex P of the TSI. For example, the definition of reduced friction is given in Annex P.

Also minimum **service braking requirements** are specified in the TSI. The following minimum decelerations are required:

- 0.6 m/s² is required for speeds up to 230 km/h
- 0.35 m/s² is required for speeds of 230–300 km/h.

IN service braking tests, the electric regenerative brakes may also be activated. Electromagnetic brakes shall not be activated.

Note 1: **"**Specific equipment isolated" means that the electric brake shall be de-activated if this brake is dependent on the overhead contact wire. Thus, during emergency braking the required braking performance shall be provided by the mechanical friction brakes and electro-magnetic brakes only.

Note 2: In case B a distributor valve acting on one or two bogies shall also be de-activated. For example, the latter means that a 4-car train with 8 bogies shall have a maximum of 7 bogies with activated braking in the acceptance tests. A 6-car train with 12 bogies shall have a maximum of 11 bogies with activated braking.

Note 3: On existing infrastructures, infrastructure managers are permitted to define further requirements concerning the different signalling and control systems. Additional braking performance or reduced speeds may be required.

Note 4: The thermal brake performance shall allow a train to run at the maximum downhill gradient on the line, with a speed that is 90% of the maximum operational train speed. The thermal performance shall be used for calculating the limiting gradient where the maximum train speed can be operated.

Note 5: According to the TSI, brake tests shall be conducted at temperatures between +5 and +25°C and shall not be undertaken in snow. However, see the specific requirements for Sweden below.

Additional braking performance required for Sweden

On the existing Swedish rail network, the pre-signalling distances are relatively short; see Section 2.6. Therefore a higher level of deceleration is required than specified in the TSI. Also other requirements apply, in particular for winter conditions; see the list below.

- **The required deceleration is 1.07 m/s^2 for speeds up to 200 km/h**, i.e. with the current ATP system. This is required for conditions similar to Case B in the TSI, for emergency braking as well as for service braking. Service braking requirements are thus 78% higher than TSI requirements.
- For **speeds above 200 km/h**, it is anticipated that ERTMS/ETCS will be installed, allowing deceleration according to the TSI to be applied.
- Deceleration and other functional requirements must also be applied in **snow and cold;** see further Sections 5.1 and 5.2.3. Acceptance tests shall also be performed at temperatures below 0°C, with powder snow on the track. The mean deceleration under these conditions must not be less than 1.03 m/s^2.
- **Eddy current brakes** (with energy dissipation in the rails) are not allowed on Category II and III lines. This is a permanent specific case for Sweden in the TSI.

Details of Swedish requirements can be found in BVS 544.98007 [N22]. Brake pads shall comply with the relevant clauses in UIC 541-3 [N21], in particular Section 2.1.2.3.

10.2 Regenerative electric braking as the normal braking mode

It is anticipated that future high-speed trains according to the Gröna Tåget concept will be equipped with several braking means, preferably and probably the following:

- **Disc brakes** on all axles; the exact number and size of the discs to be determined at the design stage
- **Electro-magnetic track brakes** on at least 50% of the bogies. The leading bogie is proposed to always have track brakes in order to clean the track for succeeding wheels.
- **Regenerative electric brake**, with traction motors and their converters working in the braking mode.

Proposals

It is anticipated and proposed that the adhesion utilization is modest, see Section 9.1. It is proposed that at least 50% of the axles be powered. With the power proposed in Sections 9.1–9.2 (short-duration 20 kW per tonne up to a top speed of 280 km/h), and a normal operational acceleration/deceleration of 0.6 m/s^2 the adhesion utilization will be in the order of 0.12 at speeds up to 110 km/h and 0.07 at 200 km/h, in both driving and electric braking modes.

With the proposed power and adhesion utilization it is possible to use the electric **regenerative brakes as the normal braking mode**, provided that the overhead power supply can receive the regenerated power. These principles have several advantages:

- Electrical energy is regenerated at braking, which can save some 20–30 % of net energy intake, depending on the operational case.
- Braking is performed without wear to the mechanical disc brakes
- The train's performance is expected to be robust
- Wheel tread wear and damage are expected to be low.

High power and modest adhesion utilization facilitate eco-driving with maintained short travelling time. See also Sections 4.2–4.5 in this report, as well as Sjöholm [6].

The TSI [N1] has very modest requirements based on the practice of older loco-hauled high-speed trains. TSI requires a maximum adhesion utilization of 0.15 during braking at speeds of up to 200 km/h. Above 200 km/h, lower adhesion shall be utilized. This is higher than European trains with distributed power and much higher than the Japanese Shinkansen trains.

Braking performance and robustness for a modern high-speed train are proposed to be set higher than the minimum requirements in the TSI.

11. Environmental performance

11.1 Energy use

Electric trains are widely considered to have low environmental impact in comparison to other transport modes. In particular, this is due to the low energy consumption per passenger-km (pkm) and to the possibility to use electric power produced with low or almost zero greenhouse gas (GHG) emissions and other air pollutants.

However, higher speeds would increase energy consumption if trains of "low-speed design" were to be used although this is not usually the case. In order to still remain a superior transport mode as regards energy consumption and also to reduce costs, high-speed trains must be improved in comparison to previous trains for lower speeds. This is also what has historically been done.

Two examples:

(1) When *X2* high-speed trains (top speed 200 km/h) replaced older loco-hauled InterCity trains (top speed 160 km/h) in Sweden, the energy use per passenger-km decreased from 108 Wh (with load factor 44%) to 77 Wh (at load factor 55%), i.e. by 29 including losses in the railway's electric supply; Andersson [10].

(2) One of the world's fastest trains is likely the world's most energy efficient train: the Japanese Shinkansen high-speed trains between Tokyo and Osaka (top speed 270–285 km/h, load factor 65%) are reported to have an energy use of 20,000 kWh on this line, or less than 50 Wh per passenger-km, also including losses in the railway's electric supply.

Generally, high-speed trains have no tendency to use more energy per passenger-km than older slower trains; rather, they use less energy. The reasons are mainly the following:

- When a train is designed and built for higher speed a number of **design changes** are made in order to make the train suitable for higher speed. The most obvious change is to reduce air drag. This is done partly for safety and economic reasons and partly to maintain superior environmental performance.
- A new high-speed train can benefit from the **latest technical achievements**, such as improved aerodynamic design to reduce air drag, increased regeneration of electric energy when braking, increased efficiency in train-borne and stationary electrical power equipment, systems for eco-driving, etc.
- High-speed trains have usually shown a **higher load factor** (i.e. an increased share of seats are occupied by travellers); this is most likely due to a more attractive and competitive offer to the travellers. In the long-distance market high-speed trains usually have a load factor of 55-70%, while older (and slower) trains, with a lower proportion of long journeys, usually have 40-50%. A train's energy use is almost independent of the actual number of passengers. A higher load factor thus reduces energy use per passenger.

Studies conducted for Gröna Tåget

Several studies related to the possible and probable energy use in future Gröna Tåget operations have been conducted. A first investigation was made by Lukaszewicz et al [11]. Energy use for operations on the existing Stockholm–Skövde–Gothenburg line was estimated for a top speed of 250 km/h (although lower speeds were also used where curves restricted speeds along the line). See the map in Section 2.1.

A proposed very-high-speed line Stockholm–Jönköping–Gothenburg was also investigated in [11], with assumed top speeds of 250, 280 and 320 km/h and with varying numbers of intermediate stops. On the latter line, two different levels of aerodynamic performance were investigated, where the sum of air drag and impulse resistance is about 16–19% lover for the more ambitious target (see Section 7.6). A simplified eco-driving (for simplicity assuming 80% electric regenerative braking) technique was applied. The dedicated very-high-speed line will have more **tunnels**, which causes increased air drag. Based on recent planning, it was estimated that the share of tunnels will be 10–12% of total route length, assuming to increase the average air drag by about 7%, total running resistance by 5–6% and energy use by 3–4% (cf. also Section 7.5). The effect of tunnels is included in the estimations of energy use presented in Table 11-1.

Studies have also evaluated the use of **regenerative braking and eco-driving** (see Sjöholm [6]). A fast regional service with frequent stops (Gothenburg-Copenhagen) was also evaluated in [6]. Eco-driving was studied taking a simplified approach:

- Regenerative electric brakes are used as the normal operating braking mode;
- Coasting is applied before speed reduction (but not before downhill gradients);
- Acceleration is avoided if just a short section in front is allowed for higher speed.

It should be noted that 90% regenerative electric braking is used here because regeneration will sometimes not be possible. For details, see Section 4.2 and Sjöholm [6].

Another issue is the **energy losses** in the train and in the electric supply of the railway system. The traction system in Gröna Tåget is assumed to have average energy efficiency during a typical load cycle of 84%. Although believed to be a conservative assumption, this figure is comparatively high, due to the proposed use of synchronous PM motors (see Section 9.2). A traditional traction drive with asynchronous induction motors is assumed to have an energy efficiency of 82%.

The load factor **(percentage of occupied seats) is one of the key factors in the estimation of energy use per passenger-km. The future load factor is, however, uncertain and will change over time, depending on fare strategies and competition. As mentioned above, the average load factor of long-distance high-speed trains is usually in the range of 55−70%, i.e. it varies considerably. An illustrative example is the Swedish high-speed train X2. From 2000−2004 the average load factor was in the range of 55−60%, but improved up to 70−73% between 2006** and **2010 after SJ AB introduced yield management, with fares depending on time and actual travel demand for every departure. The earlier load factor of 55% was also high compared with the old loco-hauled Inter-City trains in the 1990s (load factor of 44%) [10].**

The Gröna Tåget train concept is proposed to have relatively small units (normally only 4 cars with about 300 seats), allowing longer trains (8 or 12 cars) to be formed when travel demand is high. This makes the Gröna Tåget flexible in size. The risk of running trains with too high capacity, in relation to actual travel demand, is reduced. For this reason, Gröna Tåget's load factor is assumed to be some percentage points higher, for example 65% instead of 60% for a longer, more inflexible train in long-distance service. For Gröna Tåget, this means 280 occupied seats on an average 6-car train (half of the departures with one 4-car unit, half with two units) with high comfort and generous luggage space, having 430 seats. The same number of seats will be occupied assuming a load factor of 60% for an average 6-car train with 465 seats.

The assumed load factors are low in relation to what has been achieved in Swedish long-distance trains since SJ introduced flexible fares. However, it is uncertain whether the high load factor can be maintained in the future with open access and competing operators. We therefore take a cautious approach, although the future load factor may be higher than assumed; energy use per passenger-km may therefore be lower.

Table 11-1 summarizes studies of energy use within the Gröna Tåget programme. The data are based on [6, 11] with supplementary estimations for this report. The different cases are intended to cover a broad spectrum of possible train services.

Table 11-1 Estimations of travel time and energy use for Gröna Tåget

		Top speed (km/h)	*Number of stops* [a]	*Load factor*	*Travel time* [b] *(h:min)*	*Energy use* [c] *(Wh/pkm)*
1.	Stockholm–Skövde-Gothenburg, existing upgraded line (455 km)	250[e]	4+1	60–65%	2:48	46
”	**Reference X2**	**200**	4+1	60%	**3:07**	**71**
2.a	Stockholm-Jönköping-Gothenburg, new dedicated HS line (467 km)	320 [d]	0	60–65%	1:58	62
2.b	Stockholm–Jönköping–Gothenburg, new dedicated HS line (467 km)	320[d] 280[d]	7+1 7+1	60–65% 60–65%	2:35 2:45	57 50
	Same line, but with moderate ambitions for train performance	280[e] 250[e]	7+1 7+1	60–65% 60–65%	2:47 2:54	56 50
3.	Gothenburg–Malmö–Copenhagen, upgraded line (342km)	250[e]	14	45%	2:51	60

[a] Average number of intermediate scheduled stops at stations, occasional signal stops and speed restrictions are assumed.(See Sjöholm [6] for details).

[b] Estimated realistic scheduled travel time, including a conventional 10% time margin (compared to fastest possible time) and dwell time at stations.

[c] Consideration is taken to increased air drag in tunnels and all losses in the train's and the railway's electric supply.

[d] Aerodynamic resistance with ambitious targets (see Section 7.5). Max. tractive power: 9,000 kW.

[e] Aerodynamic resistance with moderate efforts (see Section 7.5). Max. tractive power: 7,200 kW.

Note 1: Estimations in Table 11-1 assume **wide-body trains**. These are estimated to have 25% more seats and 10% higher aerodynamic resistance than trains with continental width (with the same number of cars). A preliminary estimation has been made for trains with continental width, assuming that the trains must convey 25% more cars to have the same capacity; for example, a train unit of 4 cars will become a 5-car train (cf. Figure 3-3). Trains with continental width are thus estimated to have about 10% higher energy use per pass-km compared to wide-body trains.

Note 2: 8-car average trains (instead of 6) will reduce energy use per passenger-km by about 7%.

Note 3: If **aerodynamic resistance** is increased by 10%, the resulting energy use is increased by 4−7%, with the higher figure at very high speed and few stops, while the lower figure is more relevant for fast regional trains with more frequent stops.

Note 4: The future **load factor** is an uncertainty. A cautious assumption (60−65%) has been made for future flexible long-distance trains. This is some percentage points better than assumed for the comparable X2. If the load factor is increased to 70% for Gröna Tåget, the energy use per pass-km is reduced by 7%.

The fast regional train in Case 3 (Malmö-Copenhagen with 14 intermediate stops) has a lower load factor (45%) which is typical for this type of train services. It is assumed that a 6-car regional train will only convey 240 travellers on average. The lower load factor is the main reason for the somewhat higher energy use per pass-km. Note that the top speed is assumed to be as high as 250 km/h in this case.

Note 5: The energy use in Table 11-1 and Figure 11-1 includes

- Energy loss in the railway's electric supply system (converter station and catenary), assumed on average to be 12% of the energy intake from the public grid [10].
- **Increased air drag in tunnels (see Section 7.5 and [11]).**
- An extra 2% for idling at stations (note that measured energy includes idling).

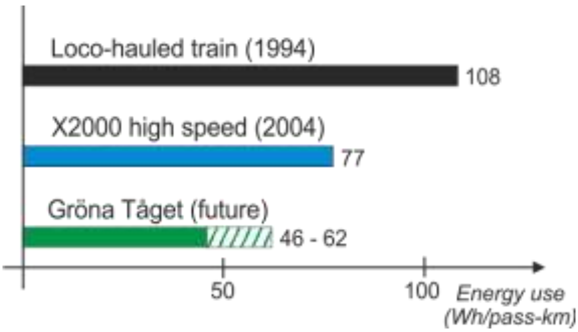

Figure 11-1 Development of energy use per passenger-km for Swedish long-distance trains, recent trains and projected for future Gröna Tåget.

In Table 11-1 and Figure 11-1, Gröna Tåget has a range with lowest and highest figures. The highest figures are for the highest average speeds, while the lowest are for modest speeds (in this case a top speed of 250 km/h, while average speed is 160–180 km/h excluding dwell time). Travel times in Table 11-1 are not immediately comparable, as the number of intermediate stops is different.

The X2 train has further improved since 2004 due to increased load factor. Indicated relations between *X2* and Gröna Tåget are however believed to be relevant.

11.2 Greenhouse gas (GHG) emissions

Greenhouse gas (GHG) emissions due to energy use of electric trains are **indirect** and depend on greenhouse gas emissions from the generation of electric power.

Electric power can be generated or produced in different ways

- from fossil fuels (mainly coal or natural gas in Europe), using the so-called condensing process, with relatively low energy efficiency (35-45%);
- from fossil fuels, using a combined process, for example combined heat and (electric) power (CHP), with higher energy efficiency of typically 70–85%;
- **from nuclear sources, with very small emissions of greenhouse gases;**
- from renewable sources, such as hydropower, wind power or solar energy as well as bio fuels, with little or no net emission of greenhouse gases.

Greenhouse gases are emitted when fossil fuels are used. In the future it will be necessary to capture and store GHG if the European targets for GHG reduction is to be met. This technique is usually referred to as CCS (Carbon Capture and Storage). For large-scale introduction of CCS, either legislation or GHG pricing will be needed.

An increased share of renewable energy sources is another way to reduce GHG emissions. Continued or increased use of nuclear power is also highly effective, although this option is more uncertain due to safety considerations.

In the following we will concentrate on that part of GHG which is due to the main component, namely carbon dioxide CO_2. This is also the component which is currently included in the ETS (European Trading Scheme) for exchange and trading of emission allowances in Europe.

The Nordic countries (except Iceland) have a common market for electric power. In this market, a number of power generation modes are used. There are considerable variations from one year to another and an average over a longer period is therefore needed. According to [10], about 53% was hydropower on average between 2000 and 2004, 23% was nuclear and another 23% thermal power. Wind power was at that time only 2%, but this share has increased and will further increase in the future. Of the 23% thermal power, only 8% was condensing power with low energy efficiency; the rest was CHP, i.e. combined heat and power production with higher efficiency.

Between 2000 and 2004 the resulting carbon dioxide emissions are estimated to have been

- 94 g CO_2 per kWh electric power, also including losses in high-voltage power transmission from power station up to the intake into the railway supply system.

The Nordic market for electric power is not a completely closed market, as some exchange is made with northern Germany and Poland. The transmission capacity is however limited at present. In the long term, the exchange is expected to increase. This opens up for a market in Northern Europe, see Sköldberg et al [29]. According to this study, the long-term effects on changes in the use and generation of electricity (until 2037) depend on the type and strength of legislation that will be in effect.

- With a price (tax) of 45 EUR per tonne of CO_2 emissions, the resulting emissions are estimated to be 160 g CO_2 per kWh electric power.
- With binding emission targets within the ETS scheme for GHG emissions, the resulting additional emissions are estimated to be close to zero.

The latter conclusion is identical to what is also projected and proposed in [10]. However, for estimation of future indirect emissions from electric rail transport, it is here proposed that rail transport be considered responsible for emissions according to the average of present or future emissions. We do not consider it to be fair that rail transport is not responsible at all (for emissions due to the use of electric power), only because there is a binding emission target set by the EU authorities.

Based on the above-mentioned facts and arguments, the following emissions are used in the prediction of GHG emissions for future electric rail transport:

- For the near future (2012-2025): **94 g CO_2 per kWh used electric power**
- In the long term (2030–2040): **160 g CO_2 per kWh used electric power**

These time spans cover most of the period where high-speed trains based on the Gröna Tåget concept are assumed to be in operation. Estimated CO_2 emissions per passenger-km, are presented in Table 11-2. This table is based on Table 11-1 although the number of cases is reduced.

Table 11-2 Estimation of CO_2 emissions for future Gröna Tåget

	Top speed (km/h)	*Number of stops*	*Load factor (%)*	*Travel time (h:min)*	*CO_2 emission[a] (g / pkm)*
1. Stockholm–Skövde–Gothenburg, existing upgraded line (455 km)	250	4+1	60–65	2:48	4.3–7.4
2. Stockholm–Jönköping–Gothenburg, new dedicated HS line (467 km)	320	0	60–65	1:58	5.8–9.9
	320	7+1	60–65	2:35	5.3–9.1
Same line, with moderate ambitions	250	7+1	60–65	2:54	4.7–8.0
3. Gothenburg–Malmö–Copenhagen, upgraded line (342 km)	250	14	45%	2:51	5.7–9.6

[a] Two figures for CO_2 are presented, the first being the average emissions in the near future and the second projected in the long term with an integrated market for electric power in Northern Europe.

It is concluded that estimated emissions, despite the higher train speeds, are very low compared with other means of transport, even if the latter will also improve.

11.3 External noise

11.3.1 Overview and requirements

Noise can be defined as annoying sound.

Although trains are considered to be generally 'environmentally friendly', external noise emissions have a negative impact on trackside residents and activities. Ultimately, noise emissions risk making the railway's surroundings unattractive and real estate values will be low. In principle, the problems are similar to those regarding highways and airports. High noise emissions – in particular during the night – risk reducing the number of rail operations. An important target is therefore to reduce noise from trains.

TSI HS RST [N1] contains a number of specific requirements regarding noise – both stationary, starting and pass-by noise. We will here mainly discuss **pass-by noise**, which has the highest impact on the annoyance caused to trackside residents. At high speeds, pass-by noise mainly involves two mechanisms, viz

- **Rolling noise** caused by the combined wheel and rail roughness and by the dynamic and sound radiation behaviour of the track and the wheelsets;
- **Aerodynamic noise** generated by high air flow velocities over sharp edges, protruding objects, cavities etc. This is most important at higher speeds.

Limits for pass-by noise are defined in TSI HS RST [N1] at a distance of 25 m from the track centre line, 3.5 m above top of rail for the speeds indicated below

- **Class 1 trains:** 87 dB(A) at 250 km/h;
  91 dB(A) at 300 km/h;
  92 dB(A) at 320 km/h.
- **Class 2 trains:** 88 dB(A) at 200 km/h.

Details on definitions and measuring conditions are specified in EN ISO 3095:2005 with Annexes N1.3 and N1.4. For instance the track must meet certain criteria regarding vibration damping and surface roughness with the purpose of limiting the track noise contribution. Noise barriers or rail dampers are not to be used in the certification tests.

In the TSI, nothing is said about sound quality, i.e. the human perception of noise.

Proposal

For Gröna Tåget it is preferred that targets for Class 1 trains be met, even if the permissible top speed would be slightly lower than 250 km/h. With this target, the **future Gröna Tåget will most likely not produce higher wayside noise than existing trains**, for example the *X2* train presently operating at a maximum speed of 200 km/h. This basic feature is crucial with respect to cost for the necessary upgrading of existing lines for higher speeds. It is also advisable to stay within Class 1's more demanding level as legislation is expected to be stricter in the future.

The great challenge is to meet the acoustic requirements in parallel with often opposing requirements as regards higher speed, increasing power in traction, low weight, tight gauging, low initial cost, low maintenance cost, etc.

11.3.2 Studies on pass-by noise levels for Gröna Tåget

Several studies related to external noise have been conducted within the Gröna Tåget programme. On-track tests have been made with the REGINA 250 test train (see Section 1.1) and some investigations have been made in the laboratory. In addition, initial investigations of sound quality for pass-by noise were made. All these studies are summarized and reported in detail in Carlsson et al [30].

On-track tests with the test train included the effects of **bogie skirts**, **low track-close barriers** and **tuned rail dampers.** As there is considerable interaction between vehicle and infrastructure in acoustics, both vehicle-borne and wayside mitigation measures were tested, to a large extent in combination.

The REGINA 250 test train was equipped with air-sprung bogies with a combined rubber and steel-spring primary suspension. All axles were powered and 75% of the wheels had brake discs (except 4 force-measuring instrumented wheels), that should contribute to some damping and rolling noise reduction. Wheels were of solid design with thick web and a massive transition between web and rim. These features should reduce the number of sound-radiating modes in the frequency band of interest.

For practical and cost reasons it was not possible to modify the quite short front and tail of the test train (originally intended for speeds up to 200 km/h), and not even the roof-mounted electrical equipment was shielded. These features were expected to produce relatively high aero-acoustic effects as well as air drag. However, from a research and testing point of view, these features were not necessarily a disadvantage.

Pass-by noise source identification

A 96-microphone array (also called an 'acoustic camera') was used to identify the location and strength of different noise sources, and also to compare the relative effects of different mitigation measures during pass-by at high speeds. Figure 11-2 shows the 'acoustic camera' microphone array. Results are usually shown as 'acoustic maps' (example in Figure 11-3) with local maxima of sound pressure levels indicated.

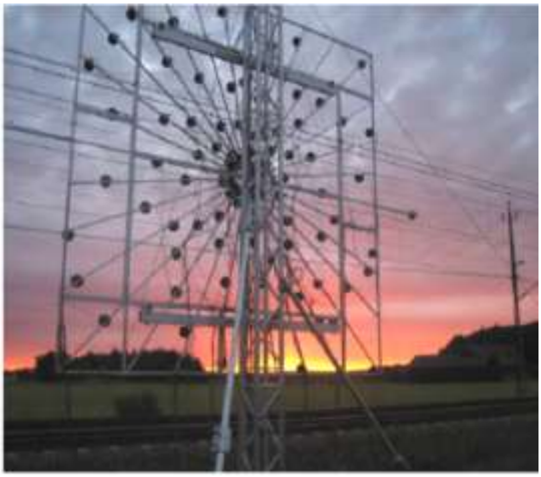

Figure 11-2 The 96-microphone array – the 'acoustic camera'. Source [30]

Tests were made on the double-track line Töreboda–Skövde. The 'near track' was made up by 60 kg rails on concrete sleepers with a 10 mm rubber pad in-between. The older 'far track' had 50 kg rails on concrete sleepers with a thin plastic pad. The sleeper distance was 0.65 m on both tracks.

Figure 11-3 below shows an example of the kind of results that this tool is able to produce. Aero-acoustic sources like the pantograph and the bogies show up in these pictures in addition to the wheel-rail rolling noise. Even if it is not straight-forward to derive the exact acoustic source strength from these plots, they are efficient to identify and locate the different sources, as well as to make relative comparisons between tested noise mitigation measures.

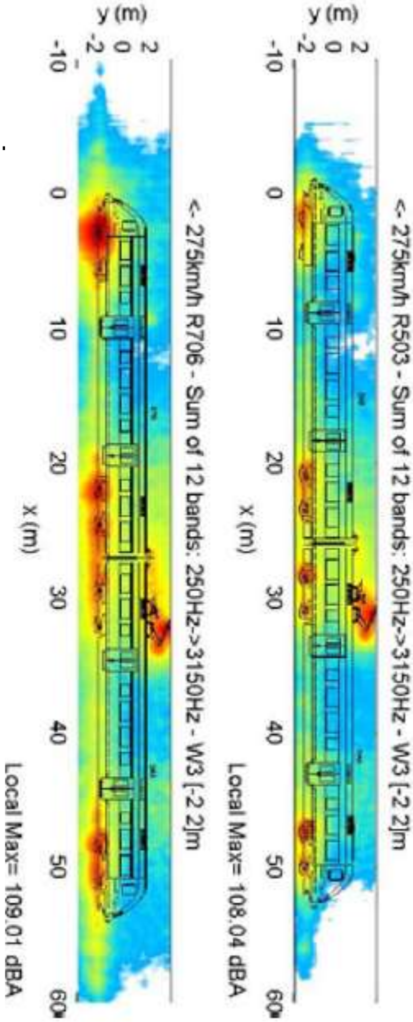

Figure 11-3 (right) Microphone array plots for REGINA 250 test train at a speed of 275 km/h on a conventional track normally used at 160–200 km/h. The picture on the far right includes bogie skirts on the leading bogie; the other picture is without skirts. Source [30]

Figure 11-4 Tested bogie skirt, medium height, low-reaching. Note that low-reaching bogie skirts will sometimes not be compatible with gauging requirements, i.e. the allowed vehicle geometry in relation to the trackside structure gauge.

On-track test results

Test results showed hat

- **Bogie skirts** alone (Figure 11-4 & 11-5) reduced pass-by noise by 2–3 dB(A).
- The combination of bogie skirts and **tuned rail dampers** reduced pass-by noise by about 5 dB(A).
- **Low track-close barriers** alone (Figure 11-6) reduced noise by 2–4 dB(A) at 25 m distance, depending on the frequency content.
- A combination of all of the above is estimated to reduce pass-by noise by 6–7 dB(A); however, this combination was not tested.

The bogie skirts mounted on the test train (Figure 11-4 and 11-5) were located close to the bogies. In spite of this, the lower part of the tested version was not compatible with the general Swedish gauging rules (i.e. the issue of the train's geometry in relation to geometry of the surrounding structures). It would, however, be possible to design a train with low skirts meeting gauging requirements, including the general European gauging standards. Bogie skirts should preferably reach lower than the wheel axle.

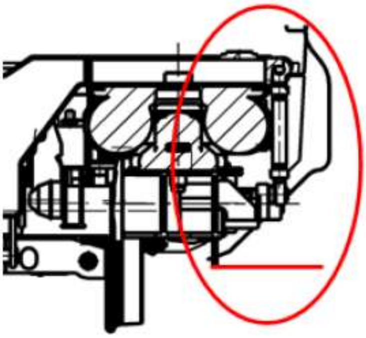

Figure 11-5 Detail of bogie cross-section, bogie skirt depth shown by the horizontal red line.

The low track-close barrier (Figure 11-6) had a height of 0.72 m above top of rail. The distance from the track centre line was about 1.75 m. The barriers had no sound-damping layer although this was found to be advantageous in laboratory tests.

Figure 11-6 On-track testing of low track-close barrier.
The REGINA 250 test train is approaching.

The most effective solution is the combination of low track-side barriers and vehicle-mounted bogie skirts. Ideally, there should be no vertical air gap between the bogie skirt and the upper part of the barrier. The noise reduction from this combination is more than 5 dB(A). This type of noise barrier was shown to be less effective for freight trains, with an improvement of 1−2 dB(A), because on many wagons a large share of the noise is radiated from the carbody on a high level above the track.

The tested low barrier was mounted on the rail and on the track-bed surface. This type of barrier is believed to be a simple and inexpensive solution in the case that passenger trains generate high noise levels. It might be a solution for limited sections along the track, for example when the surrounding local community is disturbed by excessive noise from high-speed trains. Compared to conventional high barriers, it has the great advantage that it does not impose a visual intrusion in the landscape and does not block passengers' view from the window.

Tuned rail dampers

Tuned rail dampers exist in a number of commercially available versions. One example is Tata Steel's Silent Track™ system that was tested within the Gröna Tåget programme. In principle, a tuned rail damper is a mass-spring system tuned to a frequency where damping should be maximum. The radiation area of the rail is also reduced. Measurements with the 'acoustic camera' show some 2–3 dB(A) noise reduction as an isolated measure. In combination with bogie skirts the improvement is about 5 dB(A).

Laboratory tests

Laboratory tests have been carried out at the MWL acoustic laboratories at KTH. Some of these tests have also been accompanied by theoretical studies by means of mathematical modelling and simulation. These tests and simulations regard

(1) testing and optimization of low track-close noise barriers;

(2) testing of increased rail vibration losses.

Notes on additional observations

Note 1: Roughness of wheels and rails are crucial generation of rolling noise. Very rough surfaces may increase noise by up to 12 dB(A). Hence, measures to maintain smooth wheels and rails are crucial for a low noise level.

Testing of noise according to the standards (TSIand EN) shall be done on quite smooth wheels and rails. The maintenance regime applied in Sweden up till now usually causes a slightly higher noise level, typically 2–3 dB(A).

Note 2: If different trains are tested with different noise-control measures, it must be remembered that the **individual smoothness of the wheels** can affect the test results considerably.

Note 3: An isolated increase in **rail vibration losses** does not significantly affect the rail's contribution to trackside noise, the reason being that increased losses in the rail only reduce the 'free' rail vibration outside the ends of the train. To significantly reduce the rail vibration and noise radiation, either the vibration amplitude of the rail or the noise-radiating area or the acoustic radiation efficiency must therefore be reduced. Several technical solutions were tested in the laboratory and results were also confirmed and explained by means of mathematical modelling and simulation. Due to this outcome no on-track testing was conducted.

Note 4: The **low noise barriers** are effective for frequencies above about 500 Hz, at least for rolling noise and noise from motors, gears and brakes generated at a low height position. To attenuate the noise that is reflected between the barrier and the car side, some damping of the barrier surface is preferred. A microstructure perforated panel (MPP) was tested in the laboratory with promising results. Due to time restrictions this solution was not tested on track.

Note 5: On trailer wheelsets brake disks are usually located on the axle, i.e. not on the wheels. With high requirements and high speeds **noise attenuation damping** must therefore usually be applied on the **wheels**, as is also made on today's trains.

11.3.3 Studies of pass-by sound quality

An initial study was made of the sound quality of pass-by noise from different trains; see Khan [31]. The principle was to collect different train noises at two track-side locations (with and without barrier) and in a second stage perform listening tests with human subjects in the laboratory. The intention was to study whether some types of train noise were more annoying than others, despite their having the same duration and the same sound pressure level measured in dB(A).

Binaural technology according to ISO 3095 was used to measure and collect noise from five different trains. The trains were (1) *X2* high-speed train; (2) Loco-hauled InterCity train; (3) Double-decker EMU *X40*; (4) Loco-hauled freight train and (5) Commuter train *X10*. All measurements were made on track with UIC 60 rails and a 10 mm thick rail pad on concrete sleepers. Note that the Gröna Tåget test train was not part of this testing; the intention was to make an initial study of whether this kind of research would be appropriate. More details about this study are presented in [31].

Before the listening tests, the different noises were made equivalent as regards duration (7 s) and sound pressure level (80 dB(A)), composing new noise sequences from the measurements on the different trains. Two listening studies were performed, with a total of 50 human subjects, all with normal hearing ability. Listening tests were performed in a hemi-anechoic room at the MWL Laboratory at KTH.

Results

Evaluation of the tests showed significant differences in annoyance assessments between the different train sounds. The loco-hauled InterCity had an average annoyance of about 4.2 on a 10-degree scale, while the *X40* train had an average annoyance rating of 6.2. The other trains exhibited an approximately equal annoyance rating of between 4.8 and 5.1. The results also showed that annoyance decreased for passenger trains with the presence of a wooden barrier (although the sound pressure levels during the listening test were identical), while freight trains showed small differences.

It is concluded that **trains may generate different external noise quality**. However, no further investigations were made within the Gröna Tåget programme, because other issues were prioritized by the participating partners. No technology proposals can therefore be made in this respect at the present time.

11.4 Particle emissions

Particle emissions from trains may be a challenge in the future, as requirements for human health are likely to be made more stringent. This is at least the case at closed stations (underground in tunnels).

Abbasi et al [32] reviewed most of the recent documented studies about exhaust-emission and non-exhaust emission in rail transport. However, exhaust emissions are not relevant for electric trains. Abbasi et al studied adverse health effects, particle size, and morphology, chemical compositions, suggested solutions to reduce particles, current legislation, and recorded particles with the size of 10 μm and smaller.

Abbasi et al [44] also collected the particle emissions from the Gröna Tåget test train. These particles were analysed and compared with particles generated from a pin-on-disc model. The results show that the pin-on-disc laboratory and simulation model can be used to estimate particle emissions for future vehicles, see figure 11-7.

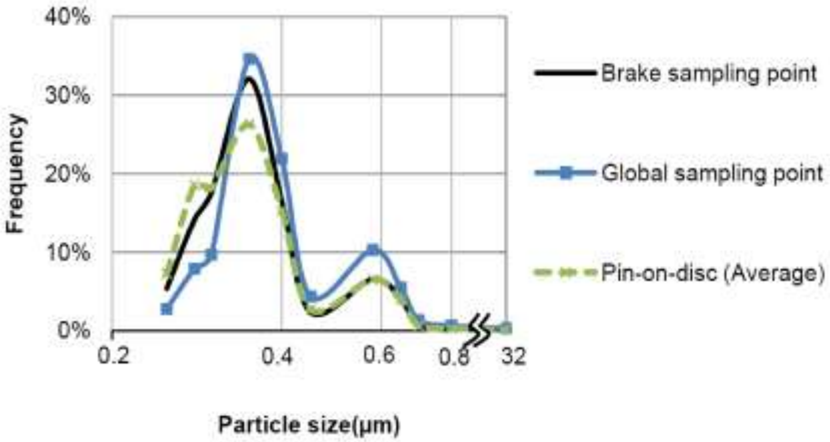

Figure 11-7 Particle size and distribution from Gröna Tåget and from pin-on-disc simulation. Source: KTH [32].

The proposed Gröna Tåget train concept – with a high amount of electric braking – has the potential to **minimize the wear to brake pads**, which is a major source of non-exhaust airborne particles.

Further, the **wear to wheels and rails** also generates particles. Contact pressure, creep and lubrication can change the amount and size distribution of airborne particles generated from the wheel-rail contact, see Sundh et al [33] and Olofsson et al [34]. In the proposed Gröna Tåget concept, particle emissions from the wheel-rail contact should be small through wheelset radial steering technology, described in Section 8.7.1.

Discussion and proposals

Generally the risk of excessive and detrimental particle emissions should be small in the Gröna Tåget concept. The radial steering bogie, together with a high amount electric braking, will be advantageous for Gröna Tåget as regards particle emissions. This concept should generate lower particle levels than ordinary rail vehicles.

If a thorough analysis of particle emissions is desired and requested for future trains, the work done is a valuable basis. Simulation and laboratory investigations on particle generation can be combined with the methodology developed for simulation of brake wear and wheel-rail wear.

11.5 Recycled and renewable materials

The Gröna Tåget concept presents an opportunity to introduce an increased proportion of recycled and renewable materials in the production process.

For metals, the utilization of recycled materials in production is an area that mostly governs itself. The recycled metal requires less energy and lower temperatures to process compared to virgin metal which in turn leads to a reduction in costs. The limiting factor is often the amount of scrap metal available on the market. A drawback of including recycled metal in the manufacturing process is the amount of additives and polluting substances introduced into the mix. This is one reason for using larger amount of virgin metal when these additives need to be controlled.

The potential for increasing the amount of recycled polymers is greater but more complex. Using recycled thermosetting polymers in production means grinding down the thermosetting polymer and using it as filler in new thermosetting polymers. Thermo-polymers can be melted down and reshaped, but this leads to a deterioration of the mechanical properties, which means it is not as suitable for high-performance parts. Appearance can be affected by the collection process; polymer scrap collected in-house can be reused with the same colour, while polymer scrap collected from external sources means a mixture of colours, often resulting in grey or black polymers.

Experience from Volvo Cars indicates that the inclusion of recycled polymers is best suited to components with less strict requirements concerning material properties and components not directly visible. The potential savings in energy related to production are still valid but the inclusion of recycled polymers often needs to be explicitly requested.

The inclusion of recycled polymers can be used as a marketing tool and to highlight the commitment of the corporate social responsibility programme just as it has seen increased use as a marketing tool in household appliances.

The biggest potential for improvement is to be found in including renewable materials in the concept. Wood-based products can be used in floor blocks, as in the C20 metro cars in Stockholm, but also in decorative surfaces, seating, tables and trays. Renewable fabrics and recycled yarns can be used in seats and decorative surfaces. Renewable fibres can replace non-renewable materials in fibre reinforcements as well as for noise insulation and seat filling. The automotive industry has identified several applications for renewable materials and fibres. These applications are also suitable for the Gröna Tåget concept.

12. Safety

The safety record for rail passenger transport has been very good in recent decades, in particular since efficient ATP systems were introduced in the Nordic countries. High-speed operations at speeds of 200 km/h or more have worldwide shown a very good overall record, counted as fatalities per performed passenger-km. Despite these promising results, serious accidents might still occur, up till now predominantly with conventional trains for lower speed. However, a serious accident with 10−100 fatalities for a high-speed train would cause not only anger, sorrow and distress for the people involved, but also the risk of a general lack of confidence in high-speed rail as an appropriate means of passenger transport.

There are specific areas where safety could be further improved by quite simple means; the first are measures to ensure that the train **after a derailment stays in upright position** above the track centre line, preventing it from turning over and/or striking other trains or structural objects. Such a property is called **derailment worthiness.** Another issue that may be considered is improved **crash worthiness**.

12.1 Derailment worthiness

Neither TSI nor EN presents any requirements regarding derailment worthiness, other than to specify suitable limit values for lateral and vertical track forces in order to prevent flange climbing, see Sections 8.2.1 and 8.2.2.

However, based on recent experience it is rather usual that incidents including derailment occur due to broken axles, broken wheels, broken rails, faulty switches, track misalignments, objects falling from the train itself or objects being present on the track (for example cars) when the train approaches.

In research presented by KTH in 2007, a total of 42 incidents or accidents were known to have occurred at speeds higher than 70 km/h, most of them during the last 25 years, 14 of them in Sweden and the rest in various countries around the world, see Brabie et al [53, 55]. The most devastating of these was the serious accident at Eschede (Germany) in 1998 where 100 people died. Although there was an unfortunate combination of events at Eschede, the primary cause was a broken wheel leading to a lateral deviation of one car end that struck a bridge pillar. The Eschede accident was a unique exception in the world's high-speed rail history, but similar accidents could have happened elsewhere in the world, including Scandinavia.

Certainly, many more incidents (and likely even accidents) than the 42 mentioned have occurred, although not well known to the public. It is striking that most of the known incidents and accidents emanate from countries with a comparatively open mind to making accident investigations public (Sweden, the UK, the USA, Canada, and to some extent France, Germany and Japan).

In Sweden, a number of incidents have occurred over the years, the most noticeable being seven cases for *X2*, with broken axles, broken wheels and objects falling from the train. Due to the special design of *X2* – with its particular derailment-worthiness – serious accidents have been avoided. However, one serious accident occurred with a conventional loco-hauled passenger train in 1980, as a consequence of a broken wheel.

In the UK and France, a number of incidents and also serious accidents have occurred due to broken rails, wheels or axles and other malfunctions of trains or infrastructure. In France, at least three incidents involving derailment are publicly known for the TGV high-speed trains, of which two derailed at 247 and 294 km/ h respectively. Passenger train derailments have also happened in the USA, where the common use of double-decker coaches in long-distance trains (with high centre of gravity) have made them more prone to turn-over after derailments and therefore often brings about serious consequences.

Some of the investigated derailments had devastating consequences with several fatalities, but many of them had a lucky outcome in the sense that no fatalities occurred. In most of the "lucky" cases, the derailed trains stayed upright until brought to a stop.

Figure 12-1 Aerial view of a derailed passenger train at Bigger, Canada.
Source: Transportation Safety Board of Canada.

The conclusion from this research is that train features – in particular **bogie design** and **inter-car connections** – are very decisive for the outcome of a derailment. After analysing the course of events in most of the above-mentioned incidents and accidents, some candidates for favourable vehicles features were suggested. The efficiency of these features (to help the train to remain upright after a derailment) was tested by means of simulation.

In almost all cases, simulations confirmed the observed course of events. Through simulations it was also possible in several cases to make a quantitative analysis of suitable settings of different parameters of avoid catastrophic consequences of a derailment. See further Brabie et al [54, 55]. The simulation model was developed by KTH and is available for external use if requested. This model also includes the course of events after the derailment, when wheels are running and bouncing on the sleepers. The model uses the MBS software GENSYS [56].

In the list below, a number of vehicle features are shown, all contributing to improved derailment worthiness. In cases (2) and (3), parts of the running gear provide **substitute guidance mechanisms** if the ordinary wheel-rail guidance is lost.

(1) **Mechanical restrictions** (displacement limitations) in vertical and longitudinal directions **between wheelsets and bogie** may prevent derailment after an axle failure on the outside of the wheel. In an investigated case, combined restrictions of ±20 mm both vertically and longitudinally were found to be effective in all cases, but other combinations may also be effective. The basic principle is shown in Figure 12-2.

(2) **Substitute guidance** provided **by the wheelset**, either by the **brake discs** or by especially **low-reaching brackets on the axle journal boxes**. These features may prevent lateral deviation after a derailment due to broken wheels, broken axle on the inside of the wheel, or flange climbing. Axle box brackets may also prevent lateral deviation due to a broken outer rail in a curve. An appropriate geometry of brake discs and brackets is essential. See Figure 12-3 and ref [54, 55].

(3) **Substitute guidance** provided by a **low-reaching bogie frame** or a **low-reaching transversal beam** in the bogie. These features can prevent serious consequences of a broken wheel, a broken axle inside or outside the wheel or flange climbing. The low-reaching bogie frame may be effective also for a broken outer rail. In order to further enhance the effect of the transversal beam, a **staggered beam** can be used. An appropriate geometry of the bogie frame is essential. See Figure 12-4 (a, b) and ref [54, 55].

(4) **Low centre of gravity** is essential, or at least avoiding a too high centre height, for example as on American double-decker cars. Simulations indicate that a height of centre of gravity for the carbody of more than about 2.0 metres above top of rail will cause a heavily increased risk of vehicle turn-over. However, a **transversal beam** in the bogie – see (3) above – with a maximum height of about 0.20-0.25 m, will be very efficient to prevent a lateral displacement of the vehicle with subsequent turn-over also for higher centres of gravity. For details, see [55].

(5) Restriction of the lateral displacement (or the swing angle) of the **centre coupler** is an efficient means to avoid large lateral deviation of a single derailing car in the train, see Figure 12-5. Simulations indicate that a restriction of coupler displacements allowing only about 0.25 m relative lateral displacement between carbody ends will be sufficient to prevent a lateral displacement of the derailed vehicle with subsequent turn-over. Note that such a coupler restriction is only about 40% of normally employed coupler motions. However, this coupler restriction is still compatible with the need to negotiate an S-curve in a cross-over on a double track (track distance 4.5 m, turnout radius 190 m), see [55] for details.

(6) **Longitudinal dampers between carbody ends** have also been shown to be effective in preventing lateral deflection and turn-over. It is required that one damper be employed at each corner of the carbody, with each damper providing a force of the order of 30 kN (at 0.1 m/s piston velocity). This measure will stabilize the train deviations laterally.

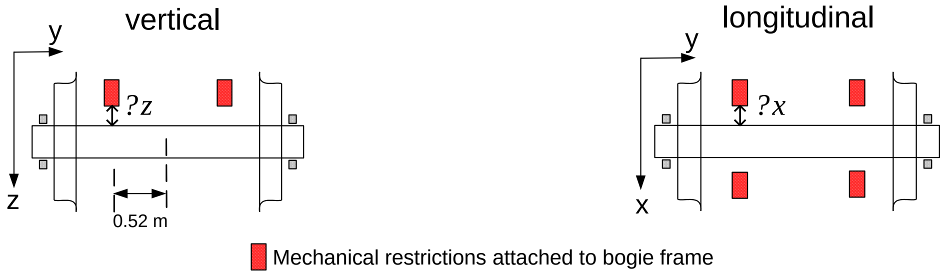

Figure 12-2 Vertical and longitudinal restrictions between wheelset and bogie frame. Source: KTH [55].

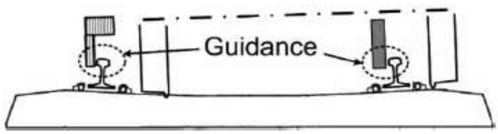

Figure 12-3 Low-reaching axle box and brake disc, both providing substitute guidance. Source: KTH [55].

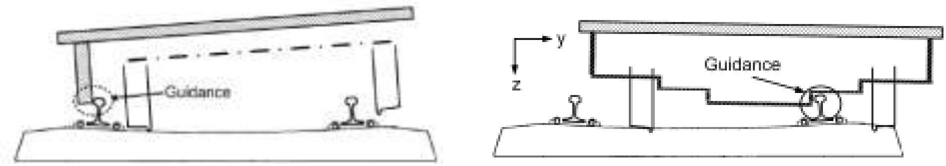

Figure 12-4 Low-reaching bogie frame (a) and transversal beam (b), providing substitute guidance. Source: KTH [55].

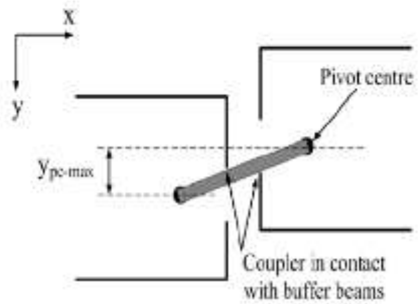

Figure 12-5 Restriction of lateral displacement of centre coupler will also restrict displacement between carbodies. Source: KTH [55].

Many of these features, in particular parts of (1), (2) and (3), have been found to prevent serious consequences for the *X2* train in Sweden, and regarding (2) also for Shinkansen trains in Japan and multiple unit trains in Germany and the UK. Longitudinal dampers between carbodies (6) in combination with a low centre of gravity (4) have several times proven to be efficient in TGV derailments in France.

Most of the efficient means to prevent lateral displacement and vehicle turn-over are quite simple to apply, provided that they are built into the train from the first stage of design. It may be much more complicated and expensive to upgrade bogies and other parts of the train at a later stage.

Proposals

It is proposed that a **combination of measures** be built into Gröna Tåget, in order to prevent derailment or to prevent lateral displacement and vehicle turn-over if derailments occur. Catastrophic consequences originating from a number of primary causes should be considered, such as

- Broken wheels
- Broken axles (inside and outside of the wheel)
- Broken rails (in particular outer rails in curves)
- Wheel flange climbing (for different reasons)
- Track misalignment (although limited in size)
- Objects on the track.

The most optimum and feasible combination should be determined from the actual conditions and the proposed train design. Realistic cases, based on previous experience, should be considered. The database (or catalogue) of cases in the mentioned references [53, 55] can be used. In order to investigate and determine suitable geometrical parameters the available software and methodology can be used.

Once again it is worth pointing out that high-speed rail operations have shown a very good safety record, much better than airplanes and ordinary trains, not to mention private cars. Nevertheless, this record could be further improved by quite simple means.

12.2 Crash worthiness

TSI HS RST [N1] requires that ”the static and dynamic strength of vehicle bodies shall ensure the safety required for the occupants”.

Firstly, the TSI only considers front collisions. In the event of a frontal impact the carbody structure shall (1) limit the deceleration to 5 G (49 m/s^2); (2) maintain structural integrity of the occupied areas, including a ”survival space” in the driver’s cab; (3) reduce the risk of derailment and (4) reduce the risk of over-riding of two adjacent vehicles. To absorb the energy in ”collapse zones” or ”crumple zones” with controlled deformation must be provided. The ”crumple zones” shall be located in non-occupied areas close to the ends of each vehicle, in front of the cab and/or at inter-car gangways. In the next part of the same sentence TSI allows crumple zones (with up to 30% deformation) to be located in toilets or vestibules if the first target ”cannot possible” to comply with. The ”survival zone” in the driver’s cab (0.75 m in length) is mandatory, although the risk of fatal outcome would be significant if the driver stays in that zone in a front-end collision.

TSI defines four front collision scenarios, of which the first two are collisions with an identical train or a heavy freight wagon (80 t) at a relative speed of 36 km/h. One scenario is collision with a small or low obstacle (for example a car or an animal). The remaining scenario is collision with a 15-ton lorry at a level crossing at a speed of 110 km/h.

Details of requirements and the assessment and validation can be found in TSI HS RST, Annex A.

Proposals

TSI requirements must be respected. TSI should, however, as in many other cases, be seen as specifying minimum requirements. Some additional requirements should be seriously considered in efforts to improve safety. Some – in particular (2) and (3) below – could be complicated and costly, which motivates a thorough safety and cost assessment. Other measures are simple and inexpensive – in particular (1) and (5) – the latter likely resulting in lower cost.

(1) In addition to a ”survival space” in the driver’s cabin, a door leading to the space behind the cabin shall be provided. **Escape from the cabin** through this door must be very quick; the door must not be locked from the cabin side. Nor must the space behind the door be blocked by permanent or temporary obstacles, including travellers or their luggage. This feature is important for drivers’ safety and is also traditionally part of safety requirements in Sweden. It is expected to be effective and very cost-efficient.

(2) A collision speed (with a lorry) higher than the stipulated 110 km/h should be considered. The low collision speed (110 km/h) is based on the assumption that the driver might brake and reach this speed from the moment that he or she sees the lorry in front of the train until the moment of collision.

The highest train speed at European level crossings is normally 160 km/h. In Sweden, level crossings exist at train speeds up to 200 km/h. They have barriers and electromagnetic supervision. This system is logically connected to the ATP system, so that trains are stopped if an obstructive road vehicle is present in the crossing. However, a road vehicle moving onto the track and breaking the barrier may collide with a train.

In the last-mentioned case, the train may brake from 200 km/h to about 160 km/h, with the same pre-warning distance as in the reference case, braking from 160 to 110 km/h. The probability of such an event would however be much lower than the case of a collision at a crossing with ordinary barriers and without any supervision and connection to the ATP system.

It is proposed that **higher demand on collision safety**, with a **higher collision speed**, be considered. Before a decision as to whether such a safety improvement is motivated or not, a thorough safety assessment should be made.

(3) The specified collisions with other rail vehicles in yards at a relative speed of 36 km/h will not be the worst or not even the most likely collision scenario. Another likely case is that the **train collides with a firm buffer stop** at the end of a track, for example inside a station. Such an event happened in Sweden recently at about 36 km/h. The ends of the cars, i.e. the vestibules where passengers risk being standing waiting for the final stop, are proposed to withstand such an impact with limited deformation of the available vestibule space, say less than 30%. The crumple zones in such an impact at low height should preferably be located in the buffer zones and underframes of the leading and second vehicles of the train. In such a severe case, the specified maximum retardation of 5 g will likely be exceeded.

Before decisions are made on these issues a thorough safety assessment should be made, also including a cost-benefit analysis.

(4) In **collisions with animals** and possibly also small cars it is essential that the obstacles be moved away from the train and track, without intrusion into the underframe and the leading bogie, which would cause derailment. Such cases could preferably be simulated with similar techniques to those mentioned in Section 12.1 regarding derailment worthiness.

(5) If the train turns over, the windows are a critical issue. In such cases, passengers often fall out from broken windows. For high-speed trains, the **windows** should **not be larger than necessary** for travellers to have a good view in a seated position. Windows on high-speed trains usually have a height in the range of 0.5-0.85 m, where Japan's Shinkansen trains and the Italian Pendolino (also in Finland) are on the low side and the Swedish X2 in the middle.

It is proposed that windows have a height in the order of 0.60 m. Such a relatively low window height is preferable also for carbody stiffness, mass and cost, as well as for heating and cooling installations in the interior compartments. A lower window can also allow smaller sections of reinforcing walls between the window surfaces, in reality possibly improving passengers' view.

(6) The **interior safety** can be further improved by storing heavy luggage in separate shelves near the entrances, not on shelves at high level above the seats. It could also be considered to install hatches on shelves above the seats.

13. Other important matters

13.1 Carbody

Carbody width – exterior and interior

As a main alternative, a wide-body train is proposed for Scandinavian interoperability. Such a train is highly feasible from an economic point of view. A final cross-section of the carbody cannot yet be defined (December 2011), as the final studies in Denmark and formal acceptance in all Scandinavian countries still remain to be done. However, based on the Swedish gauge SEa in EN 15273 as well as investigations being made in Norway and Denmark so far, a preliminary carbody cross-section has been defined.

Figure 13-1 (left) shows an approximate cross section of the proposed (preliminary) carbody, while Figure 13-1 (right) is more precise. The same figures have earlier been shown in Sections 3.2 and 2.9 respectively.

Based on the present studies, the wide carbody may have an **exterior width of up to 3.54 m** at a height of about 1.8 m above top of rail. This is the cross-section shown in Figure 13-1.

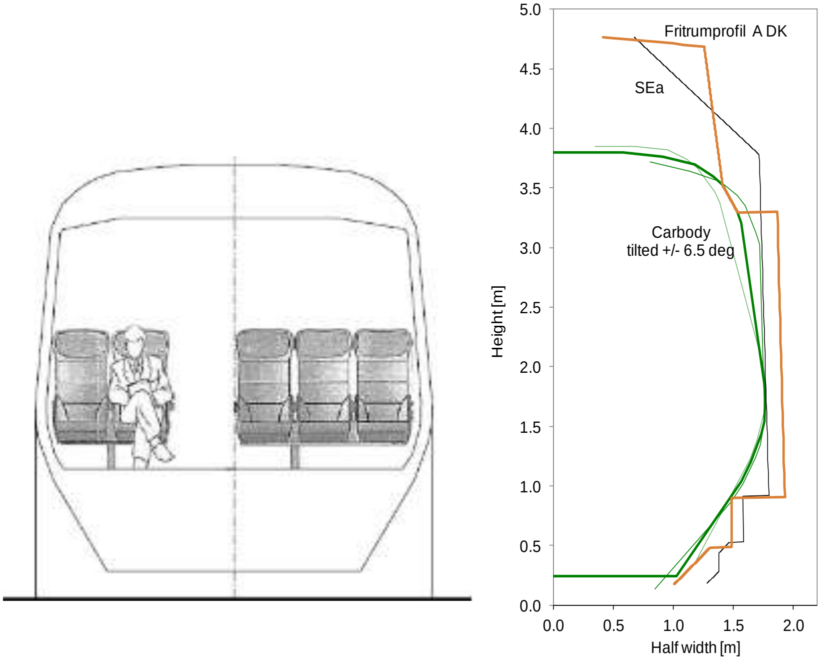

Figure 13-1 Carbody external cross-section (preliminary) for a wide carbody, interoperable electrified main lines in Scandinavia.
Vehicle displacements and tolerances are included in the right figure.
Sources: Fröidh [2] and Persson (Bombardier)

The carbody cross-section allows one more comfortable seat abreast than is common in narrower carbodies, for example according to the continental G1 or DE1 gauges, or the earlier common gauges in Sweden, Norway and Denmark. This is under the assumption that the **wall thickness is about 0.10 m** (including insulation) at elbow height. The interior width at elbow height will then be up to 3.34 m. This width allows for individual armrests at all seats; both 3-seat and 2-seat groups. It also provides for a normal Scandinavian aisle width of 0.52−0.54 m. The interior width may be some 0.04 m narrower and still provide good comfort for long-distance travellers, although individual armrests in the 2-seat group may be compromised. Width and comfort should be maximized within the limitations of the available space within the infrastructure and carbody design restrictions.

The proposed preliminary carbody cross-section is designed under the assumption that the train can be operated in the non-tilting mode in Denmark. It would be possible to also design for carbody tilt in Denmark, although the carbody width must be more restricted at the higher levels.

The alternative to a wide-body train, is a train with "continental" width, meeting the G1 and/or G2 gauges according to TSI and EN 15273. Such a carbody with full length (19 m bogie centre distance) will have an exterior width of 2.89 m according to Section 2.9. The interior width will be about 2.70 m. This will not allow for individual armrests and a normal Scandinavian aisle width. It is also less favourable with respect to cost per passenger-km than the wide-body alternative proposed above. The cost difference is about 15%; see section 3.2 and Fröidh [2].

Another alternative may be the German DE1 gauge that is 0.14 m wider than G1/G2. The DE1 gauge can be used on selected German routes, at least for the routes used by the ICE high-speed trains. DE1 will <u>not</u> be more favourable than G1 regarding cost, but will make it possible to provide the desired comfort, including individual armrests and a desirable aisle width.

Floor height

Ideally the interior floor should be level with the platform so that level entrances can be provided. On many rail networks, the platforms have about the same height as the interior floors (1.20–1.25 m above top of rail), for example on the Japanese Shinkansen lines and in parts of the USA. In Europe, including the Nordic and Scandinavian rail networks, the platforms have varying heights for historical reasons, where most platforms have a height in the range 0.50−0.90 m. In practice it is almost impossible to rebuild the low platforms to high platforms for level entrance, of cost and compatibility reasons. For the routes that are candidates for the proposed high-speed train concept, platform heights of 0.55–0.76 m are anticipated; see Fröidh [2].

Interior floor height must be compatible with

- Functional requirements from the travelers' point of view, ideally level entrances and interior floors
- Technical realities and a cost-effective solution.

From a technical point of view the main restriction is the **wheels**. For a high-speed train with a top speed of over 200 km/h, a standardized wheel diameter of 0.92 m is advisable. Smaller wheels result in higher stresses, which may be a critical issue due to the dynamic vertical loads that may be produced at high speed. Moreover, the necessary **brake discs** for high-speed emergency braking require a minimum wheel size.

With be above-mentioned technical restrictions and realities, an **interior floor level of 1.18–1.20 m** is proposed; see Figure 13-2. This is based on the assumption that full carbody tilt is provided, i.e. a maximum tilt angle of 6.5 degrees relative to the wheels. A reduced floor thickness may be necessary locally above the wheels.

The **vestibule floor height** should preferably be **1.15 m**, which will provide for convenient boarding and alighting of the trains. The steps from a platform height of 0.55 m could then be 0.20 m each, or possibly 0.22, 0.19, 0.19 m, both alternatives complying with TSI [N3] requirements. The height difference between the vestibule floor and the rest of the floor (0.03–0.05 m) can be overcome with a short ramp.

Entrances for the majority of travellers, as well as for travellers with reduced mobility, are briefly described in Sections 3.4 and 6.1–6.2, and further in Fröidh [2].

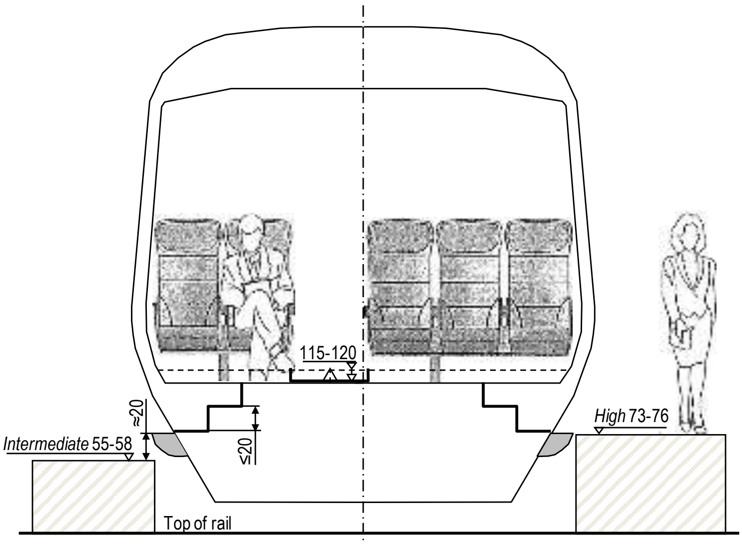

Figure 13-2 Floor height compared with platform height. Source: Fröidh [2]

Doors

External doors must have at least 0.80 m free width where passengers with reduced mobility (PRM) have to board the train; see TSI HS PRM [N3]. This is also the case for internal doors to be used by PRM.

However, for travellers to be able to board the train conveniently and quickly with two pieces of luggage, a free width of about 0.90 m is preferable. The latter is proposed for all or most doors through which heavy luggage has to be carried. It is not a requirement specifically for PRM, but also for ordinary travellers.

13.2 Train control system (TCS)

This is far from a specification of a train control system. This section will only point out one important feature that is desirable with respect to the particular train concept of Gröna Tåget.

Short start-up time

The main proposal for Gröna Tåget is to make it possible to use comparatively small train units (4 cars, about 300 seats) which can be coupled together into longer trains when needed. This makes the trains more flexible, which has several advantages (see Section 3.3). One opportunity is to let two parts of the train have different origins or destinations, although the two parts are run together in the same train on the busiest parts of the route. This means that the initial train configuration is divided into two individual trains bound for different final destinations. In the other direction, two individual train units have to be joined and coupled together into a longer train. These procedures usually call for a restart of the computerized train control system.

Short travelling time is one of the most important factors to attract travellers to go by train. To avoid unnecessary delay at the stations where trains are divided or coupled together, it is important that the start-up time of the train control system - and other systems which are necessary to operate the train – is short.

It is proposed that the 'ready-to-go' **start-up time** of all train systems after coupling or decoupling operations, is kept at a maximum of 60 s.

13.3 Train crew facilities

Basic facilities for a functional working environment for the driver are specified in the TSI HS RST [N1]. Some notable requirements are:

- The driver shall have access to the train, either directly to the driver's cabin or through an adjoining compartment at the rear of the cab
- The cab shall be accessible both from a platform and from an outside level 0.2 m below top of rail on a stabling track
- The driver shall in seated position have a clear view forward for signals at both sides; also an opening window sufficiently large to put his/her head through the aperture shall be provided at each side.
- The interior layout of the cab and the seat shall take anthropometric dimensions of the driver into account; a second forward-facing seat shall be provided for possible accompanying crew.
- Front windows shall have good visibility under all conditions, also when pierced or starred. Front windows shall have safety glass of specified strength and shall remain in position. They shall have de-icing and cleaning facilities.
- Drivers and other train crew train shall have access to adequate storage facilities for clothing and necessary equipment.

Requirements related to health, safety and ergonomics are an open point in the current TSI.

Proposals

As requirements related to health, safety and ergonomics are an open point in the TSI, it is most important that the definition of an appropriate driver environment be made in close co-operation with representatives of drivers and other train crew. Such a definition must also include the important aspects of man-machine interaction. Much work has already been done and should naturally be used. In Dimgård et al [61] and [62] − part of the Gröna Tåget programme − it is pointed out that relevant and distinct information shall be presented to the driver at the right moment. This seems self-evident, but nevertheless - based on experience - a great deal of less relevant information risks being presented. Experiments can be used in the definition work. See also Fröidh [2], Section 5.2.

A well-founded definition of driver's environment can also be part of the ongoing standardization on the pan-European level.

13.4 Train maintenance

Cost for maintenance is generated as **direct cost for spare parts and labour**, and also as cost for **additional trains needed for standstill during repair and waiting time**.

Example: A 4-car train with an investment cost of 132 million SEK induces a capital cost of 12 million SEK per year (annuity over 20 years, 6.5% interest), or 33,000 SEK per day, or 48,000 SEK per working day. The income from a 4-car train may be in the order of 150,000–300,000 SEK per day, or 220,000–440,000 SEK per working day, see Fröidh [2].

Originally the intention in the Gröna Tåget programme was to conduct a thorough study of experience-based maintenance and repair costs and how to reduce them.

Due to lack of detailed experience-based data from operators and train service providers, it was not possible to conduct the intended study mentioned above. An initial study, see Leander [60], has been made. In this study, it was not possible to take full consideration to corrective maintenance due to different causes of damage or to workshop inefficiencies. Nor do the data - in their present form - take full account of waiting time at workshops due to limited workshop availability or to deficient availability of spare parts. Nevertheless, this study gives indicative overall costs and sources of cost. The maintenance cost (excluding repair due to damage and vandalism and excluding additional trains needed during standstill), is estimated to be 17.9 SEK per train-km for a 4-car train.

Based on the above-mentioned limited study [60] and overall estimations from participating operators and train suppliers, the Gröna Tåget programme has estimated a total maintenance cost of about 6.60 SEK per km for a powered car and 4.20 per km for a trailer car (in practice, the traction power equipment can be divided over different neighbour cars). This includes scheduled light maintenance (including cleaning and snow removal), heavy maintenance and repairs due to damage and modernization after about 10 years. Light maintenance (daily or weekly at workshops close to most end-destinations) is estimated to account for about 60% of this. Modernization costs are estimated to amount to about 10% of the vehicle's original investment cost. See also Fröidh [2]; Section 4.1. These costs are 24% higher than in [60], but also include damage and vandalism, as well as snow removal in winter.

All estimated costs are based on experience from recent high-speed trains and do not assume any rationalization or measures to reduce maintenance costs below current levels. Neither of these estimations takes account of the cost of additional trains needed for standstill during repair and for waiting time. This cost is usually not accounted for as maintenance cost, but rather as capital cost for trains. The latter is a separate cost separated from the maintenance issues.

Regardless of the above-mentioned study and overall estimations, it has been pointed out by participating operators that waiting time and repair time after damage may constitute a substantial part of the total maintenance cost.

Proposals

Some conclusions can be drawn and some recommendations can be made:

- Collisions with animals usually cause damage to the couplers, the front cover, the windscreen or the headlights. Sometimes, the front bogie is also damaged. Common repairs, such as after **collisions with medium-sized animals** (see Section 2.3) should preferably be able to be made in **less than four hours.** After collisions with **big animals**, repairs should be able to be made **within 24 hours**. These repair times require spare parts in modules which are easy to exchange.
- Other common repairs, such as replacement of a **damaged wheelset or pantograph** should be able to be made in **less than four hours**. The latter should allow the train to be returned to service for the afternoon peak, after taking the train out of service after the morning peak, including transport and some waiting time.
- According to [60] the **cost of spares** constitutes a substantial portion (about 60%) of the cost (excl. cost of additional trains needed for standstill during repair and waiting). It should be analyzed how this cost could be reduced, for example by ordering larger quantities in each batch or at the initial order of the trains.

It is proposed that a thorough and detailed study of maintenance cost, including possible cost reductions, be made by train operators in co-operation with train suppliers and maintenance service providers. Substantial maintenance costs can very probably be saved with regard to both scheduled maintenance and the cost of additional trains needed for repair and waiting.

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[N5] Technical Specifications for Interoperability: High-speed - Operation (TSI HS Operation)

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The Green Train (in Swedish "Gröna Tåget") is a high-speed train concept, that is economical, environmentally friendly and attractive to travellers. It is suited to specific Nordic conditions with a harsh winter climate, often varying demand and mixed passenger and freight operations on non-perfect track. The main proposal is a train for speeds up to 250 km/h equipped with carbody tilt for short travelling times on electrified mainlines. The concept is intended to be a flexible platform for long-distance and fast regional passenger trains, interoperable in Scandinavia.

The Gröna Tåget programme delivers a collection of ideas, proposals and technical solutions for rail operators, infrastructure managers and industry. This is part B of the final report, specifying the concept's functional requirements from a technical and economic perspective, with an emphasis on the areas where research has been done within the Gröna Tåget research and development programme.

Other summary reports deal with market, economy and service aspects (Final report, part A) as well as a design for an attractive, efficient and innovative train from a traveller's point of view.

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