Submitted for World Congress on Railway Research (WCRR´01), Köln, Nov. 2001
Paper 99

EXTRA WIDE-BODY PASSENGER TRAINS IN SWEDEN
- background and introduction

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Summary

Besides higher average speed and a higher number of yearly train kilometres, an improved space utilisation is a very efficient mean to increase productivity and reduce train traffic cost. One of the possibilities to do so is to introduce high-powered wide-body multiple unit trains.

The first extra wide-body trains in Sweden are 3.45 m wide in comparison to the ordinary Swedish width of about 3.10 m. This provides good possibilities to furniture the cars with 2+3 comfortable seats in second class and 2 + 2 seats in first class. The increased space utilisation makes it possible to shorten the average length of future passenger trains by about 20 %. Thereby the operators' cost per passenger kilometre can be reduced by 5 - 10 %.

Passengers´ preferences have been investigated in a number of studies at KTH during the 1990´s. The preferences are presented as willingness-to-pay for various kinds of measures. For example, a six-month study investigated passengers' seating preferences in older regional trains with normal width and 2 + 2 as well as 2 + 3 seating. It was found that the preference for sitting 2 + 2 instead of 2 + 3 is very weak, as on average about 2 % of the ticket price. Most of the time the “middle seat” is not occupied, which contribute to a higher value for the adjacent passengers. Passengers' acceptance for wide-body trains is confirmed by a survey on ordinary trains.

A lot of other factors are much more important than passengers' valuation of 2 + 3 seating. Instead, wide-body advantages are more directly related to train operations, through reduced cost, increased capacity and lower energy consumption.

The introduction of wide body trains in Sweden is a practical result of strategic research at the Railway Group of KTH (KTH = Royal Institute of Technology, Stockholm)[1].

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1 The research of the Railway Group is multidisciplinary and is concentrated on analysing technical solutions, the potential of cost reductions as well as passengers' preferences of different types of facilities and services.

1. Background

Many people judge train travel being too expensive and in a few case not attractive enough.

1.1 Train travelling is costly

The ordinary ticket-prices for second class train travelling in Sweden is in the order 0.1 – 0.15 EURO per km. Flying is often more expensive but going by bus or car on longer distances is about half the cost. Long distance buses charge about 0.05 - 0.06 EURO per km. That is about the same price level as if two persons go by car, considering peoples' own cost estimation of car driving.

With this in mind the Railway Group at KTH in Stockholm has studied ways to reduce cost for train services.

1.2 Trains are not always attractive enough

Many modern long distance train services, especially new high-speed trains, have attracted many new travellers. At medium and regional distances trains have sometimes harder to compete with buses and cars. In addition to high ticket prices these trains are not attractive enough. Our studies show for example that regional commuters have high demands on comfort, often as high demands as the business travellers [12].

2. Competitiveness

Our conclusion is that we must reduce cost for train services. We believe it is necessary to approach the cost level of bus services and car driving to reach a good market share in the future. At the same time it is very important to design train services with high attractiveness.

2.1 The potential for cost reductions

To investigate the potential for cutting the cost of passenger train traffic, an economic cost model was developed [12, 14]. It is based partly on the Swedish National Rail Administration’s (Banverket) model for cost calculations and partly on internationally available cost data. The model has been used to define the cost and cost elasticity in terms of a number of parameters. The results reveal that the utilisation of space is one of the most important parameters. Space has an elasticity value of 0.5 (a 10% increase in the utilisation of space reduces the cost per passenger-kilometre of train traffic by 5%), given Swedish circumstances.

Mathematically elasticity is defined by the formula:

$$Elasticity = \frac{\Delta y / y}{\Delta x_1 / x_1}, \quad where \quad y = f(x_1, x_2 \ldots.)$$

for the influencing factors x_i

Cost elasticity rates of some of the influencing factors have been summarised. Figure 1 shows some of these elasticity rates. This shows that the elasticity rate for space utilisation is comparatively high – higher than that of many other factors that are frequently addressed.

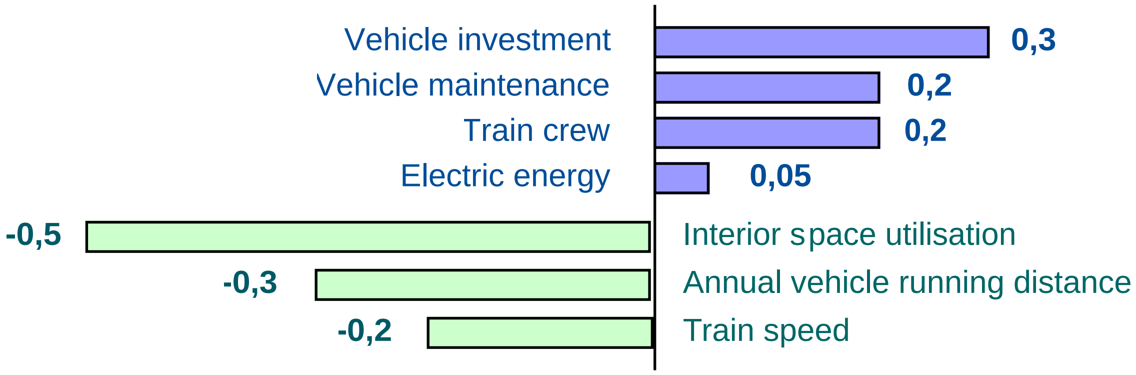

***Figure 1**. Cost elasticities; traffic cost change at marginal changes of various influencing factors.*

2.2 Space utilisation

The conclusion is that the cost level can be significantly reduced, if trains can be reduced in size, while retaining the same number of seats. Figure 2 illustrates the idea or concept of space utilisation, which is to make shorter trains for a given number of passengers. In this example space utilisation is raised by three means:

2. The second train, the EMU, has traction equipment and passenger seats in the same vehicle, i.e. the separate power vehicle (locomotive) is omitted.
3. The second train does not have a separate café, but ambulant catering at the seats.
4. The second train is wider, permitting 2 + 3 seating.

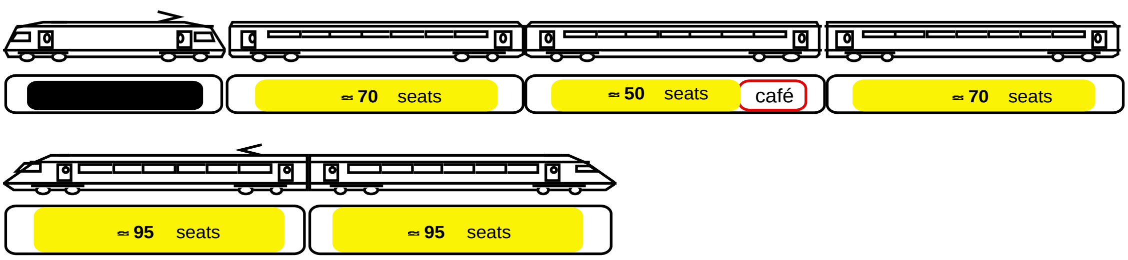

***Figure 2.** Increasing space utilisation – using smaller trains for the same seating space. Although being an extreme case the picture compares the principal difference between a short loco hauled train and a wide multiple unit train with the same number of seats.*

Two interesting options for increased space utilisation are double-deckers and wider carbodies. Both have a potential to reduce the train operator's cost for passenger services.

European single-level high-speed Inter-City trains have typically 2 – 2.4 seats per metre of train. The French TGV-Douplex is a *double-decker* with about 2.8 seats per train metre. However, the Japanese *wide-body* Shinkansen trains provide approximately 3.3 seats per train metre [1]. The high space utilisation in Japan is partly due to the lack of a restaurant car (ambulant food service is provided) and a quite small proportion of first class accommodation, however the Japanese benchmarking shows the potential of the wide-body concept.

Potentially a double decker can have up to 50 % more seats than a single decker and a wide train with 2 + 3 seating can have up to 25 % more seats than a train with 2 + 2 seating. With these presumptions both concepts have a potential to reduce the train operator's cost by 5-10 % [12].

It is however judged by KTH that *double-deckers and wide-body trains have in reality about the same numbers of seats per train metre, other factors being equal.* (This is at least the case if trains are quite short (150 – 500 seats) or have a high demand on power.) This might be surprising. However, it must be kept in mind that the technical equipment in a double-decker train must either be accommodated in a separate power unit (locomotive) or within the carbody of a multiple-unit vehicle. In a single-level train, also in wide-bodies, most of the equipment can be accommodated in the available underfloor space of the passenger car, typically 30 – 35 m^3.

The potential for cost reductions by wider trains

It is natural to associate the analysis of the number of seats with an increase in carbody width, which permits the same seat width as in the 2nd-class coaches of today. A coach that is 3.4 - 3.5 m wide could be furnished with five seats of about the present width. The wall thickness should be kept down.

The following estimate has been based on SJ data relating to the distribution of investment and maintenance costs for different technical systems[2] in small regional EMU-trains. In table 1, "factor" stands for the cost increase that is regarded as reasonable for a wider car.

Table 1. *Estimated differences in investment and maintenance costs for wide-bodied versus normal cars.*

	Investment			Maintenance		
	Normal (%)	Factor	Wide car	Normal (%)	Factor	Wide car
Running gear	12	1	12	17	1	17
Propulsion equipment	24	1.03	26	13	1	13
Brake & pneumatics				15	1	15
Electrical assembly	11	1.05	11.6			
Carbodies	14	1.1	15.4	1	1	1
Heating/sanitation	10	1	10	7	1	7
Interior	29	1.1	32	47	1.1	52
Total	100%		107%-units	100%		104%-units

2 SJ Technical Division

The estimation above indicates that wide-bodied vehicles are 7 % more expensive to purchase and 4 % more expensive in terms of maintenance costs per vehicle. Kurz & Reemtsema at DB [16] indicate an increase in price of 14% for wide-body trainsets (of the same length). This is twice as much as our calculation shows. The premises for their calculation are not explicit.

Using cost elasticities, we can calculate the new cost level. This means that the total traffic costs should increase by $0.3 * 7\% + 0.2 * 4\% \approx 3\%$. This is illustrated in the following diagram.

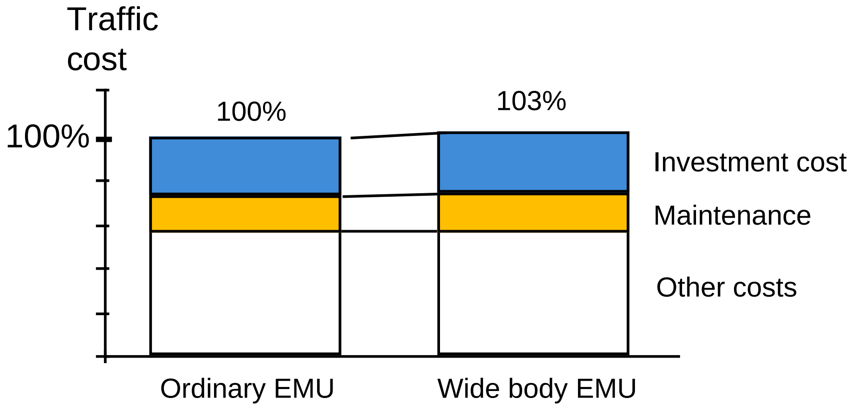

***Figure 3**. Graphic illustration of total traffic cost increase for wide-body EMU trains in service (These cost figures do not take account of the possible increase in the number of seats.)*

The increase in the number of seats reduces the costs in proportion to the space elasticity of 0.5. A coach with an extra row of seats ought to have 25% more seats, but, in some areas, e.g. near the vestibules, it is not feasible to have more than four seats side by side. So, if it is assumed that a wide-bodied coach has 91-93 seats instead of 95 and that this is compared with the 76 in an ordinary second class coach of today, 92/76 = 121% i.e. 21% more seats (Kurz & Reemtsema calculate 22% more seats).

The result is about 10% reduction in traffic costs, excluding the impact of the increase in the operator's total traffic cost for wider-bodied train. If this cost increase of 3% is included, we arrive at 10-3% = *7% lower cost per seat-kilometre* for wide-bodied vehicles with a 3 + 2 seating arrangement.

2.3 Passengers' acceptance of sitting 3+2

Among railway professionals it has been discussed and sometimes questioned whether wide-body trains are attractive to passengers, if used as to accommodate more seats. In particular, the issue of the “middle seat” when sitting 2 + 3 has been discussed.

As an improvement in the utilisation of space can be suspected to have a negative effect on comfort, this issue has been studied in detail. Passengers’ behaviour and valuations have been investigated in a number of studies using stated preference interview technique [6, 7], at KTH during the 1990´s. Preferences are presented as willingness-to-pay for various kinds of measures [14, 21].

Our first studies (presented in [9]) focused primarily on space-related comfort attributes such as legroom, reclining backrests and the number of seats side by side (across the width of the car). The value of complete interior design concepts has been studied in new and refurbished trains, such as Swiss and German double deck trains as well as German and Swedish InterRegio cars [8, 13, 17].

The 2 + 3 study

A six-month study in 1996 [5] investigated passengers' seating preferences with four methods. The data was collected on regional trains having an outside width of about 3.1m. It is then possible to use a 3 + 2 seating arrangement using bus seats (≈48 cm) but not using the standard train seat width (≈53 cm).

The study started by observing in what way people choose seats from main stations where the train was empty, or almost empty. Figure 6 shows an example of the seats that were taken during one observation. This revealed passenger preferences.

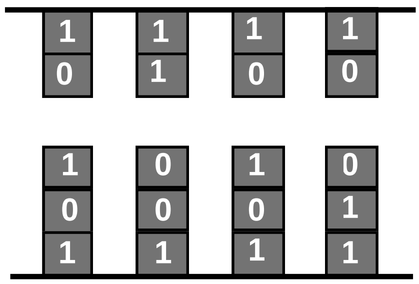

Figure 4. *An example of an observation in an X14 car. Grey represent seats, 1 = occupied, 0 = free seat.*

Passengers on the same trains were then interviewed using three Stated-Preference (SP) methods. A computer interview contained a standard pair-wise choice experiment (SP1) and a best/ worst experiment about similar attributes. Finally, a second SP experiment (SP2) was conducted in which people had to choose seats on drawings with seat arrangements, where only two seats were still free.

Sitting by the window and having the adjacent seat free are the requests with the highest values on a utility scale. Although face-to-face or face-to-back had an average value close to zero, it ranked fairly high in terms of importance. Clearly passengers have strong views about the way they sit in this context, but their preferences differ.

Table 2. Values of attributes used for the evaluation of 2 + 3 seating [5].

Attribute	Value (%) of fare
Sitting by the window	+7.5
Sitting at the side where there are three seats aside	-2,0
Sitting in the centre seat of three seats	-4.7
Sitting in a narrow seat	-2.4
Having your own armrest	+5.6
The seat beside you is free	+11.6

For each seat in the train the relevant attribute values can be summarised. (The attribute of not having one's own armrest has not been used in the calculations for the diagram below.)

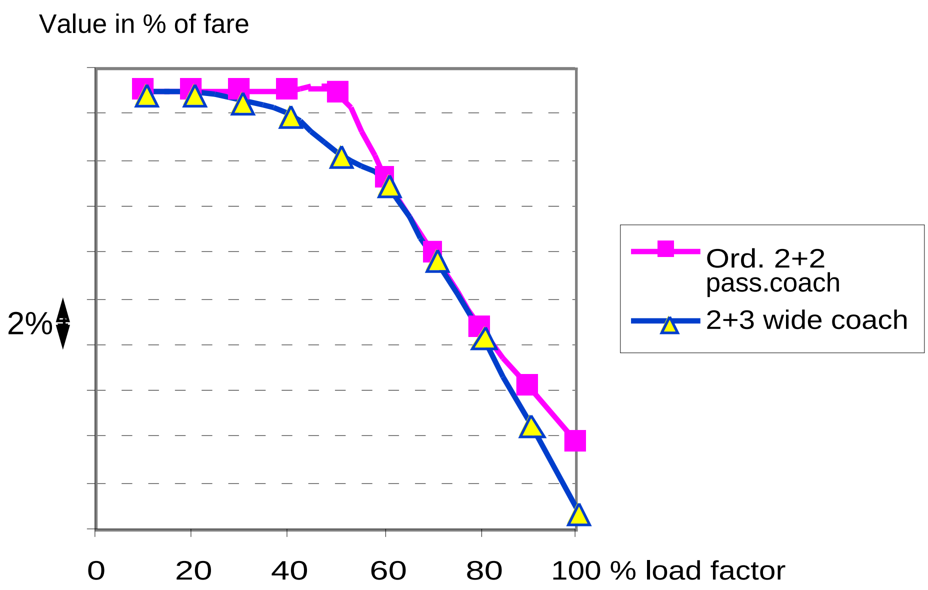

Figure 5. *The (relative) average value of having a seat at different load levels. It can be seen that the value of comfort decreases rapidly with the load factor. The maximum difference between 2 + 2 and 2 + 3 seating is 2-3 % at about 50% and 100% load factors; the average difference is lower.*

It can be seen that the large variation in seat value depends on, or correlates to, the load factor. The value of getting a seat decreases by 15 - 20 % from a situation in which there are few passengers on board and everybody has a window seat with no passenger next to them to the situation in which almost all the seats are occupied. The difference between 2 + 2 and 2 + 3 seating is much smaller, with an average of 1 –2 %. Most of the time the "middle seat" is not occupied, which contribute to a higher value for the adjacent passengers.

The result of this work was confirmed 1998 when an ordinary Swedish InterCity coach was rebuilt with 2 + 3 seats in part.

Figure 6. *Interior of the "InterRegioMax" test coach with 2 + 3 seating. Photo: Kottenhoff)*

Even that study [11] showed that passengers' valuation of travelling in a, in this case hypothetical wide-bodied coach with 2 + 3 seating is slightly negative, corresponding to 2 % of ticket price. This means that passengers' willingness-to-pay is two per cent lower on average when travelling in a wide coach with 2 + 3 seating. (The ordinary width coach with 2 + 3 seating received lower value; about -6 % of the ticket price.)

3. Space efficient trains in other countries

In some countries there are capacity problems on certain lines. There can also be capacity problems in railway stations, more or less related to limited length of platforms. One solution is trains with higher capacity where the double-decker is the most used. In France, Germany, and Switzerland the cost reduction aspect has also been mentioned.

Wide-body is not a quite new thing, it has been used in special train systems. The best example is the Japanese high-speed trains “Shinkansen”; most of them built as wide-body trains with about 3.4 m width. The advantage is that this allows five seats (2 +3) abreast, which raises capacity.

In Japan there are also some 3.40 meter wide Shinkansen trains which are double-deckers. In some of their coaches there are 2 + 3 seats in the lower level and 3 + 3 seats in the upper level. The latter seat arrangement of course gives a significant reduction of comfort.

Figure 7. *The Japanese "MAX"- Multi Amenity Express is a high-speed train with double decks and wide body. The name suggests not only high capacity but also high comfort. (Photo: Kottenhoff)*

In Continental Europe ordinary passenger-coaches are 2.8-2.9 metres wide but some newer vehicles are wider. The Danish State Railways has developed and introduced local trains in Copenhagen that are 3.6 metres wide, facilitating six seats aside. NSB in Norway has a sleeper coach in service that is 3.24 m wide and 27 m long.

Table 3. Examples of existing train types with wider bodies.

Denmark	S-bane trains	3.60 m
Denmark	IC/3	3.10 m
Norway	Sleeper coach	3.24 m
Germany	ICE	3.07 m
Holland	SM90 (wide body) [4]	3.20 m
Japan	Shinkansen	3.38 - 3.40 m

There are even examples on wide-body trains in European continental countries, where UIC regulation are often used:

The reasons for wide carbodies are not always to increase capacity. In the German ICE trains that are 3,07 meters, increased comfort – wider interior dimensions – was the reason. DB (Deutsche Bahn) is now evaluating even wider trains; new generation trains about 3.3 – 3.4 metre wide. Wide-body trains have been compared with double-deckers and their conclusion was that the wide-body-trains are more cost-effective [16].

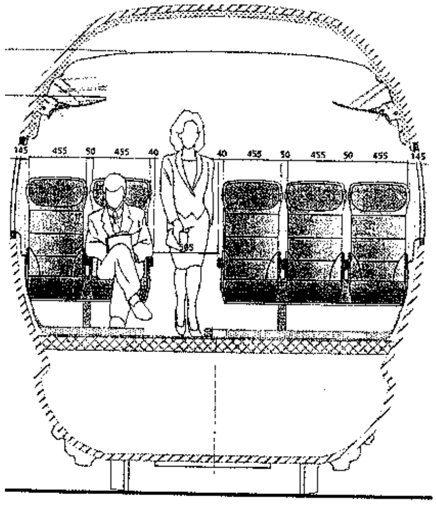

Figure 8. *An outline for wide future German ICE trains, as sketched by DB [16]*

4. Wide-body train introduction in Sweden

It is concluded that wide-body trains would be one of the means of improving the competitiveness of rail services. Wide-bodies is an alternative to the higher double-deckers, with some inherent advantages over the latter.

4.1 Wide bodies and the infrastructure

A most important issue is whether wide-body trains can be accommodated within the structural gauge of the railway. KTH conducted an initial investigation on this issue [1, 2]. It was concluded that it would be possible to accommodate a carbody width of 3.4 - 3.5 m at “elbow height”, within the present structural gauges in Sweden and Norway, likely also in Denmark. It was assumed that the defined structural gauges could be used without excessive margins, partly using advanced gauging techniques based on simulations rather than simple and conservative geometric rules. It was also assumed that wide-body trains must not approach sidings and industrial tracks with loading platforms with upper edges typically 1.15 – 1.20 m above top of rail.

The structural gauge in Sweden is defined by the Swedish National Rail Administration (Banverket); see Figure 9. This authority also has to approve any rail vehicle running on the Swedish national tracks. Figure 9 also shows the normally used loading gauge A, according to Swedish standards.

Based on the KTH-study [1, 2] the Swedish industry (Bombardier Transportation Sweden, former Adtranz Sweden) made a feasibility study on the concept of wide-body trains. In early 1998 the company made a decision to go ahead with a detailed design and to introduce this concept into the market. The finally proposed and built train is shown in Figure 10, with cross-section in Figure 9. The maximum outside width is 3.45 m over a length of 25.8 m.

In the feasibility stage the possible vehicle gauge was studied in co-operation between Banverket, Bombardier (former Adtranz) and possible rail operators. The conclusions of the feasibility study can be summarised as follows [20]:

- The wider body can be accommodated in the region above loading platforms (1.20 m above rail), although exceeding the present Swedish standard loading gauge.
- The vehicle cross-section has to be narrowed in the lower regions, in order to suit existing platforms up to a height of 0.73 m (0.78 m including margins); see Figures 9 and 10.
- Passengers waiting on platforms (from height 0.55 m and up) with passing wide-body trains will not experience any excessive inconvenience. This is partly due to the fact that a modern train with smooth exterior produces comparatively slight air turbulence.
- The trains should be restricted not to approach sidings with loading platforms.
- Approval should initially be made on a line-to-line basis, because the wide-body trains do not comply with the present Swedish standards (practically this process has in most cases run very smoothly).

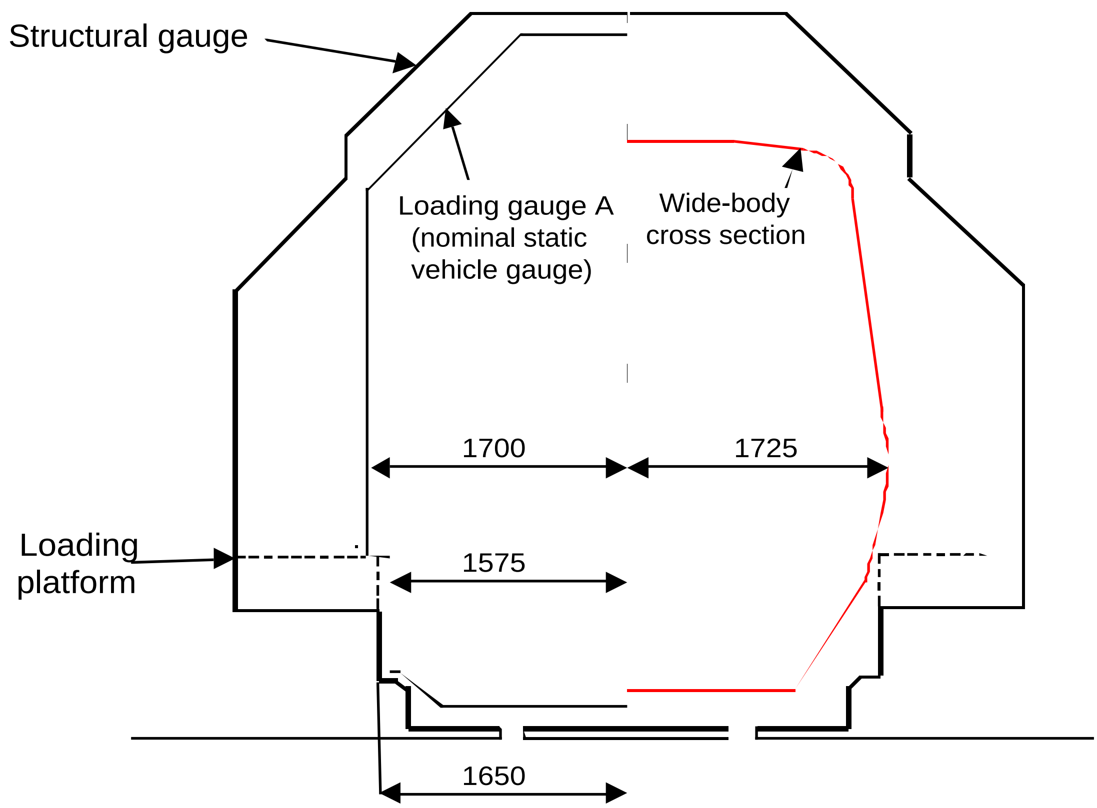

Figure 9. *Structural gauge and nominal vehicle gauge (loading gauge A) in Sweden. Also the new wide-body section is shown. Note that in Sweden and Norway the structural gauge is widened in curves in order to accommodate a 24 m long bogie vehicle without any reduction in vehicle width.*

Figure 10. *The newly developed wide-body train, called Crusaris Regina. (Photo: Adtranz/Bombardier)*

4.2 The Regina train

The newly developed trains are called *Crusaris Regina*. Bombardier Transportation has up till June 2001 orders on 108 cars, to be delivered in 2- and 3-car consists. These units will operate on different regional train services and have a great flexibility to operate in trains from 2 cars up to 12 cars. The first train was put into regular service in January 2001. The main features are as follows:

Table 4. *Crusaris Regina features*

Crusaris Regina	
Maximum speed:	180 or 200 km/h.
Car length, over couplers:	26.95 m (end car); 26.60 m (mid car)
Acceleration, full load:	0.8 m/s^2
Exterior / interior width	3.45 / 3.19 m
Maximum power:	1590 – 2600 kW per pair of cars
Weight per car, empty:	ca 60 tonnes
Carbody built in stainless steel	
Number of seats per car	90 – 110 (2nd class, incl. tip-up seats)
Seating, 2nd class:	2 + 3 (normally)
Seating, 1st class	2 + 2 (normally)

Toilet for disabled and wheelchairs

Wheelchair space and wheelchair lift

Passenger opinions

In the summer 2001 a survey was made by one of the regional transit companies (*X-Trafik*), which has introduced train services with the newly developed wide-bodied Crusaris Regina, with travel time up to 2 hours. In total, 375 ordinary more or less experienced regional passengers responded to the survey, thereby expressing their overall graded valuation on the new trains as well as making their own spontaneous comments. A total of 312 comments (positive or negative) were made on comfort, train interiors and facilities, covering most aspects from chairs, ride quality and noise, air conditioning, space, general appearance, boarding and debarking convenience, etc. (in addition there were still more comments on timetables, station convenience, train crew, etc.). It is interesting to note, that just one (1) negative comment was made on the 3-seating arrangement and another three slightly negative comments on the width of the chairs (which can be related to carbody width). On the contrary, there were six positive comments on “spacious appearance”, which may be interpreted as a positive feeling partly due to the wider interior space. The latter effect has not been indicated or discussed before, and needs to be studied more closely.

From this interview and previous KTH studies it is concluded that *wider carbodies with 2 + 3 seating is of almost no significant concern to most train passengers* . In fact, there are very few passenger reactions to it.

5. Future research and development

The trains of today are still quite heavy. In the future, new composite-materials and also further development of electric equipment can make trains lighter. It will also be possible to reduce the number of technical systems and produce an all-electric train. This in combination with standardisation of components and larger series by using the same wide body modular train for different markets will likely on a longer term cut the price off [1, 2, 10].

Another important factor for increasing productivity and reduce cost is higher average travelling speed, improving the productivity of both trains and train crew. This will also contribute to increased willingness-to-pay and increased market share. It is shown that different measures taken together can reduce the total traffic cost by 30-50 % in the future [1, 10].

Further research by KTH has shown that wide-body trains can be used on many markets [18], not only high-speed, InterRegio, local and regional trains but also for day-and-night trains. To make night-trains profitable it is necessary in the future to design trains that can bee used both in night-service and in day-service. The wide body is a prerequisite to design a comfortable night compartment with two beds along the side-wall, for night travel, which can be transformed to a seating compartment with four seats for day-travel [19].

Another conclusion is that a future InterCity high-speed train (200 – 800 km) very closely resembles the InterRegio train (20 – 300 km) in terms of design and performance, for example a maximum speed of 200 - 300 km/h. Conclusions from studies reveal that the customer requirements in both these segments are rigorous and fairly similar [12, 13, 17]. It should be possible to design *one* modular concept being so flexible that it can be used on different markets, from regional to medium and long-distance.

Thereby the railways can buy larger batches of rail vehicles and use a number of small and frequent multiple-unit trains. These can be multipled in peak-hours instead of operating a few long loco-hauled trains. With frequent direct-trains in combination with trains stopping at many stations it will be easier for the railways to compete with cars, bus and plane. The competitiveness will then rely on frequency and speed as well as on price, comfort and service.

For space-efficient trains, it is important to continue research and development to fully understand the relations between used space, experienced space [15], ergonomic factors and passenger's positive / negative feelings, as well as their willingness-to-pay. It is also important to implement such research into improved train designs, including comfortable and space-saving chairs.

The first application in Sweden is for fast regional trains with travel time up to 2 hours. The maximum interior width is 3.19 m at "elbow height". It is also desirable to develop trains with even higher comfort in the long term. It is then favourable to increase interior width to at least 3.3 m. In such a case it is important to introduce new wall designs with reduced thickness (and maintained strength). An active suspension will reduce the lateral spring travel and thus allow a further 50 – 70 mm of carbody width within the same carbody dynamic envelope.

Further, it is highly desirable to develop standardised advanced methods for vehicle gauging, based on simulations, thus making it possible to fully utilise the available structural gauge.

6. Discussion and conclusions

A fundamental technical and economic analysis on efficient and attractive passenger train operations has been conducted in a university-based research environment (*Railway Group of KTH)*, in co-operation with Swedish industry, rail administrations and rail operators [1]. Conclusions of this analysis are partly under implementation. Among others, a first version of wide-bodied trains is developed and introduced on Swedish regional lines. The wide-body train is an alternative even to double-decker trains, having advantages in many cases:

- level floor within the train making it possible to arrange ambulant catering service,
- lower centre of gravity, possible carbody tilt and higher curving speeds,
- simpler interior construction.

On the other hand it is quite easy to arrange a level entrance in a double decker from normal height platforms (550 - 600 mm) to the lower deck.

By use of cost elasticity ratios we have calculated a double decker with 50% more seats to be 5 - 10 % cheaper in service than ordinary trains. This is about the same as for wide-body trains. The problem is that many real double-deckers are not that space-efficient, making it less cost efficient than the wide train concept. On the other hand, passengers' valuation seems to slightly be in favour of the double-decker. The willingness-to-pay is slightly positive for the double decker [13, 17].

The general advantages of space-efficient trains are higher capacity, lower energy consumption and - most important to us - lower cost per passenger kilometre.

In some other countries, for example Japan, Switzerland and France space-efficient trains have been introduced mainly for capacity reasons. Given the infrastructure (signalling, platforms etc) the possible number of trains per hour and the maximum length of trains are constant. Thus *the capacity, expressed as number of seats per hour, is essentially proportional to the number of seats per train metre.*

Energy consumption is to a large extent dependent on the train mass and on the aero-dynamic drag. By increasing the number of passengers per train metre, both of these factors will be heavily reduced, expressed as per seat. It is concluded that *energy consumption per seat-km is reduced almost inversely proportional to the number of passengers per train metre* [3].

A wide-body train with 20 - 25% more seats will be about 5-10 % cheaper for the (Swedish) operator. The reason is that shorter trains have lower investment, maintenance and energy costs. This will - in principle - make it possible to reduce the ticket costs in the future. If ticket costs are reduced by more than 2 % most passengers will prefer the wide 2 + 3 trains before ordinary 2 + 2 trains.

It is believed that it would be possible to further develop the wide-body concept, also in other countries than Sweden.

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