Wide-body trains in Scandinavia

The Denmark case

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Summary

Wide-body trains constitute a cost effective solution that can be used in both Sweden and Norway. In a Scandinavian perspective, service into the Copenhagen area – including the tracks to Helsingør – is desirable, but an optimum vehicle for Sweden and Norway will not fit into the Danish gauge DK1. The present study reports on measurements and calculations made to show whether the desired service is technically possible with modest changes in the current infrastructure. Banedanmark has identified what tracks that need to be checked for three different service scenarios.

The study covers the clearance between vehicle and obstacles as well as clearance between identical wide-body vehicles on adjacent tracks. The kinematic gauging rules have been applied for vehicle movements and margins according to EN 15273 throughout the study.

A total of 27 obstacles were reported by Banedanmark that potentially could be restrictions for a wide-body train on the tracks identified by Banedanmark. 3 of these were outside the defined area of operation and therefore not within the scope of this study. 12 of the remaining 24 obstacles were found to be inside the required free space D (Danish: Fritrumsprofil D). Track distances as small as about 4.0 m were found during a track distance campaign led by Gröna Tåget in December 2013.

The evaluation shows that the swept envelope (based on the kinematic rules applied in Denmark) of the proposed future wide-body vehicle fit into the free space D on the concerned tracks for straight track and all curves with larger radii than 420 m. The local conditions at the current obstacles placed in more narrow curves are favourable making it possible to pass also these obstacles with the proposed vehicle. These conclusions are based on the 'installation limit' according to EN 15273.

The evaluation further concludes that the distance between adjacent tracks, with one exception, is large enough to comply with EN 'installation limits' for two identical wide-body vehicles. In fact, on all locations except one, there are considerable additional margins. The exception is tracks 61 and 62 at the Belvedere maintenance facility where the margin is smaller than required in the EN-standard. If operation with wide-body trains on both of these tracks is desirable, further detailed investigations are proposed, possibly including on-site tests.

The conclusion is that operation with proposed wide-body trains is technically possible from the Øresund link to København H and parts of Belvedere service depot with today's obstacles and track distances. The possible operational area can be expanded to cover København H – Helsingør as well, with moderate repositioning of current obstacles. As these conclusions are based on EN requirements rather than current general Danish rules, a positive attitude from Danish authorities is needed for final approval.

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1. Wide-body trains – why and how?

1.1 The Green Train programme

The Green Train (in Swedish, *Gröna Tåget*) is a research, development and demonstration programme with the overall objective to define an economical, flexible and environmentally friendly train concept [1, 2, 3]. The objective is also to develop technology for future high-speed trains for the northern European market, particularly for Scandinavia (Denmark, Norway and Sweden). Most technologies are also expected to be suitable for other world markets.

The programme has conducted fundamental analysis and research on the different issues as well as design and testing of new technologies. The programme is carried out in close cooperation between academia, industry, train operators, consultants and the Swedish Transport Administration. The total budget is some SEK 150 million (EUR 17 million).

The programme has covered many important areas, including economy, capacity and market aspects, conceptual design, vehicle gauging, traveller attractiveness and interiors, travel time, energy efficiency and noise, winter performance, track friendliness and carbody tilt, aerodynamics, electric propulsion and current collection. Important main goals are

- Attractiveness to passengers, in particular regarding travel time and interior design
- Low total cost per seat and passenger-km, allowing low fares and operator profitability
- Good reliability and availability, also at Nordic winter conditions
- Track friendliness, i.e. low track deterioration and ability to run on non-perfect track
- High capacity, as well as flexibility to suit different capacity needs
- Interoperability on the electrified main lines of Scandinavia
- Environmentally friendly, in particular low energy use per seat and low external noise.

The most important "green" effect of the Green Train is that the train will have a *high market share,* anticipating that the train has superior performance regarding energy use and emissions, compared with other means of transport.

1.2 Why wide-body trains?

To achieve the goals stated above, the train concept including the *sizing of the train* is a crucial issue. The *number of comfortable seats per metre of train* is a most important parameter for the overall capacity, total cost and energy use per seat or seat-km.

Combining the goals and demands above it turns out that a *wide-body* train is an appropriate solution for Scandinavia, provided that it is wide enough to comfortably convey 2+3 seats side by side in 2nd class and 2+2 in 1st class. An interior width of at least 3.3 m is then desirable for long-distance journeys, which would require some 3.5 m of exterior width. This will allow for an attractive middle seat also on the 3-seat side, with individual arm rests. In 1st class such a width will allow for some 15−25 cm space between the two seats in the same row, depending on the specific seat and aisle dimensions.

The most known example of wide-body trains are the Shinkansen trains in Japan, usually having an external width of 3.38 m and some 3.2 m of interior width at elbow height. Another example is the trains for S-banen i København.

According to investigations in the Green Train programme the following applies for a wide-body train, compared with a single-deck train of the standard width used in continental Europe:

- Total cost (per seat-km) is reduced by 10−15%
- Energy use (per seat-km) is reduced by about 15%
- Capacity is increased by about 25%.

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Another main consideration is *speed and travel time.* A short travel time will make the train attractive to many passengers and also enhance productivity, as more kilometres can be produced by the same train and train staff during a year. On many existing main lines in Norway and Sweden *carbody tilt* is very desirable for long-distance services, as the curving speed can be increased. Typically the travel time can be reduced by 10−15% on lines with considerable presence of curves. Therefore carbody tilt must be an option for the Green Train.

The alternative to a wide-body train would be a *double-decker,* offering about the same number of seats per metre of train. There are two reasons why a double-decker solution is not suitable in this case:

1. Carbody tilt and increased curving speed will not allow for a high carbody and a high centre of gravity.
2. Double deckers with a height of about 4.60 m cannot be accommodated within the available structural gauge on several main lines in Norway, in particular 'Bergensbanen' and 'Sørlandsbanen' where severe obstacles occur [9].

The reason why a double decker will not allow for more useful space and seats than a wide-body train is the need for staircases, the necessity of quite large separate luggage shelves (due to the very limited ceiling height) and the absence of 30−40 m^3 of space for technical equipment below the floor level (such equipment must be located above the floor in double-deckers). The latter is a substantial problem in motor coaches, i.e. powered cars with propulsion, with large volumes of equipment. Further, above the bogies only a single deck can be provided due to height limitations.

1.3 Wide-body trains in Scandinavia

Another crucial condition for the suitability of wide-body trains is, of course, that such a train can be made interoperable on electrified main lines in Scandinavia, i.e. that it can be accommodated within the available structural gauge without excessive and costly changes. This is the case for Sweden, since the Swedish gauge SE-A according to EN 15273-2 [5], Figure 1, is large enough for an exterior width of about 3.54 m for a full-length car (ca. 26 m with full width). The SE-C gauge could embrace a still wider carbody.

In Norway the gauge NO1 [7], taking account to the tightest structural gauge somewhere in the system, leads to a 0.10 m less wide vehicle than based on the Swedish gauge SE-A. However, a special investigation for the electrified main lines was made by Jernbaneverket in 2011. A limited number of obstacles of rocks in mountain tunnels and cuttings were found that were considered as possible to remove. Following this investigation Jernbaneverket judged that wide carbodies according to the Swedish standards can be allowed on these lines with few quite non-expensive removals of obstacles [8].

In a Scandinavian perspective, connections between Sweden and Denmark are very important, with highest priority for the København (Copenhagen) area, including Københanvn H (the Central Station) through the tunnels to the depot tracks at Helgoland. Also the line from København to Helsingør (46 km north of København) may be of future interest for the cross-border service Øresundstog between Denmark and Sweden. Although the distance from the Øresund Bridge to the Danish capital area is short, it is the key link for regional as well as long-distance passenger services from Sweden (and possibly Norway) to reach a commercial and social prime area. Wide-bodied trains would benefit these services by better economy and capacity but requires the final link to accommodate those trains.

The Øresund link Malmö - København is built for the Swedish gauge SE-A and is prepared for SE-C. The new Fehmarn Belt link is planned for the Swedish gauges SE-A and SE-C. It should be noted that *SE-A is sufficient for wide-body trains* defined as in this study.

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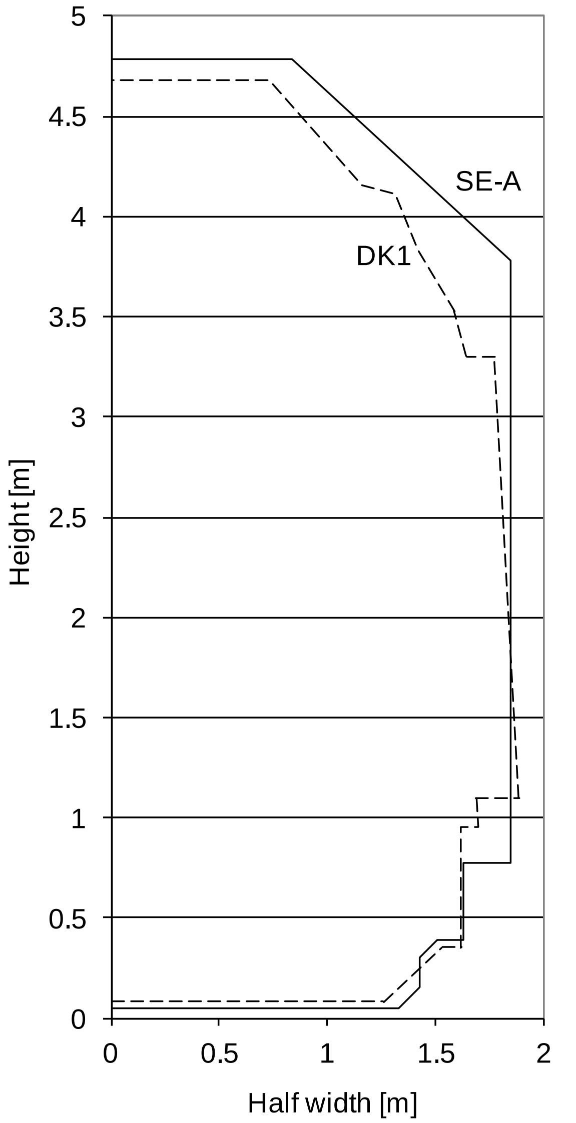

Figure 1: Reference gauges SE-A (Sweden) and DK1 (Denmark).

1.4 Scope of this study

The main scope of this study is to investigate whether it would be technically and economically feasible to run wide-body trains in the København area between the Øresund Bridge and Helsingør. The primary interest for rail operators between Denmark and Sweden is to get permission to operate its trains to København H (main station) and possibly also to the Helgoland depot. For a local operator service continuing to Helsingør could be of interest. However, the trains must also reach parking tracks, waste disposal stations and cleaning platforms. In a meeting in August 2012 Banedanmark reported what tracks are desirable to use for three different service scenarios [17], compare Figure 2. The examined track area covers the envelope of all three service scenarios, listed below.

1. Service over the Øresund Link into København H (main station). The trains are then reversed and run via a disposal station to cleaning platforms at Belvedere.
2. Service over the Øresund Link via København main station to Østerport station. Trains are then continuing to Helgoland for waste disposal and cleaning.
3. Service over the Øresund Link via København main station to Helsingør. Waste disposal and cleaning is made at Helsingør.

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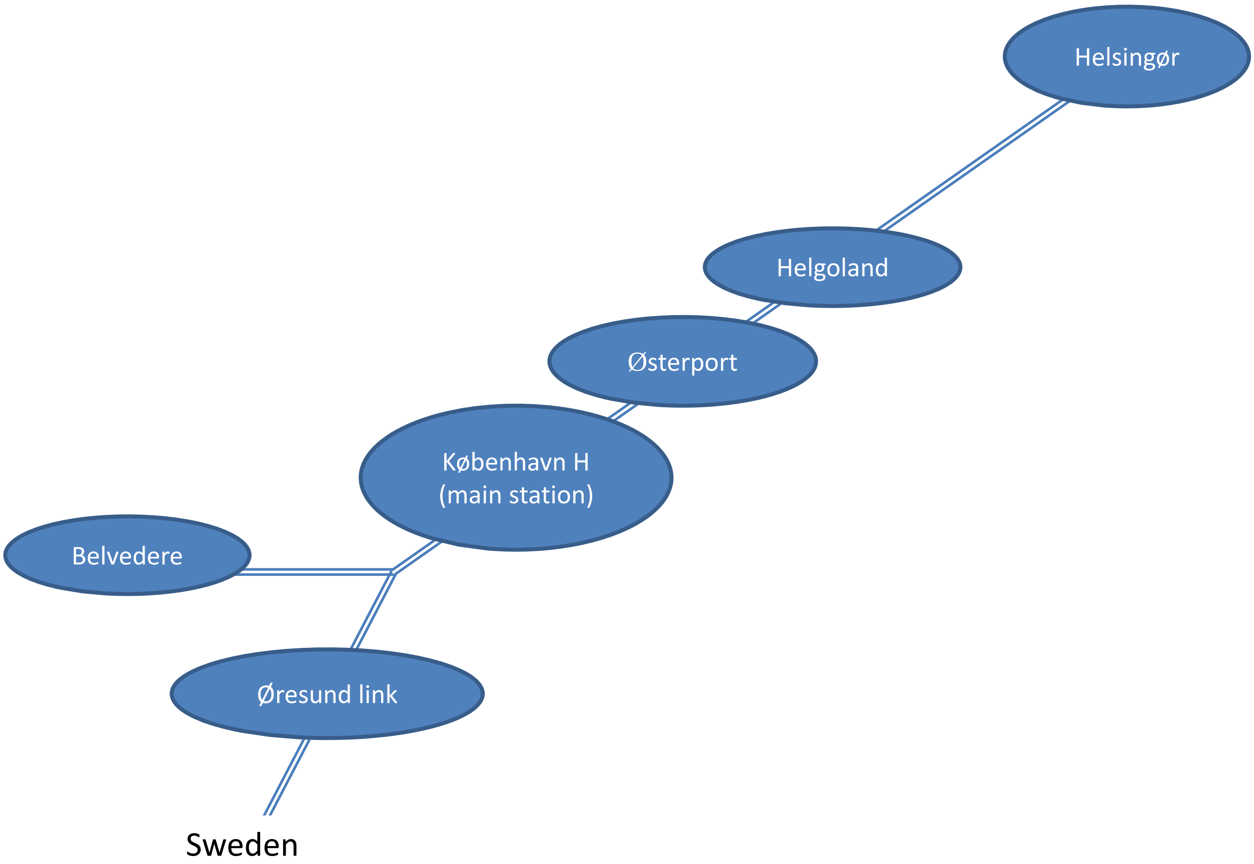

Figure 2: Principal track layout for the scope of the study

This investigation includes both the issue of *obstacles beside the track* and also the issue of *distance between two adjacent tracks*, where two wide-body trains are expected to meet.

As a result proposals for the exterior size of a wide-body train may then be possible. It would also be possible to propose inexpensive removal of obstacles along the line.

This study investigates under what conditions wide-body trains are feasible from a technical point of view. However, procedures for a formal application and acceptance will not be carried out in the Green Train programme. The latter has to be made by operators and/or train suppliers.

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2. European gauging standards

2.1 Methodology

The standard for European railway gauging is EN 15273 [4, 5, 6], in force since 2009. This standard includes most European national railway gauges and the methodologies associated to them, as well as the general interoperable standard also described in UIC 505 and 506. We are here limiting to those using a reference gauge to split the responsibility between infrastructure and vehicle. In general, gauging processes which include many simplifying (worst case) assumptions are easier to apply, while gauging processes which have fewer assumptions require more detailed input information and are more complex. However the use of detailed input information gives an opportunity to reduce the minimum permitted clearances without increasing risk. This trade-off is the reason why the different gauging processes have evolved.

The different methods referred to in this study are the *kinematic* and the *dynamic*. The kinematic method is used in Denmark and on most central European networks. The dynamic method is used in Sweden and Norway, and similar methods are used on the British Isles. The most important differences are:

1. The dynamic method applies the worst *likely* vehicle movements, while the kinematic usually applies *movements to the hard stops*.
2. The vehicle roll motion is by the kinematic method divided in one vehicle part, assuming track cant or cant deficiency of 50 mm, and one infrastructure part in case of cant or cant deficiency above the same value, also assuming worst-case roll flexibility of the vehicle (flexibility coefficient = 0.40). In the dynamic method the vehicle part is responsible for all vehicle roll, applying the actual roll flexibility and assuming the worst-case cant and cant deficiency.
3. The curve space-widening of the infrastructure is in the Central-European kinematic method made for a very short two-axle freight car (7.75 m length with full width). The dynamic method as applied in Sweden and Norway refers to a space-widening necessary for a coach-like vehicle with a length of 24 m with full width. For a long coach this gives a much larger reduction of the carbody width relative the reference gauge for the kinematic method than for the dynamic.

2.2 Clearance between vehicle and obstacles

There must be clearance between vehicle and obstacles as well as between different vehicles on adjacent tracks. Table 1 gives the minimum margins according to EN 15273-3 [6] for a kinematic gauge between the reference gauge and obstacles. The EN standard differentiates between three different limits:

1. Nominal installation limit. The nominal margin that should be attained for new installations.
2. Installation limit. The minimum margin that should be attained for new installations.
3. Limit. The margin that should be attained in service.

The installation limit (2) is considered to be the most relevant limit for the present study. This choice is based on that the limit (3) must be met also after some time in service when the track has moved within maintenance margins. The installation limit has been used throughout this study.

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Table 1: Parameters for calculating margin between reference gauge and obstacles with the kinematic method in EN 15273-3 [6] valid for all speeds and track qualities except where noted.

Parameter	Abbreviation	Value	Comment
Lateral track position	T_{track}	0.025 m	
Cross level error	T_{D}	0.020 m	0.015 m for speeds above 80 km/h
Vehicle suspension dissymmetry	T_{susp}	0.23°	
Vehicle loading dissymmetry	T_{load}	0.77°	
Vehicle oscillations	T_{osc}	0.013 m (inside) 0.065 m (outside)	0.007 m for good track quality 0.039 m for good track quality
Safety coefficient	k	1.2	
Height above top of rail	h		Variable in equations

For the installation limit, the EN standard assumes independence between the parameters and calculates the total margin according to Equation 1. With values for low speed and low quality track the total margin for obstacles on the outside of a curve becomes according to Equation 2. Figure 3 shows the installation limit margins for inside as well outside obstacles.

$$\Sigma_a = k\sqrt{T_{track}^2 + \left(\frac{T_D}{1.5}h + 0.4\frac{T_D}{1.5}(h-0.5)\right)^2 + \left(T_{susp}(h-0.5)\right)^2 + \left(T_{load}(h-0.5)\right)^2 + \left(0.4\frac{T_{osc}}{1.5}(h-0.5)\right)^2} \quad [1]$$

$$\Sigma_a = 1.2\sqrt{0.025^2 + \left(\frac{0.020}{1.5}h + 0.4\frac{0.020}{1.5}(h-0.5)\right)^2 + \left(tg0.23°(h-0.5)\right)^2 + \left(tg0.77°(h-0.5)\right)^2 + \left(0.4\frac{0.065}{1.5}(h-0.5)\right)^2} \quad [2]$$

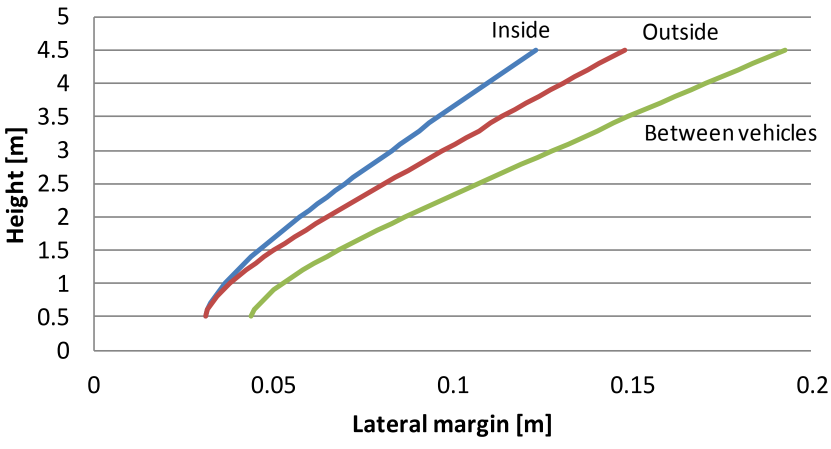

Figure 3: Installation limit margins for obstacles on the inside, on the outside and between vehicles on adjacent tracks at different heights for kinematic gauges.

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The margins prescribed by EN 15273-3 depend on the actual curve geometry (track cant) and the allowed cant deficiency. The infrastructure manager may also add own margins to the minimum ones according to EN. In the German EBO [16] an additional (but very limited) margin is applied, being dependent on the track cant and actual allowed cant deficiency. Denmark currently applies the same height-dependent margin for straight track and all curved tracks, independent on cant and cant deficiency.

Table 2 shows the margins between reference gauge and obstacle at a height of 1.8 m (being an approximate height where a wide carbody usually has its maximum width). It should be noted that margins for kinematic gauges take account for vehicle movements like suspension tolerance, loading dissymmetry, oscillations (= dynamic suspension movements) and worst-case carbody roll. Note that low track quality for low speeds is throughout assumed.

Table 2: Margins between reference gauge and obstacles as proposed for the kinematic rules in EN 15273-3 and margins applied by Germany and Denmark at 1.8 m height for speeds up to 80 km/h. D = track cant; I = cant deficiency.

Track case		Margins between reference gauge and obstacle		
		EN 15273-3 [6]	Germany [6, 16]	DK [10, 11]
Straight		59 mm	61 mm [1)]	147 mm
Inside curve,	D = 50 mm	53 mm	61 mm [1)]	147 mm
	D = 160 mm	91 mm	123 mm	147 mm
Outside curve,	I = 50 mm	59 mm	61 mm [1)]	147 mm
	I = 150 mm	94 mm	123 mm	147 mm

1) Track gauge limited to 1445 mm

- *The minimum margin between the reference kinematic gauge and obstacles according to EN 15273 is 53−94 mm at a height of 1.8 m, depending on actual cant and cant deficiency. They are applicable for modest track quality at speed up to 80 km/h. Germany applies 2−32 mm additional margin above the EN level. Denmark applies additional margins up to 94 mm. The independence of actual cant and cant deficiency in Denmark is the main cause to the difference.*

2.3 Clearance between two vehicles on adjacent tracks

Minimum margin according to EN between two vehicles is based on the margins calculated for the vehicle to obstacle in Section 2.2. The vehicle to vehicle margin is received by adding the margin for inside and outside obstacles (index 1 and 2 respectively) according to Equation 3. Table 3 shows the result at the height 1.8 m for low speed low quality tracks. The differences between EN 15273-3 and the local regulations are large at 1.8 m. The local additions are height dependent, at 3.25 m height Deutsche Bahn (DB) only adds 0.029 m to the values given by EN 15273-3. Banedanmark applies the smallest margin at 1.10 m, where they add 0.106 m. As for the vehicle-obstacle case (Section 2.2) the German EBO has a differentiated margin dependent on actual cant and cant deficiency.

$$\Sigma_b = \sqrt{\Sigma_{a1}^2 + \Sigma_{a2}^2} \qquad [3]$$

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Table 3: Minimum margins between two reference gauges proposed in EN 15273-3 and applied by Germany and Denmark at 1.8 m height for speeds up to 80 km/h. D = cant; I = cant deficiency.

Track case	Margins between two reference gauges		
	EN 15273-3 [6]	Germany [6, 16]	DK [10, 11]
Straight	79 mm	210 mm	294 mm
Curve D / I = 50 mm	79 mm	210 mm	294 mm
D = 160 mm / I = 150 mm	149 mm	330 mm	294 mm

- *The applied margin between two reference kinematic gauges on adjacent tracks according to EN 15273 is 79−149 mm at a height of 1.8 m, depending on actual cant and cant deficiency. They are applicable for modest track quality at speed up to 80 km/h. Germany applies up to 181 mm additional margin above the EN level. Denmark applies additional margins up to 215 mm. The independence of actual cant and cant deficiency in Denmark is the main course to the difference.*

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3. Obstacles and track distances

3.1 Obstacles

Infrastructure managers keep register of obstacles in the vicinities of the railway. Banedanmark has provided information on current obstacles [15] for tracks in the scope of this study, see Figure 2 for principal track layout. This information is based on measurements made in the period 2004 to 2013. A total of 27 obstacles were reported by Banedanmark that potentially could be restrictions for a wide-body train on the defined tracks of interest. Figure 4 shows one example of obstacle together with the required free space according to gauge D (Danish: Fritrumsprofil D) [11], strictly valid for other tracks than electrified main tracks, setting a minimum free space for existing tracks. The obstacle in Figure 4 is inside the required free space D, constituting an interference risk for any train.

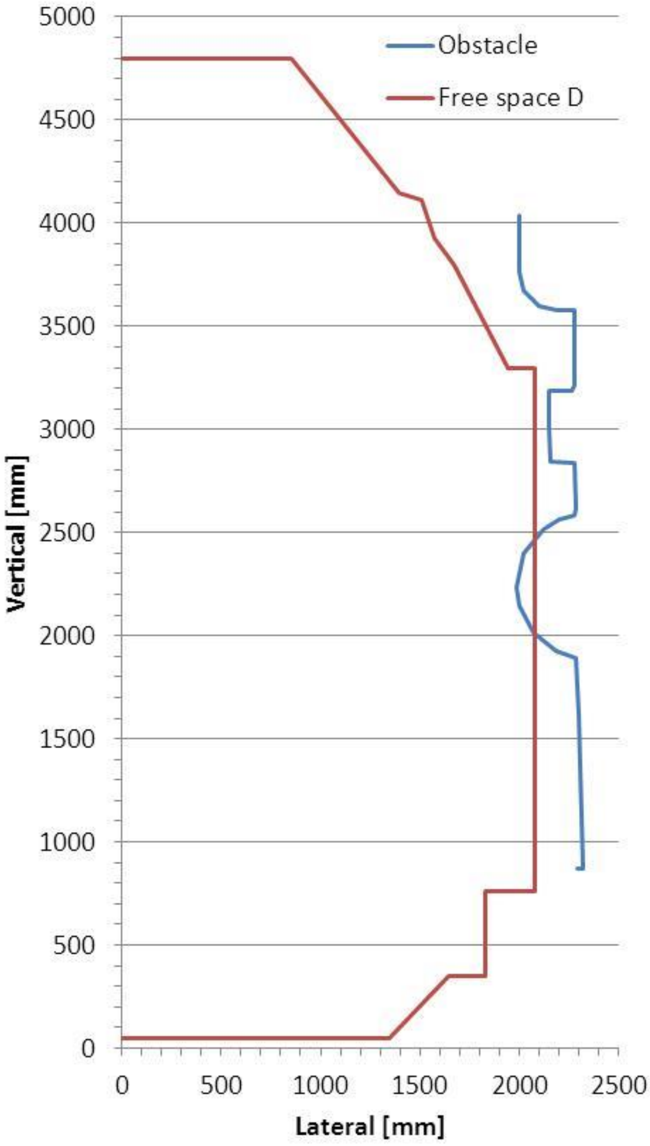

Figure 4: Signal H5a on track 5 at København H (main station) and free space according to gauge D [11]. The position for the obstacle (part of a signal) is taken from Banedanmark's register [15].

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Table 4 gives the list of potential obstacles for a wide-body train and their relation to the required free space D. Space widening in curves with smaller radii than 1500 m is considered.

Table 4: Potential obstacles [15] and their relation to the required free space D [11].

No	Line 2)	Position [km]	Radius [m]	Track	Obstacle	Distance to free space D [m]
1	Phm – Kh	3.801	Straight	1	Signal 11	**-0.012**
2	Phm – Kh	3.801	Straight	2	Signal 21	**-0.037**
3 1)	Kh - Ro	1.600	3066	1	Km sign	0.025
4	Phm – Kh	0.000	Straight	2	Platform barrier	**-0.108**
5	Phm – Kh	0.256	200	5	Signal H5a	**-0.090**
6 1)	Kh - Ro	1.430	Straight	6	Signal 2015	**-0.026**
7	Kh - Hg	0.360	1055	1	Signal E	**-0.280**
8	Kh - Hg	0.530	550	4	Signal F	**-0.086**
9	Kh - Hg	0.070	Straight	6	Signal G6a	0.050
10	Kh - Hg	1.330	800	2	Sign	0.058
11	Kh - Hg	1.360	2700	1	Signal 1013	**-0.002**
12	Kh - Hg	1.375	Straight	1	Sign	**-0.263**
13	Kh - Hg	1.790	Straight	1	Signal 1017	0.018
14	Kh - Hg	1.750	6000	2	Sign	0.027
15	Kh - Hg	1.760	Straight	2	Sign	0.025
16	Kh - Hg	1.790	Straight	2	Signal 2017	0.054
17	Kh - Hg	1.790	Straight	2	Signal 1017	0.002
18	Kh - Hg	3.060	2857	1	Sign	**-0.332**
19	Kh - Hg	2.098	Straight	4	Signal A	0.032
20	Kh - Hg	2.098	Straight	4	Signal B	**-0.011**
21	Kh - Hg	2.537	360	12	Signal E12	0.146
22 1)	Kh - Hg	2.777	34759	16 3)	Structure	0.010
23	Kh - Hg	4.989	Straight	1	Signal UD	0.018
24	Kh - Hg	5.435	719	1	Railing	0.051
25	Kh - Hg	7.038	2734	2	Signal A4	0.071
26	Kh - Hg	11.800	2358	2	Km sign	**-0.020**
27	Kh - Hg	46.146	Straight	1	Sign	**-0.267**

1) This obstacle is not within the examined track area
2) Hg = Helsingør; Kh = København H (main station)
Phm = Peberholm; Ro = Roskilde
3) Connecting track to S-bane

- *In total 27 obstacles were pointed out as possibly critical by Banedanmark. 3 of these are found to be outside the area in the scope of the present study. 12 of the remaining obstacles are located inside the free space D. Most of the obstacles are signals, but it is unclear if it is the signals themselves or signs associated with the respective signal. The infrastructure manager should have an own interest to clear the required free space.*

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3.2 Track distances

The track distance has been examined between obstacle poles, i.e. switching paths where only one train is allowed at the time are excluded. The distances are verified by two different methods, either laser measurements or by visual inspection. There have been three different measurement campaigns, 2009 by Banedanmark, 2011 by Infranord and the recently performed one by LKO 2013. Generally the last performed one is assumed to give the most accurate results as this was a dedicated track distance measurement and it is also the most recent one. One example result is given in Figure 5, which shows the track distance between the main tracks north of København H. This section includes the Boulevard tunnel around Nørreport station, known to have track distance around 4.0 m, which also the most recent measurements confirm. Slightly larger track distances are reported further north, more details in Table 5.

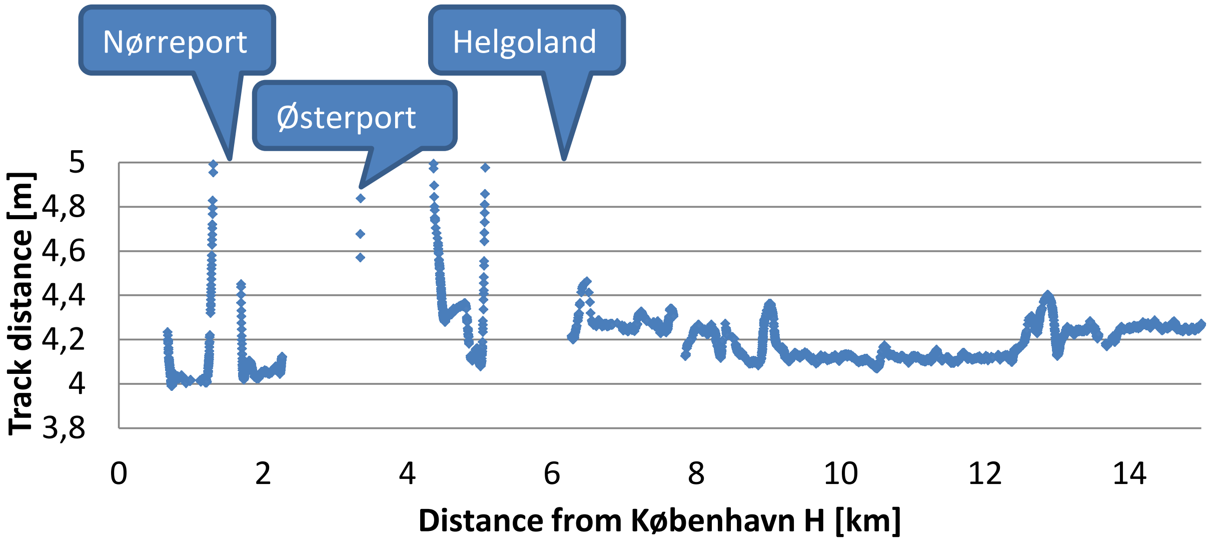

Figure 5: Track distance between the two main tracks north of København H (main station) as function of distance.

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Table 5: Summary of track distances.

Track section	Concerned tracks	Status and smallest noted track distance
Øresund link	Main	Measured 2011 About 4.5 m
Belvedere	61, 62, 63, 71, 72, 73b and 74	Measured 2013 4.00 m between track 61 and 62 at km 1.4
København H	1 – 8, 22, 24, 26, 30, 40, 41, 45, 50, 51 – 52 and 301 – 304	Measured 2013 4.16 m between track 45 and 46 at km 0.8 4.04 m between track 302 and 303 at km 0.3
København - Klampenborg	Main	Measured 2013 4.00 m at km 1.2
Østerport	1 − 4 and 12	Measured 2013 4.14 m between track 2 and 3
Helgoland	1 − 15	Visual inspection and partly verified with measurements 2013 About 4.25 m, but 4.14 m between track 2 and 3
Klampenborg	1 − 4	Measured 2013 4.30 m between track 3 and 4
Klampenborg – Helsingør	Main	Measured 2013 About 4.2 m, but occasionally as low as 4.07 m
Rungsted Kyst	1 − 3	Platform
Nivå	1 − 3	Measured 2013 About 4.5 m
Snekkersten	1 − 4	Measured 2013 4.45 m between track 3 and 4
Helsingør	1 – 3 and 31 – 33	Measured 2009 4.19 m between track 1 and 2
	10 – 15	Measured 2013 4.24 m between track 12 and 13

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4. Evaluation of existing wide-body train to current obstacles

4.1 Vehicle movements

In this chapter the vehicle to obstacle and the vehicle to vehicle clearances are calculated for an existing example wide-body vehicle (Swedish “Regina”, classes X50−X55) with properties according to Tables 6 and 7. The body cross section is shown in Figure 7. The movements include geometric overthrow in curves, rail to wheel displacement and worst case suspension displacements. The considered movements follow EN 15273-2 with rules applied to kinematic gauges and are given in Table 7.

Table 6: Vehicle properties. Cross section of the vehicle body is shown in Figure 7.

Property	Abbreviation	Value
Bogie distance	a	19.000 m
Bogie to carbody end	n_a	3.400 m
Bogie to carbody middle	n_i	9.500 m
Axle distance	p	2.700 m
Flexibility coefficient	s	0.24

Table 7: Considered movements according to EN 15273-2, kinematic rules.

Property	Curve with obstacle on inside	Curve with obstacle on outside	Straight
Lateral geometric overthrow	$\frac{1}{2R}\left[an_i - n_i^2 + \frac{p^2}{4}\right]$	$\frac{1}{2R}\left[an_a + n_a^2 - \frac{p^2}{4}\right]$	Not applicable
Lateral rail to wheel displacements	0 m	0.0275 m	0.0275 m
Lateral diagonal position rail to wheel	Not applicable	$\frac{a + n_a}{a}$	$\frac{a + 2n_a}{a}$
Lateral suspension displacement at bogie pivot	0.090 m	0.090 m	0.090 m
Lateral diagonal position suspension	1	$\frac{a + 2n_a}{a}$	$\frac{a + 2n_a}{a}$
Roll suspension displacements	$\frac{s}{30}(h - 0.5)$	$\frac{s}{30}(h - 0.5)$	$\frac{s}{30}(h - 0.5)$
Vertical geometric overthrow	Not considered	Not considered	Not considered
Vertical displacement at bogie pivot	0.115 m (down) 0.030 m (up)	0.115 m (down) 0.030 m (up)	0.115 m (down) 0.030 m (up)
Vertical diagonal position	1	$\frac{a + n_a}{a}$	$\frac{a + n_a}{a}$

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4.2 Vehicle to obstacle interference

The total movement is received by adding all the displacements in Table 7 together. The total movement is added to the nominal carbody size to give the position of the displaced carbody, see Figure 7. This is done for each obstacle individually at 1 m longitudinal steps for the vehicle to ensure that the minimum margin is found. Calculation is made for the carbody ends for obstacles on the outside and for carbody middle for obstacles on the inside.

The displacements are exemplified in Figure 6 for obstacle 5 at København H. Signal H5a is located on the outside of a short curve with radius 200 m. In this case, the two carbody ends get closer to the obstacle due to the curve when the carbody middle comes further away. In this case the vehicle risks interfering with the obstacle. Details for all obstacles are given in Table 8.

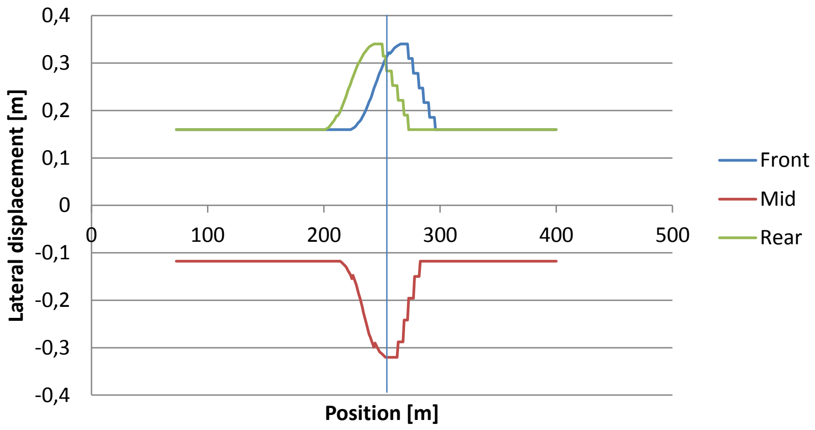

Figure 6: Carbody displacement as function of track position in the vicinity of signal H5a on track 5 at København H. The vertical line indicates the position of the signal.

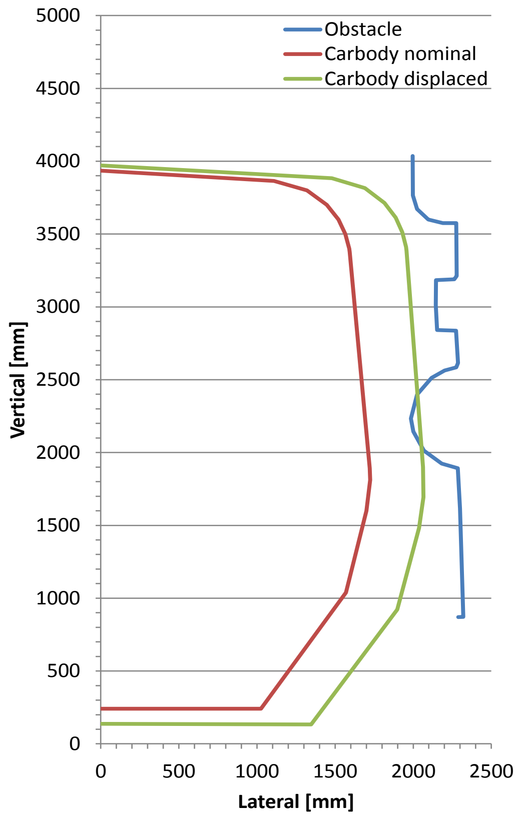

Figure 7: Carbody at nominal and displaced position at signal H5a on track 5 at København H

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Table 8: Minimum margins (EN 15273-3) and calculated additional margins to current obstacles.

No	Obstacle	Speed [km/h]	Radius [m]	Constant geometry +/-20m	Side	Critical height [m]	Minimum margin [2] [m]	Calculated additional margin [m]
1	Signal 11	120	Straight	No	Out	3.062	0.099	0.089
2	Signal 21	120	Straight	No	In	3.110	0.086	0.122
3 [1]	Km sign	70	3066	No	In	1.908	0.055	0.112
4	Platform barrier	40	Straight	Yes		1.908	0.062	**-0.060**
5	Signal H5a	40	200	No	Out	2.233	0.085	**-0.129**
6 [1]	Signal 2015	70	Straight	Yes		2.618	0.085	0.054
7	Signal E	50	1055	No	Out	3.229	0.105	**-0.218**
8	Signal F	50	550	Yes	In	2.274	0.064	**-0.022**
9	Signal G6a	40	Straight	Yes		3.417	0.111	**-0.006**
10	Sign	70	800	Yes	Out	1.669	0.055	0.077
11	Signal 1013	70	2700	No	In	2.207	0.063	0.099
12	Sign	70	Straight	No	Out	1.079	0.040	**-0.073**
13	Signal 1017	70	Straight	Yes		3.378	0.110	**-0.022**
14	Sign	70	6000	No	Out	1.669	0.055	0.071
15	Sign	70	Straight	No	In	1.689	0.050	0.138
16	Signal 2017	70	Straight	No	Out	3.517	0.115	0.023
17	Signal 1017	70	Straight	No	Out	3.366	0.110	**-0.040**
18	Sign	60	2857	No	Out	0.896	0.036	**-0.106**
19	Signal A	60	Straight	Yes		3.564	0.116	0.001
20	Signal B	60	Straight	Yes		1.689	0.056	0.078
21	Signal E12	40	360	No	In	2.485	0.070	0.193
22 [1]	Structure	40	34759	No	In	1.689	0.050	0.095
23	Signal UD	90	Straight	Yes	In	3.627	0.100	**-0.021**
24	Railing	90	719	Yes	In	1.988	0.069	0.092
25	Signal A4	70	2734	No	Out	2.118	0.069	0.114
26	Km sign	100	2358	No	In	1.777	0.052	0.069
27	Sign	60	Straight	Yes		1.148	0.041	**-0.084**

1) This obstacle is not within the examined track area according to Figure 2.

2) For kinematic gauges according to EN 15273-3 [6], installation limit. The real flexibility coefficient for the example vehicle is used.

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- *For the existing wide-body vehicle a total of 11 current obstacles are detected with less margin than the minimum ones required in EN 15273-3. The largest deficiency is 0.218 m and this is calculated for obstacle 7. Obstacles locations and lateral positions are according to Table 4.*

4.3 Vehicle to platform interference

The vehicle size must allow passing platforms at low speed up to the maximum permissible speed. København H is placed in a tight curve and could therefore be expected to be critical for vehicles with long carbodies as the example vehicle. The nominal platform height is 0.760 m, but measured height positions (relative to top of rails) are used here [13] together with nominal platform to track centre distances [14]. A calculation for the existing wide-body vehicle is shown in Table 9 using the kinematic rules in EN 15273-2. Calculations are made for all platforms on København H. Platforms on track 1, 3, 5 and 7 are on the inside of the curve, while the platform is on the outside for track 2, 4, 6 and 8. The carbody middle is the critical cross section for the inside platforms and the carbody ends for the outside platforms. The smallest margin is found for track 7 at position 0.278 km where the margin is equal to the minimum margins according to EN 15273-3 with fully worn wheels and suspensions fully displaced inwards and downwards, the latter including deflated air springs. Although this combination is very unlikely to happen it may strictly be possible.

Opening of doors should also be considered, in particular low entrance doors, which do not pass above the platform while opening. This calculation is made for curve-inside platforms at København H as the doors of the example vehicle are placed between the bogies. The calculation is based on the actual position of the doors in open position. When calculating on open doors placed inside bogies, the kinematic rules in EN 15273-2 reduce the carbody lateral displacement with 0.035 m compared to normally used displacements. Despite this, the example vehicle gives smaller calculated margins than allowed for two platform locations. For track 1 at 0.248 km the margin is 0.029 m and for track 7 at 0.278 km the margin is 0.006 m compared to the minimum margin of 0.033 m. However, interference between doors and platforms at zero speed is not a safety issue; the worst case would be some limited scratches on the door and the platform, and that the doors cannot be fully opened if the air springs are deflated.

- *All platform locations have at least the minimum vehicle to platform margin according to EN 15273-3. Margins smaller than the minimum are calculated for open doors at two platform locations, assuming deflated air springs. The small impact of a door to platform contact, as well as the low probability, should make the calculated margins acceptable.*

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Table 9: Calculated margins carbody to platform for the example vehicle.

Track	Pos [km]	Radius [12] [m]	Platform position: Measured height [13] [m]	Platform position: Nominal lateral [14] [m]	Minimum margin [m]	Calculated additional margin [m]
1	0.105	400	0.740	1.698	0.033	0.045
1	0.248	200	0.753	1.798	0.033	0.023
2	0.116	300	0.696	1.723	0.033	0.059
2	0.140	260	0.705	1.738	0.033	0.047
2	0.161	457	0.725	1.698	0.033	0.057
2	0.252	480	0.757	1.698	0.034	0.038
3	0.109	400	0.647	1.698	0.032	0.109
3	0.200	765	0.705	1.673	0.033	0.098
3	0.244	300	0.727	1.723	0.033	0.041
4	0.097	453	0.768	1.698	0.034	0.026
4	0.227	237	0.728	1.768	0.033	0.048
4	0.250	215	0.728	1.798	0.033	0.061
5	0.107	390	0.672	1.713	0.032	0.104
5	0.243	200	0.732	1.798	0.033	0.038
6	0.100	380	0.712	1.713	0.033	0.064
6	0.189	292	0.712	1.738	0.033	0.059
6	0.250	420	0.712	1.698	0.033	0.058
7	0.101	329	0.718	1.723	0.033	0.061
7	0.223	986	0.724	1.673	0.033	0.098
7	0.278	252	0.766	1.738	0.033	0.000
8	0.097	340	0.727	1.723	0.033	0.052
8	0.179	1895	0.724	1.673	0.033	0.096
8	0.216	215	0.711	1.798	0.033	0.073
8	0.257	2015	0.732	1.673	0.033	0.092
8	0.285	370	0.730	1.713	0.033	0.049

4.4 Vehicle to vehicle interference at adjacent tracks

4.4.1 Main tracks

The measured track distances need consideration of local conditions to judge if they are acceptable for service with wide-body vehicles. In particular the actual curve radius and the cant or cant deficiency is important, since these parameters influence the vehicle displacements.

Evaluation has been performed taking into account the movements in Table 6 and 7, the local track geometry and margins according to EN 15273-3 (kinematic gauges). The curvature has for the distance between main tracks been modelled with straight track, curve transitions, circular curves and the corresponding cant [12]. The calculation has been done for each recording of a track distance. The smallest additional margin (additional to the EN requirements) is calculated to 0.142 m at kilometre 0.740 just north of København H, compare Figure 8.

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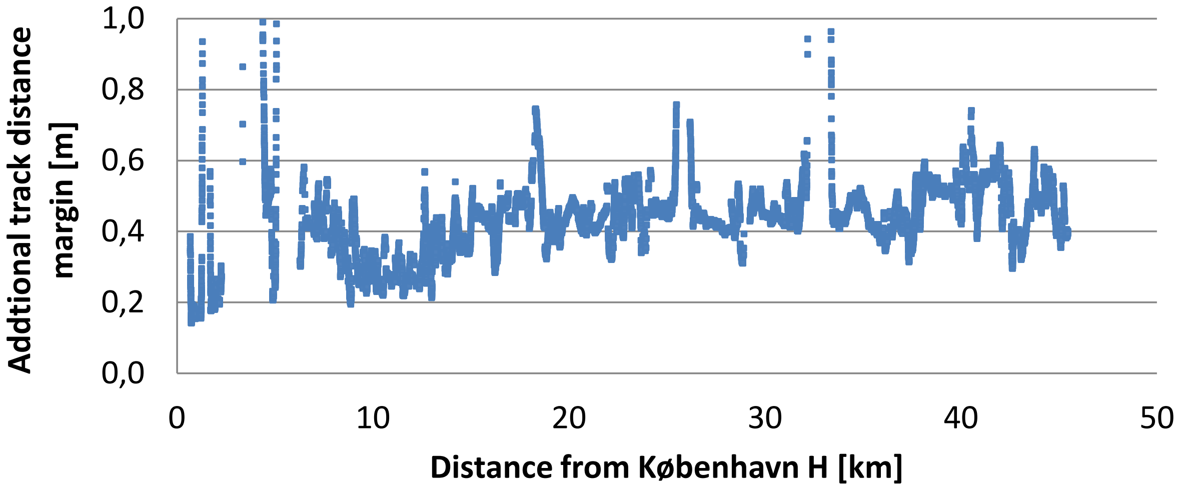

Figure 8: Additional track distance margin, between the main tracks København to Helsingør, compared with the minimum requirements for kinematic rules in EN 15273-3 [6].

- *All calculated margins between two identical (existing) wide-body vehicles on adjacent main tracks are considerably larger than the minimum margins stated in EN 15273-3 [6].*

4.4.2 Side tracks

In the first stage a simple method (A) has been applied for the side tracks, by assuming the tightest curve applied continuously, which leads to conservative results in most cases. The more precise method (B), used between main tracks in Section 4.4.1, is applied on side tracks in case that the margin calculated with the simplified method is small, see Table 10. This means that the actual variation of the curve radius through the site is considered.

All side tracks except one in the scope, according to Banedanmark [17] and Figure 2 in Section 1.4, have margins considerably larger than stipulated in EN 15273. The exception is the tracks 61 and 62 at Belvedere maintenance facility. The nominal track geometry is here taken from the adjacent main track, which gives some uncertainties in the result. With this uncertainty in mind the margin calculated by the kinematic method is only 0.007 m. This is the only measured track distance that leads to a smaller calculated margin between two vehicles than stipulated by the EN-standard. As said earlier, the kinematic simplifying assumptions regarding vehicle movements in suspensions and between wheels and rails are almost certainly conservative if added in combination. Comparing with a calculation made according to the dynamic rules according Annex J in EN 15273-2 (Sweden) increase the margin of about 0.100 m; an indication of the conservatism when applying the kinematic rules in this low-speed case.

- *It is concluded that all side track distances, except the one below, are considerably larger than stipulated in EN 15273-3, in order to attain safe passage of two identical existing wide-body vehicles on adjacent tracks.*
- *The distance between tracks 61 and 62 at Belvedere is smaller than stipulated by the EN-standard. As the curvatures on these tracks are not exactly known some uncertainties still remains. Further, comparison with dynamic calculation rules indicates conservatism when applying kinematic rules in this low-speed case. Hence, safe operation might still be possible but is uncertain; see also discussion in Section 6.1.*

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Table 10: Calculated margins for side tracks in relation to the minimum margins given in EN 15273-3 [6]. Method A assumes the tightest curve radii for the concerned tracks, method B takes the actual track geometry.

Tracks	Track distance [m]	Tightest curve [m]		Vehicle movements [m]		Calculated margin [m]		Minimum margin [m] 1)
		Track 1	Track 2	Vehicle 1	Vehicle 2	A	B	
Belvedere 61 - 62	4.000	300	300	0.289	0.254	**0.007**	**0.007**	0.079
Belvedere 62 - 63	4.482	300	300	0.289	0.254	0.489		0.079
Belvedere 63 - 64	4.412	300	300	0.289	0.254	0.419		0.079
Belvedere 71 - 72	4.182	0	0	0.160	0.160	0.413		0.079
Belvedere 73 - 74	4.044	0	0	0.160	0.160	0.275		0.079
Belvedere 74 - 75	4.192	0	0	0.160	0.160	0.423		0.079
Helgoland 2hsp - 3	4,138	1708	0	0,187	0,160	0,342		0,079
Helgoland 10 - 11	4.254	300	300	0.289	0.254	0.261		0.079
Helsingør 12 - 13	4.242	310	575	0.285	0.180	0.323		0.083
Helsingør 13 - 14	4.356	575	0	0.230	0.160	0.517		0.079
Helsingør 14 - 15	4.332	0	0	0.160	0.160	0.563		0.079
Hgl - Kk 2hsp - s	4.078	600	600	0.227	0.177	0.186	0.280	0.117
Klampenborg 1 - 2	4.330	0	590	0.160	0.178	0.525		0.096
Klampenborg 3 - 4	4.304	590	565	0.228	0.182	0.435		0.088
Kl - Hgl 2hsp - s	4,618	929	929	0,205	0,150	0,797		0,095
København 301 - 302	5.764	300	200	0.289	0.331	1.694		0.079
København 302 - 303	4.036	200	300	0.351	0.254	**-0.019**	0.267	0.079
København 303 - 304	4.232	300	225	0.289	0.305	0.188	0.239	0.079
København 304 - s	4.510	225	225	0.330	0.305	0.425		0.079
København 3 - 4/24	5.320	190	215	0.361	0.315	1.193		0.081
København 4/24 - 26	4.610	215	0	0.338	0.160	0.663		0.079
København 13 - 50	4.730	300	300	0.289	0.254	0.737		0.079
København 21 - 22	4.226	0	0	0.160	0.160	0.457		0.079
København 22 - 40	4.216	0	380	0.160	0.222	0.385		0.079
København 40 - 41	4.472	380	0	0.263	0.160	0.600		0.079
København 45 - 46	4.160	190	300	0.361	0.254	**0.078**	0.391	0.096
København 49 - 50	5.068	0	300	0.160	0.254	1.205		0.079
København 50 - 51	4.420	300	580	0.289	0.180	0.501		0.079
København 51 - 52	4.426	580	2350	0.229	0.120	0.627		0.079
Nivå 2 - 3	4.540	580	2800	0.160	0.117	0.814		0.079
Snekkersten 2 - 3	4.618	767	300	0.213	0.254	0.696		0.083
Snekkersten 3 - 4	4.450	300	320	0.289	0.244	0.462		0.083
Østerport 1 - 61	5.014	450	150	0.248	0.407	0.902		0.086
Østerport 2 - 3	4.144	491	483	0.241	0.196	0.247		0.089
Østerport 3 - 4	4.558	483	450	0.242	0.203	0.653		0.089
Østerport 4 - 12								
Østerport 4 - 16	4,552	1250	0	0,195	0,160	0,748		0,079

1) For kinematic gauges according to EN 15273-3

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5. Evaluation of proposed wide-body train

5.1 Vehicle movements

The vehicle to obstacle and the vehicle to vehicle clearances are calculated for a proposed future vehicle with properties according to Tables 11 and 12. The movements include geometric overthrow, rail to wheel displacement and worst case suspension displacements including deflated air springs. The considered movements follow EN 15273-2 (kinematic gauges) and are given in Table 12. Only the width at carbody middle is considered here as the carbody ends could be tapered if needed.

The body cross section is shown in Figure 9. In comparison with the existing wide-body vehicle described in Chapter 4, the vehicle exhibits the following changes:

- Total width 3.54 m instead of 3.45 m
- Reduction of width at upper corners: up to 200 mm
- Reduction of suspension displacements (in particular at small curve radii): up to 60 mm.

Table 11: Vehicle properties. Cross section of the vehicle body is shown in Figure 9.

Property	Abbreviation	Value
Bogie distance	a	19.000 m
Bogie to carbody end	n_a	3.400 m
Bogie to carbody middle	n_i	9.500 m
Axle distance	p	2.700 m
Flexibility coefficient	s	0.20

Table 12: Considered movements according to EN 15273-2, kinematic rules

Property	Movement
Lateral geometric overthrow	$\frac{1}{2R}\left[an_i - n_i^2 + \frac{p^2}{4}\right]$
Lateral rail to wheel displacements	0 m
Lateral diagonal position rail to wheel	Not applicable
Lateral suspension displacement at bogie pivot	0.030 m
Lateral diagonal position suspension	1
Roll suspension displacements	$\frac{s}{30}(h - 0.5)$
Vertical geometric overthrow	Not considered
Vertical displacement at bogie pivot	0.115 m (down) 0.030 m (up)
Vertical diagonal position	1

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5.2 Vehicle to free space interference

This study is made with reference to the free space D (Danish: Fritrumsprofil D), which according to Banedanmark is the minimum space required on the existing København H and the line to Helsingør. However, margins must be considered as obstacles may be just outside the required free space.

As a basic requirement minimum margins (installation limit) according to EN 15273-3 [6] are applied here. Both margins and movements according to Table 12 are deducted from the free space D to determine the maximum size of the carbody. A proposed carbody may then be drawn inside the limitation, compare Figure 9. Not even this methodology leads to a sufficiently wide carbody with a desired maximum width of at least 3.50 m for the smallest curve radii.

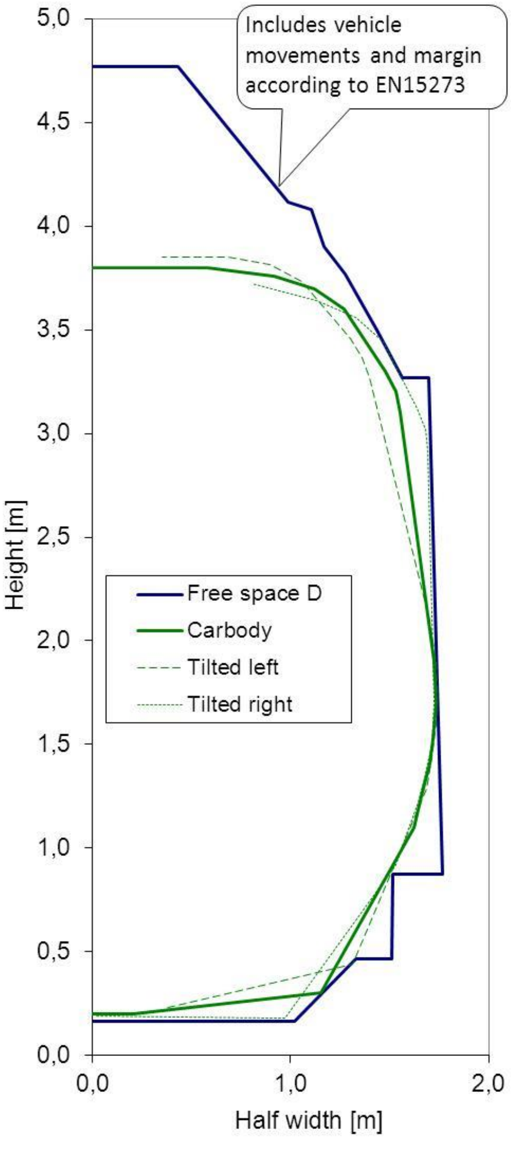

Figure 9: Free space D with vehicle movements and margins deducted. Proposed carbody size shown in neutral as well as tilted positions.

The free space D is sufficient for a 3.54 m full-length wide carbody for straight track as well as all curves with radii down to 420 m, applying the EN rules. There are two current obstacles placed in curves with smaller radii in track areas within the scope of present study. Obstacle 21 has a considerable margin to the free space D and is unproblematic. Obstacle 5 is placed inside the free space D in a 200 m circular curve and must be moved to clear the free space D. The tight radius requires an additional 75 mm to be cleared according to the kinematic rules making it possible for the proposed vehicle to pass the obstacle within the margins applied.

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5.3 Vehicle to platform interference

The proposed wide-body vehicle has smaller lateral suspension displacements compared to the existing example vehicle. This could be used to increase the carbody width at platform height or to increase the margin is deemed necessary.

5.4 Vehicle to vehicle interference at adjacent tracks

The proposed future wide-body vehicle takes less space than the existing due to its smaller lateral suspension displacements compared with the existing example vehicle. As a consequence, the proposed vehicle can run on tracks with smaller track distances between adjacent tracks, despite the wider body. As the existing wide-body vehicle has large margins on main tracks (see Section 4.4), the proposed future vehicle has still larger margins.

However, not even the proposed future wide-body vehicle meet the minimum distance requirements according to EN 15273 for tracks 61 and 62 on the Belvedere maintenance facility. As said in Section 4.4 there are several uncertainties. Safe operation with two wide body vehicles on these tracks might still be possible but is uncertain; see also discussion in Section 6.1.

The minimum track distance as function of curve radii is shown in Table 13. The calculation is made for a "worst case" with high cant and cant deficiency and for a case with 50 mm cant and cant deficiency. The latter is a minimum case which should be considered even if the installed cant or cant deficiency is lower also including straight track.

Table 13: Minimum track distance as function of curve radii allowing two proposed vehicles to meet at adjacent track. Margins according to EN 15273-3 are included.

Curve radii [m]	Minimum track distance [m] Cant = 160 mm cant deficiency = 150 mm	Minimum track distance [m] Cant = 50 mm cant deficiency = 50 mm
250	4.217	4.105
300	4.150	4.039
400	4.067	3.956
500	4.018	3.906
600	3.984	3.873
700	3.961	3.849
800	3.943	3.831
900	3.929	3.818
1000	3.918	3.806
1500	3.885	3.773
2000	3.868	3.757

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6. Discussion and conclusions

6.1 Obstacles, track distances and restrictions

12 obstacles are currently positioned inside the free space D on the track sections investigated. Adjustments of these positions are enough for safe operation of the proposed future wide-body vehicle, according to the requirement (installation limit) in EN 15273. The existing wide-body example vehicle would require additionally a few obstacles to be moved. All of them are signs, signals or platform barriers. From the present supplied information it is not clear whether the signal obstacles are the signals themselves or signs associated with the respective signal. Although the practical implications of adjusting the position of these obstacles are not part of this study, it is anticipated that their positions can be adjusted at moderate costs.

The evaluation of track distances results in large margins in addition to the EN requirements for two identical wide-body vehicles on adjacent tracks. This is for all investigated track locations except one. The exception is between track 61 and 62 at Belvedere maintenance facility, although some uncertainties remain. Excluding the use of this facility for wide-body trains may be one option, but it might also be possible to exclude the use of track 62 only. Another option is to perform on-site tests to investigate the real margin at practical operations. Finally, it might be possible to shift track 61 sideways if deemed necessary.

6.2 Use of alternative margins

The kinematic gauging rules have been applied for vehicle movements and margins according to EN 15273 throughout the study. The rules for calculation of vehicle movements are known to be quite conservative. However, each infrastructure manager may also apply additional margins.

For vehicle to obstacle Germany apply 2 − 32 mm additional margin at a height of 1.8 m, where the highest value is for inside curves at high cant. Denmark currently adds 53 - 94 mm, the largest addition is for inside curves at low cant. Use of German or Danish additional margins requires that a few more obstacles are moved to fulfil the criteria. German additional margins at platforms will exclude use of track 7 at København H for the existing vehicle, while the proposed future vehicle can be designed with less generous width at platform height. Use of Danish additional margins at platforms will not allow the existing vehicle to stop at or pass any platform at København H. This is mainly because there is no dependence on cant or cant deficiency in the current Danish rules. The proposed future vehicle will in such a case get a severe width restriction at platform height giving reduced floor width making it difficult to comfortable seat 2 + 3 seats in a row.

In section 4.4.1 the smallest additional track distance margin was calculated to 0.142 m for the existing wide-body vehicle. The German requirement on additional margin is also fulfilled with a marginal of 0.011 m. 0.073 m is lacking to fulfil the current Danish requirement on additional margin. The proposed future vehicle fulfils both the German and the Danish requirement on additional margins.

6.3 Conclusions

An optimum wide-body vehicle for Sweden and Norway will not fit into the Danish gauge DK1. However, operation with wide-body trains is technically possible from the Øresund link to København H and parts of Belvedere service facility with today's obstacles and track distances. The possible service area can with anticipated modest infrastructure adjustments be expanded to cover København H – Helsingør as well, including side tracks.

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12 obstacles are currently positioned inside the free space D on the track sections investigated, and they are anticipated to be repositioned. Doing so will allow the *proposed* future wide-body vehicle to run without risk of infrastructure interference on the studied tracks. The *existing* wide-body example vehicle would require additionally a few obstacles to be moved.

The distance between track 61 and 62 at Belvedere maintenance facility is the only track distance with smaller margin than required in the EN-standard. If operation with wide-body vehicles on both tracks is necessary, further detailed investigations is proposed.

The present study has shown that is it technically possible to run wide-body trains in the Copenhagen area, but a positive attitude from the Danish authorities is needed for approval.

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